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Estimation of the quantity of metals to phase out fossil fuels in a full system replacement, compared to mineral resources

Simon P. Michaux

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Michaux, S. P. 2024. Estimation of the quantity of metals to phase out fossil fuels in a full system replacement, compared to mineral resources. *Geological Survey of Finland, Bulletin 416,* 293 pages, 88 figures, 111 tables and 12 annexes.

The task to phase out fossil fuels is now at hand. Most studies and publications to date focus on why fossil fuels should be phased out. This study presents the physical requirements in terms of required non-fossil fuel industrial capacity, to completely phase out fossil fuels, and maintain the existing industrial ecosystem. The existing industrial ecosystem dependency on fossil fuels was mapped by fuel (oil, gas, and coal) and by industrial application. Data were collected globally for fossil fuel consumption, physical activity, and industrial actions for the year 2018.

The estimated sum total of extra annual capacity of non-fossil fuel power generation to phase out fossil fuels completely, and maintain the existing industrial ecosystem, at a global scale is 48 939.8 TWh.

A discussion on the needed size of the stationary power storage buffer to manage intermittent energy supply from wind and solar was conducted. Pumped hydro, hydrogen, biofuels and ammonia were all examined as options in this paper. This study uses four stationary power buffer capacities: 6 hours, 48 hours + 10%, 28 days and 12 weeks. This power buffer is assumed to be supplied through the use of large battery banks (in line with strategic policy expectations).

An estimate is presented for the total quantity of metals required to manufacture a single generation of renewable technology units (EV's, solar panels, wind turbines, etc.) sufficient to replace energy technologies based on combustion of fossil fuels. This estimate was derived by assembling the number of units needed against the estimated metal content for individual battery chemistries, wind turbines, solar panels, and electric vehicles. The majority of the metals needed were to resource the construction of stationary power storage to act as a buffer for wind and solar power generation.

It was shown that both 2019 global mine production, 2022 global reserve estimates, 2022 mineral resources, and estimates of undersea resources, were manifestly inadequate for meeting projected demand for copper, lithium, nickel, cobalt, graphite, and vanadium.

Keywords: energy, fossil fuels, oil, gas heating, coal, nuclear energy, solar energy, wind energy, hydroelectric power stations, transport, vehicle classes, electric cars, batteries, hydrogen, rail traffic, shipping, aviation, ammonia, metals, recycling, minerals, production, reserves, resources

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PREFACE

The green and digital twin transition is in many ways the defining societal, industrial, technological, and academic trend of our times. The main goals of this transition are to rid the world from the use of fossil fuels and their emissions, while at the same time decoupling the consumption of natural resources from the economic growth necessary to maintain modern living standards. The technological requirements of the twin transition make it above all also a raw materials transition that shifts the focus away from fuel-centered economies towards material-centered processes. Instead of oil, coal, and gas, the renewable energy system requires an increasing amount of various metal raw materials such as lithium, copper, nickel, and many others.

The raw materials transition also enables an economy that can circulate a significantly larger proportion of the raw materials needed for energy production, storage, and distribution technologies than before. The broad adoption of the principles of the circular economy is one of the cornerstones of enabling the efficient development of the new energy systems, as it is becoming increasingly clear that the amounts of materials required to manufacture and maintain the needed technologies are most likely larger than previously anticipated. Transitioning to a renewable energy system will require a significant increase in the production of many metals, which can potentially impose a strain on global reserves and also necessitate an initial increase in primary production and mining operations, in addition to the development of circular processes.

The two contributions published in this Special Issue of the Bulletin of the Geological Survey of Finland highlight that a successful transition to renewable energy requires a comprehensive raw materials strategy that considers both the upstream metal demands and the downstream infrastructure needs. In technological and innovation space, exploring alternative battery chemistries, improving recycling rates, and developing more resource-efficient technologies will be crucial to mitigating the strain imposed on metal supply chains.

The earlier work of the sole author of these two papers has been widely quoted, debated, and criticized in the media and amongst policy makers and academic audiences in the past few years. The premises, process, and conclusions of these studies have questioned the validity of some of the basic assumptions underlying the current energy and natural resource policy, but have still, largely mistakenly, been taken as a statement in favor of the *status quo*. On the contrary, these contributions are intended as the beginning of a discourse and attempt to bring alternative, often overlooked, views into the discussion about the basic assumptions underlying the material requirements of the energy transition. Out of necessity, they make simplifications in recognizing and mapping out the scale of some key challenges in the raw materials sector that need to be overcome if the energy transition is to be realized. Calculations and estimations need to be refined and, naturally, in addition to raw materials production and the material transition, other crucial aspects such as technology and infrastructure development, workforce requirements, land use changes, and societal impacts, among others, also need to be considered.

Nevertheless, the challenges related to the complex and interconnected nature of the problem should not be taken as a cause to halt the development and innovation needed to overcome it. Further research, policy interventions, and international collaboration are all essential in securing sustainable supply chains, promoting responsible sourcing practices, and ensuring a just and equitable green and digital transition for everyone.

Espoo 30.9.2024

Aku Heinonen
Director, Science and Innovations

SCOPE OF THE REPLACEMENT SYSTEM TO GLOBALLY PHASE OUT FOSSIL FUELS

by

Simon P. Michaux[1*)]

Michaux, S. P. 2024. Scope of the replacement system to globally phase out fossil fuels. *Geological Survey of Finland, Bulletin 416*, 5–172, 50 figures, 51 tables and 10 annexes.

The task to phase out fossil fuels is now at hand. Most studies and publications to date focus on why fossil fuels should be phased out. This study presents the physical requirements in terms of required non-fossil fuel industrial capacity, to completely phase out fossil fuels, and maintain the existing industrial ecosystem. The existing industrial ecosystem dependency on fossil fuels was mapped by fuel (oil, gas, and coal) and by industrial application. Data were collected globally for fossil fuel consumption, physical activity, and industrial actions for the year 2018.

The number of vehicles in the global transport fleet was collected by class (passenger cars, buses, commercial vans, HCV Class 8 heavy trucks, delivery trucks, etc.). The rail transport network, the international maritime shipping fleet, and the aviation transport fleet was mapped, in terms of activity and vehicle class. For each type of vehicle class, the distance travelled was estimated. Non-fossil fuel technology units that are commercially available on the market were used as examples for how to substitute fossil fuel supported technology. For each vehicle class, a representative commercially available example was selected, for Electrical Vehicle and Hydrogen fuel cell systems. Biofuels and ammonia ICE was also considered. The requirements to substitute the ICE rail network and the maritime fleet with EV and hydrogen fuel cell systems were presented. It was assumed that the performance specifications of each selected example were representative for that vehicle class. The quantity of electrical energy required to charge the batteries of a complete EV system was estimated. The quantity of electrical energy to manufacture the required hydrogen for a complete H_2 Cell system was also estimated. An examination and comparison between EV and H_2 Cell systems was conducted. Other fossil fuel industrial tasks like electrical energy generation, building heating with gas and steel manufacture with coal were mapped and requirements for non-fossil fuel substitution were estimated. The estimated sum total of extra annual capacity of non-fossil fuel power generation to phase out fossil fuels completely, and maintain the existing industrial ecosystem, at a global scale is 48 939.8 TWh. This builds upon an existing 9 528.7 TWh of non fossil fuel electrical energy generation annual capacity. If a non-fossil fuel energy mix was used (based on an IEA prediction for 2050, IRENA 2022) was assumed, then this translates into an extra 796 709 new non-fossil fuel power plants will be needing to be constructed and commissioned. A discussion on the needed size of the stationary power storage buffer to manage intermittent energy supply from wind and solar was conducted. Four calculations of the size of the power buffer were done (6 hours, 48 hours, 28 days and 12 weeks). Pumped hydro, hydrogen, biofuels, battery banks and ammonia were all examined as options in this paper.

Keywords: energy, fossil fuels, oil, gas heating, coal, nuclear energy, solar energy, wind energy, hydroelectric power stations, transport, vehicle classes, electric cars, batteries, hydrogen, rail traffic, shipping, aviation, ammonia

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Abbreviations: short names of some terms used are listed here.

ICE	Internal Combustion Engine
EV	Electric Vehicle
H_2-Cell	Hydrogen fuel cell
RoW	Rest of World
LHS	Left Hand Side
RHS	Right Hand Side
tkm	tonne-kilometer, tonnes transported over one kilometre
kJ/passenger-km	kilojoules per passenger transported over one kilometre
kJ/tonne-km	kilojoules per tonne transported over one kilometre
GT	Gross Tonnage
TEU	Twenty-foot equivalent is an inexact unit of cargo capacity, often used for container ships
CAPEX	Capital Expenditure
	Graphic often used (World Map Image by Clker-Free-Vector-Images from Pixabay)

1 INTRODUCTION

It has been widely proposed that fossil fuels should be phased out as they are widely recognized to be the main origin of the industrial pollution from energy consumption, which in turn causes the generation of anthropogenic greenhouse gas (GHG) emissions, also termed climate change. Climate change, however, has happened on Earth throughout geological time. But a school of thought, now backed by legislation for mitigation, proposes that human industrialization is driving the current warming cycle (IPCC 2013). The largest driver of warming is the emission of greenhouse gases, of which more than 90% comprise carbon dioxide (CO_2) and methane. Fossil fuel burning (coal, oil, and gas) for energy consumption is the main source of these emissions, with additional contributions from agriculture, deforestation, and industrial processes. There are a number of issues and concerns associated with the continued use of fossil fuels (oil, gas, and coal). Fossil fuel energy sources are finite natural resources. A school of thought is that all fossil fuels will become depleted over time and reach peak production, thus become unreliable as a stable source of economically viable energy, and that the oil and gas industry could soon become unreliable in energy supply (Michaux 2019), and an 'after oil' plan is required to be operational in the next few years. Fossil fuels are therefore required to be replaced as a matter of urgency.

This study addresses the challenges around the ambitious task of phasing out fossil fuels (oil, gas, & coal) that are currently used in vehicle Internal Combustion Engine technology (ICE), in industry, and for electrical energy generation. The question to be answered is, if all fossil fuels were completely phased out, what would be required in context of all the industrial tasks done by oil, gas, and coal if they were performed by 'green' non-fossil fuel technology? How many non-fossil fuel technology units, and of what kind would be required, to deliver the existing set of physical work done by society? The approach undertaken was to examine what would the scope of physical tasks be if the existing fossil fuel supported industrial system was phased out with non-fossil fuel systems in a direct replacement, where the existing capability was maintained (Michaux 2021). The calendar year of 2018 was selected to be the basis of the study due to the availability of data. An estimate of the following was conducted:

- Number of vehicles, by class in the current ICE system, to be replaced by Electric Vehicles (EV's) and hydrogen fuel cell vehicles (H_2-Cell).
- Number and size of batteries that would be needed, and the estimated electrical energy required to charge them over the set time frame.
- An understanding of the EV to H_2-Cell transport fleet split, when one system would be used over the other
- The size of the required hydrogen economy, based on some basic assumptions
- Estimates of a completely non-fossil fuel rail transport network (both EV & H_2-Cell)
- Estimates of a completely non-fossil fuel maritime shipping fleet (both EV & H_2-Cell)
- Estimates of producing global ammonia demand with the use of Green Hydrogen
- Estimates of producing steel, using a hydrogen atmosphere (HYBRIT 2019)
- Estimates of phasing out of fossil fuel industrial applications (like gas and coal electricity generation, and heating of buildings)
- Estimates of the number of non-fossil fuel electrical energy generation stations was estimated.
- Estimates of the size of the needed stationary power buffer to manage intermittent electricity supply from wind and solar power stations

The size of the task before us could then be assessed. This study is based on Scenario F from the report published by the Geological Survey of Finland (Michaux 2021). The GTK study (Michaux 2021) developed six scenarios, each one examining a targeted question. For example, Scenario A examined what a complete EV transport fleet would require in context of electrical energy to charge vehicles across one calendar year, and Scenario C examined the power electrical required to produce hydrogen to service a complete hydrogen fuel H_2-Cell vehicle global transport fleet. Scenario F was a combination of Scenarios A to E, where what was learned was integrated into a single system. This paper used some of those outcomes from Scenario F and focused on the physical material flows needed to phase out fossil fuels in a direct system replacement, in a global context. Once the 2018 industrial scope was mapped, a series of non-fossil fuel technologies that were commercially available at the time of writing were selected as substitutes. The number and quantity of non-fossil fuel technology units needed to phase out fossil fuels completely was estimated. It became clear that the size of the task was very large. If the developmental targets set by political leadership (European Commission 2019) are to be attempted, then procurement of technology and construction of new power stations would have to happen at a much faster rate than it does now.

A conceptual technology that is not yet viable but might be available on the market in 5 to 10 years' time, was considered not useful.

This paper did not undertake estimates in carbon footprint or carbon emissions. This could have been done but considered outside of scope. The risk in getting the physical requirements and carbon emission conclusions tangled and interdependent was considered a reason not to do this. This paper also did not make any predictions on unit cost, market price or estimations of capital expenditure (CAPEX). At the time of writing this paper, double digit financial inflation was observed in many countries around the world. Any estimates for CAPEX would most certainly quickly become erroneous. This study also focuses on the global industrial footprint as it was in 2018. The human population is predicted to grow from 8 billion in 2022 to more than 11 billion in 2050. The demand for electricity in 2050 is predicted to be more than 3 times what it was in 2018 (IRENA 2022 and Fig. 31). IRENA also predicts that actual energy consumption will decrease, where global primary energy consumption in 2019 was 110 278 TWh (397 EJ), predicted energy consumption in 2050 could be 96 667 (348 EJ).

This study does not attempt to examine what phasing out fossil fuels in 2050 would entail as there is not the available data for activities like the predicted distance travelled by vehicles in 2050. Market predictions of what might the technology market share be in 2050 and 2040 (to a few decades into the future) were projected onto the physical activities of 2018, using non-fossil fuel technology. Fossil fuel technologies to be phased out in this study were ICE powered vehicles of all classes (heavy trucks, light trucks, buses, commercial vans, passenger cars, rail locomotives and maritime shipping vessels), electrical energy generation systems (oil, gas, and coal), plastics production, petrochemical fertilizer production, gas heating of buildings, and coal fired steel production. Non-fossil fuel technologies considered for transport capability substitution were battery powered electric propulsion vehicles (EV) and hydrogen fuel cell powered vehicles (H_2-Cell). Non-fossil fuel technologies considered for electrical energy generation capability substitution solar power, wind turbines, hydro, geothermal, nuclear, and biomass to waste CHP systems. Assumptions were made regarding market share of technology application, and energy mix of power generation systems.

As previously mentioned, the year 2018 was used as the basis for all data collection. At the time of publication, this will be 5 years in the past. 2018 is the most recent year of complete data available. In 2020, the Covid-19 pandemic was declared, global supply chains were disrupted, and economic consumption of all goods was significantly changed. The year 2020 and 2021 has data artifacts that reflect this. 2019 could be the last year of sensible data seen for some time. The purpose of this study was to examine the scale of the physical task to phase out fossil fuels, at a time when society was operating relatively 'normally'. The year 2019 would have been the ideal year to work with, but much of the study was done in 2020 when 2018 was the most recent data available for many lines of enquiry. It was therefore decided that the calendar year 2018 was recent enough to draw useful conclusions.

2 MATERIALS AND METHODS

The focus of this study was to model the viability of the new non-fossil fuel global ecosystem using calculations made specifically for the three most significant economies in a global context. The global calculations were developed by combining separately assessed major regions, then doing a Rest of World (RoW) calculation (Michaux 2021). The results were then summed together to make an estimate of the global calculation. The examined major regions were:

- The United States (U.S.) 2018 economy
- European (EU-28) 2018 economy
- Chinese 2018 economy

These calculations estimated the quantity of electrical power consumed, the size of the transport fleet, the proportions of the different vehicle classes, and the distances those vehicles travelled. All of these were summed together to estimate the global industrial system footprint. This paper shows the calculations made associated with just the global system footprint. A bottom-up approach (as opposed to the typical top-down approach) was used to make the calculations presented here. What this means is that starting point of calculation is the physical number of vehicles in the global transport fleet, in conjunction with an estimate of what distance (physical work done) each individual vehicle travelled in an appropriate period of time. The objective was to estimate the quantity of electricity required to charge a renewable transport fleet. This can only be done with an estimate of the number of vehicles and the physical work they did across a long enough time to account for the difference in seasons, which would then be supported with electrical power from a known number of power stations. The outcome was a list of vehicles, batteries (of several different kinds), and power stations (of several different kinds). The purpose of this was to collect information for a sister paper which would calculate the quantity of metals needed to phase out fossil fuels. All other studies, which were 'top down' in form, made assumptions about the size and activity of the global transport fleet that later proved to be incorrect (for example IRENA 2020).

Other studies have used the Energy Returned on Energy Invested (ERoEI ratio) tool to compare and quantify the different energy generation systems (Hall et al. 2014, Michaux 2021, Section 6). There is now no agreement in the literature in what should or should not be included in the ERoEI calculation. This has complicated the use of this tool. This study did not use ERoEI at all in comparing the different systems. This paper mapped out the electrical power delivered to the global grid in the calendar year of 2018, by each system. Once the fossil fuel systems were removed, the power they delivered would then be delivered by a combination of non-fossil fuel energy generation systems. This was done by applying the electricity delivered by each system in context of what was actually reported by the average sized system in the year 2018. So, this paper is an application of what was actually reported and delivered to a new required capacity, defined by the physical number of vehicles and industrial actions, also mapped for the year 2018.

The approach was to examine the industrial ecosystem across one calendar year. The following calculations were conducted and assembled.

1. A mapping of the industrial ecosystem was done in context of the annual consumption of fossil fuels (oil, gas, and coal) and the physical tasks done industrially. This includes, the quantity of electricity generated, buildings heated, number of vehicles, their class type, and the annual distance traveled by each vehicle class. Also included was the distance travelled and freight carried by the rail network. The international maritime shipping fleet was also mapped in this context. A direct link between all of these physical tasks and the quantity (and type) of fossil fuel was made.
2. Determination of the true scope of useful work done for each task that used fossil fuels. Given that each energy source has an efficiency of energy delivered compared to their potential energy content (calorific value), an assessment of what useful work was actually done.
3. A list was assembled of non-fossil fuel supported technology units that can be used to substitute fossil fuel powered technology units. For example, the ICE vehicles could be substituted by EV's and H2-Cell powered vehicles. The performance characteristics of each was also collected.
4. Calculate the quantity of electrical energy needed to support the substitute non-fossil fuel technology units. For example, how much electrical energy would be required to charge the batteries in the global fleet of EV's vehicles, or would be required to manufacture the required quantity of hydrogen? Sum all industrial tasks together

into one number to represent the extra electrical energy generation capacity required.

5. Using a global energy mix proportion of non-fossil fuel electrical energy generation stations, determine how many new non-fossil fuel power stations are needed, by upscaling that proportional mix to the quantity required (Step 4). This energy mix was developed with a combination of an IEA prediction for the 2050 market (IRENA 2022, Fig. 2.3) and insights from previous work (Michaux 2021).

In this paper, the results and numbers quoted often have more decimal places, or more significant figures than is appropriate for such a broad calculation. The reason this is done is that so the reader can audit these numbers and recreate the numbers published here. If all of the calculations were quoted with fewer significant figures (for example needed additional global solar PV capacity of 17 000 TWh, where the actual calculation was 17 463.4 TWh), and those rounded figures were used to recreate the shown calculation path, then the final numbers would be different due to rounding errors and propagation of error. It is for this reason that so many tables have been included in the main paper body, each with numbers presented the way they are.

3 CURRENT PARADIGM TO PHASE OUT FOSSIL FUELS

Many countries and states have already legally committed to carbon reduction targets. Examples include Finland (Finnish Ministry of Environment 2022), Germany (German Federal Foreign Office 2010), the United Kingdom (United Kingdom Parliament 2008 and subsequent related statutory instruments), California in the United States (California Energy Commission 2018), and New York (New York State Senate 2019). The United Nations Climate Change Conference (COP21) was in Paris, France, on 12 December 2015. The Paris agreement climate change accord was established based on agreements made at this conference (United Nations 2016). The Paris Agreement is a legally binding international treaty on climate change. Its overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." The way this was to be done was to phase out all fossil fuel power generation and transport technologies. The Paris Agreement was adopted by 196 Parties, and it entered into force on 4 November 2016.

In 2018, the European Commission released a strategy to become climate neutral by the year 2050 (European Commission 2019 Going climate-neutral by 2050, EIA 2019c), including a new renewable energy target of 32% by 2030 (European Commission 2019 Going climate-neutral by 2050). By development of these strategic plans, it is hoped that through the large-scale deployment of renewables, electricity production could transition off fossil fuel technology. By 2050, more than 80% of electricity will be coming from renewable energy sources, with electricity providing for half of the final energy demand in the EU.

The United States Department of Energy launched The Net Zero World initiative in 2021 (U.S. Department of Energy 2021). This was a strategic policy development that would facilitate the United States to work with countries with the goal to lead a global transition to net zero emissions by 2050, and a commitment to working collaboratively with partners to replicate successes and inspire a race to the top across countries.

- Develop and support ambitious technical, market and investment roadmaps for clean energy transformation
- Deliver holistic support for immediate and sustained transformative projects that maximize overall impact for the region
- Foster exchanges between U.S. leaders and across countries to support peer-to-peer learning and confidence building

Specific benchmarks for partnering countries include:

- By 2022: Prepare or strengthen net zero energy technical, market, and investment plans and execute on near term opportunities.
- By 2023: Implement key policies and programs for countries to achieve net zero transitions.
- By 2024: Mobilize at least $10 billion in clean energy infrastructure and project investment.
- By 2025: Create new clean energy jobs, of which

at least 50% are held by women and 40% benefit disadvantaged communities.

The Net Zero America project (Larson et al. 2021, Jenkins et al. 2021) published a comprehensive study in what steps the United States would be required to take to transition off fossil fuel technology. This study included many of the engineering requirements to be considered, like number of power stations and of what kind. This study comes to different conclusions than the Net Zero America project as different engineering constraints were examined.

A useful reference work was published by the International Energy Agency (IEA 2021a), which describes physical metrics to be achieved by 2050. To achieve a net zero carbon emission footprint from the global industrial system, the 2019 production of 35 926 million tonnes of CO_2 emissions, would have to be reduced to 0 tonnes of CO_2 emissions by 2050 (Fig. 1 and Table 1). As some fossil emissions are hard to abate then this would assume that the annual capture of 7 602 million tonnes of CO_2 emissions in 2050 (Table 1).

To achieve this, renewable energy technology will become dominant, and the annual global elec-

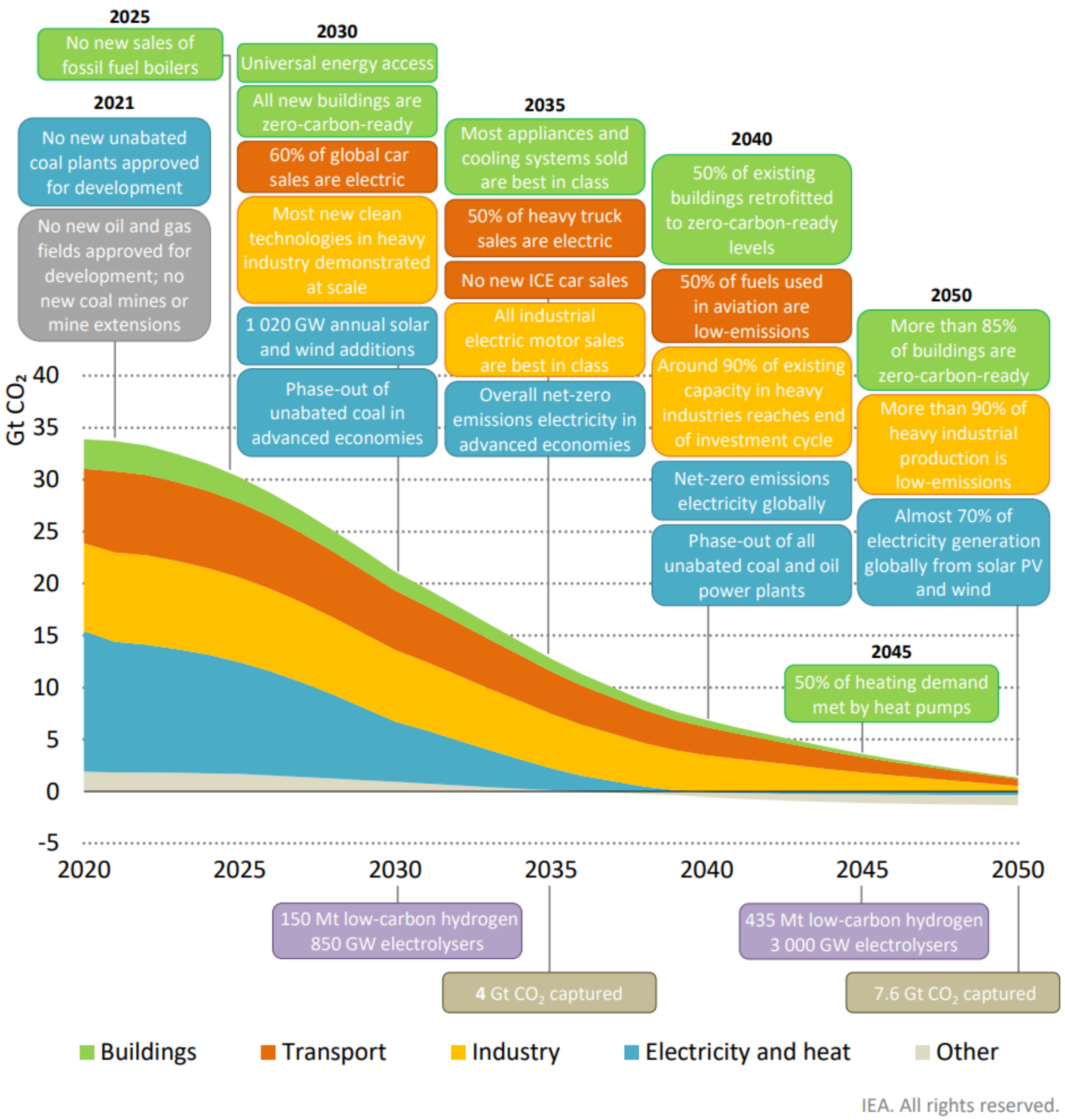

Fig. 1. Selected global milestones for policies, infrastructure, and technology deployment in the Net Zero Emissions (NZE) (Source: IEA 2021a).

trical energy generation would grow from 26 800 TWh in 2020 to 71 200 TWh in 2050 (Table 2). This is a 266% increase in capacity in 30 years. Also shown in Table 2 is a projected need of 3 100 GWh of stationary power storage by 2050. This paper will only model 2018 energy consumption and industrial activity.

Table 1. CO_2 emissions for the Net Zero Emissions pathway (Source: IEA 2021a).

	CO_2 emissions (Mt CO_2)					CAAGR (%)	
	2019	2020	2030	2040	2050	2020-2030	2020-2050
Total CO_2*	**35 926**	**33 903**	**21 147**	**6 316**	**0**	**-4.6**	**n.a.**
Combustion activities (+)	**33 499**	**31 582**	**19 254**	**6 030**	**940**	**-4.8**	**-11**
Coal	14 660	14 110	5 915	1 299	195	-8.3	-13
Oil	11 505	10 264	7 426	3 329	928	-3.2	-7.7
Natural gas	7 259	7 138	5 960	1 929	566	-1.8	-8.1
Bioenergy and waste	75	71	- 48	- 528	- 748	n.a.	n.a.
Industry removals (-)	**1**	**1**	**214**	**914**	**1 186**	**75**	**28**
Biofuels production	1	1	142	385	553	68	24
Direct air capture	-	-	71	528	633	n.a.	n.a.
Electricity and heat sectors	**13 821**	**13 504**	**5 816**	**- 81**	**- 369**	**-8.1**	**n.a.**
Coal	10 035	9 786	2 950	102	69	-11	-15
Oil	655	628	173	6	6	-12	-14
Natural gas	3 131	3 089	2 781	268	128	-1.0	-10
Bioenergy and waste	-	-	- 87	- 457	- 572	n.a.	n.a.
Other energy sector*	**1 457**	**1 472**	**679**	**- 85**	**- 368**	**-7.4**	**n.a.**
Final consumption*	**20 647**	**18 928**	**14 723**	**7 011**	**1 370**	**-2.5**	**-8.4**
Coal	4 486	4 171	2 935	1 186	117	-3.5	-11
Oil	10 272	9 077	6 973	3 242	880	-2.6	-7.5
Natural gas	3 451	3 332	2 668	1 453	303	-2.2	-7.7
Bioenergy and waste	75	71	40	- 70	- 176	-5.6	n.a.
Industry*	8 903	8 478	6 892	3 485	519	-2.0	-8.9
Iron and steel	2 507	2 349	1 778	859	220	-2.7	-7.6
Chemicals	1 344	1 296	1 199	654	66	-0.8	-9.5
Cement	2 461	2 334	1 899	906	133	-2.0	-9.1
Transport	8 290	7 153	5 719	2 686	689	-2.2	-7.5
Road	6 116	5 483	4 077	1 793	340	-2.9	-8.9
Passenger cars	3 121	2 746	1 626	547	85	-5.1	-11
Trucks	1 835	1 721	1 614	890	198	-0.6	-6.9
Aviation	1 019	621	783	469	210	2.4	-3.5
Shipping	883	800	705	348	122	-1.3	-6.1
Buildings	3 007	2 860	1 809	685	122	-4.5	-10
Residential	2 030	1 968	1 377	541	108	-3.5	-9.2
Services	977	892	432	144	14	-7.0	-13
Total CO_2 removals	**1**	**1**	**317**	**1 457**	**1 936**	**79**	**29**
Total CO_2 captured	**40**	**40**	**1 665**	**5 619**	**7 602**	**45**	**19**

**Includes industrial process emissions.*

Table 2. Key milestones in transforming global electrical generation (Source: IEA 2021a, Table 3.2).

Category	
Decarbonisation of electricity sector	• Advanced economies in aggregate: 2035. • Emerging market and developing economies: 2040.
Hydrogen-based fuels	• Start retrofitting coal-fired power plants to co-fire with ammonia and gas turbines to co-fire with hydrogen by 2025.
Unabated fossil fuel	• Phase out all subcritical coal-fired power plants by 2030 (870 GW existing plants and 14 GW under construction). • Phase out all unabated coal-fired plants by 2040. • Phase out large oil-fired power plants in the 2030s. • Unabated natural gas-fired generation peaks by 2030 and is 90% lower by 2040.

Category	2020	2030	2050
Total electricity generation (TWh)	26 800	37 300	71 200
Renewables			
Installed capacity (GW)	2 990	10 300	26 600
Share in total generation	29%	61%	88%
Share of solar PV and wind in total generation	9%	40%	68%
Carbon capture, utilisation and storage (CCUS) generation (TWh)			
Coal and gas plants equipped with CCUS	4	460	1 330
Bioenergy plants with CCUS	0	130	840
Hydrogen and ammonia			
Average blending in global coal-fired generation (without CCUS)	0%	3%	100%
Average blending in global gas-fired generation (without CCUS)	0%	9%	85%
Unabated fossil fuels			
Share of unabated coal in total electricity generation	35%	8%	0.0%
Share of unabated natural gas in total electricity generation	23%	17%	0.4%
Nuclear power	*2016-20*	*2021-30*	*2031-50*
Average annual capacity additions (GW)	7	17	24
Infrastructure			
Electricity networks investment in USD billion (2019)	260	820	800
Substations capacity (GVA)	55 900	113 000	290 400
Battery storage (GW)	18	590	3 100
Public EV charging (GW)	46	1 780	12 400

Note: GW = gigawatts; GVA = gigavolt amperes.

In the Net Zero Emissions pathway, by 2050, the entire (100%) global transport fleet will be made up of electric vehicles (PHEV and BEV) and hydrogen fuel cell vehicles (FCEV). Maritime shipping will be fueled by ammonia (46%), hydrogen (17%), and bioenergy (21%). Aviation will contract 38% in capacity, then be fueled with a combination of biofuels and synthetic hydrogen fuels. Rail transport will be a combination of electric and hydrogen fueled (Table 3).

Table 3. Key milestones in transforming the global transport sector (Source: IEA 2021a, Table 3.4).

Category	
Road transport	• 2035: no new passenger internal combustion engine car sales globally
Aviation and shipping	• Implementation of strict carbon emissions intensity reduction targets as soon as possible.

Category		2020	2030	2050
Road transport				
Share of PHEV, BEV and FCEV in sales:	cars	5%	64%	100%
	two/three-wheelers	40%	85%	100%
	bus	3%	60%	100%
	vans	0%	72%	100%
	heavy trucks	0%	30%	99%
Biofuel blending in oil products		5%	13%	41%
Rail				
Share of electricity and hydrogen in total energy consumption		43%	65%	96%
Activity increase due to modal shift (index 2020=100)		100	100	130
Aviation				
Synthetic hydrogen-based fuels share in total aviation energy consumption		0%	2%	33%
Biofuels share in total aviation energy consumption		0%	16%	45%
Avoided demand from behaviour measures (index 2020=100)		0	20	38
Shipping				
Share in total shipping energy consumption:	Ammonia	0%	8%	46%
	Hydrogen	0%	2%	17%
	Bioenergy	0%	7%	21%
Infrastructure				
EV public charging (million units)		1.3	40	200
Hydrogen refuelling units		540	18 000	90 000
Share of electrified rail lines		34%	47%	65%

Note: PHEV = plug-in hybrid electric vehicles; BEV = battery electric vehicles; FCEV = fuel cell electric vehicles.

All of these goals discussed in (U.S. Department of Energy 2020) are based around policy to influence market forces. Most the strategic documents to plan to phase out fossil fuels examined in this study, did not do an audit of the number technology units (cars, trucks, etc.), the physical work they did over a period of time, or the physical requirements to replace that capacity. There was no sense of the scale of the task before us to phase out fossil fuels. Most discussion was around what was possibly going to happen I n the markets in the next 5 years. The IEA report (IEA 2021a) gave physical metrics for society to work towards.

These metrics were used in this study to define physical requirements to phase out fossil fuels. This study will map out physical activities and tasks done in 2018 scope but use the projected proportional market shares for 2050 to define the Green

Transition. The following boundary conditions will be used in this study:

- The size of the global transport fleet of passenger cars, trucks, buses, and vans in 2018 will be used for calculations
- The size of the global maritime shipping fleet, rail transport and aviation fleet in 2018 will be used for calculations
- The distance travelled by each vehicle, train, maritime vessel, aircraft in 2018 will be used for calculations
- The quantity of electricity generated, fertilizer, plastics and steel produced in 2018 will be used for calculations
- 100% of global transport fleet will be made up of electric vehicles (PHEV and BEV) and hydrogen fuel cell vehicles (FCEV).
- Maritime shipping will be fueled by ammonia (46%), hydrogen (17%), and bioenergy (21%)
- Aviation will contract 38% in capacity, then be fueled with a combination of biofuels and synthetic hydrogen fuels
- 100% of Rail transport will be a combination of electric and hydrogen fueled

4 THE EXISTING INDUSTRIAL ECOSYSTEM FOSSIL FUEL CONSUMPTION

The purpose of this section is to examine the size and scope of the existing global energy consumption, in context of the different energy generation systems. In particular, the proportional share of fossil fuels, and how they were used was to be examined. The global resources consumed to produce energy are shown since the beginning of the industrial revolution in Figure 2. Note most of the energy use have been fossil fuels after 1900. Prior to the year 1900, freight was transported long distances with wind energy on sail maritime vessels. Also note that the sum of all the demand for energy resources has been increasing consistently in a near exponential fashion (as opposed to society becoming more efficient and reducing fossil fuel resources as technology developed). Note the radical increase in global energy consumption from 28 564 TWh in 1950 to 172 884 TWh in 2018, an increase of more than 600%. Energy consumption in 2050 is projected to be much larger than it is in 2018. This paper does not account for economic growth but will map and study the calendar year 2018 only.

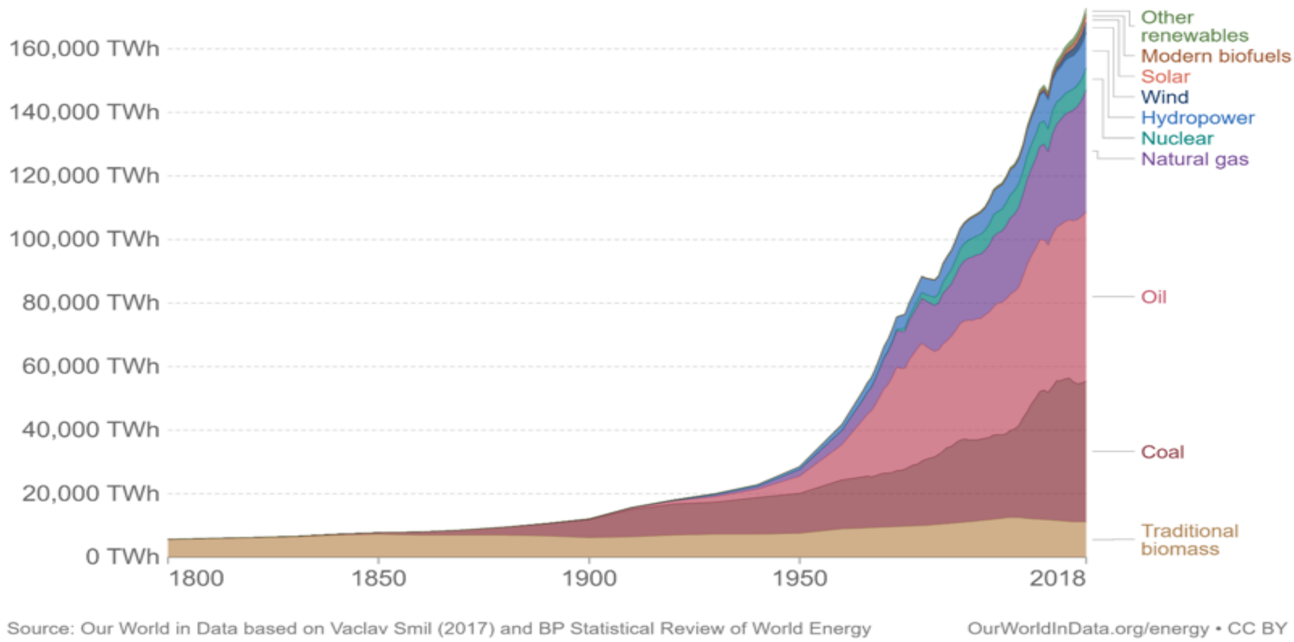

Fig. 2. Global Primary energy consumption. Units measured in terawatt-hours (TWh) per year. Classification 'other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels (Source: Our World in Data 2024, BP Statistical Review of World Energy 2019).

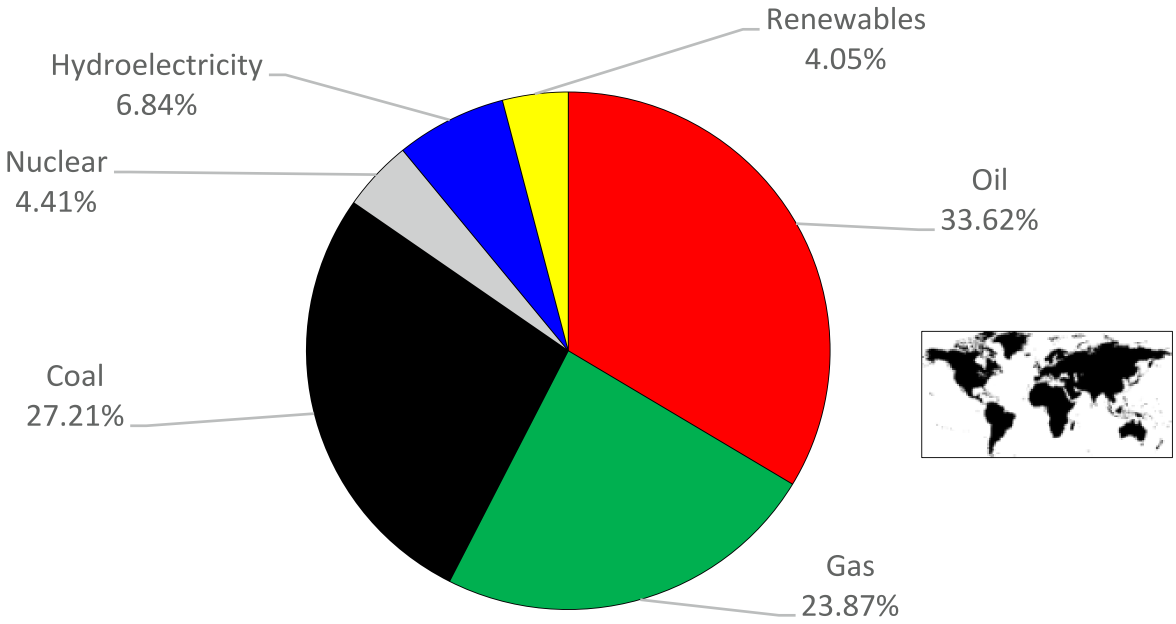

Fig. 3. Global primary energy consumption by source in 2018 (Source: BP Statistical Review of the World Energy 2019).

Figure 3 shows the primary energy consumption by fuel source for 2018. As can be observed, fossil fuels (oil, gas, and coal) account for 84.5% of primary energy consumption in the calendar year 2018. As a consequence of the 1st law of thermodynamics, most of the generated energy 172 884 TWh in 2018 would have been lost in heat (Schernikau & Smith 2023). Figure 4 shows the energy generation efficiency of combustion of fossil fuels.

Most energy generated in a developed society is consumed in three basic applications: heat for manufacture (U.S. Department of Energy 2014), transport (ICE vehicles) and the generation of electricity. Electricity is to modern civilization what blood is to the human body (Schernikau & Smith 2023, Smil 2016a,b). Energy generation with the combustion of fossil fuels is very energy inefficient. More than 60% of the energy content is lost as heat in the energy generation process (Fig. 4). In Figure 4, the displayed efficiency is 38%, which would apply to the current coal station fleet of the European Union (where the current coal station fleet of United States is slightly more less efficient). However, natural gas combination cycles (efficiency of new systems >60%) and new technology coal plants (efficiency >45%) would have fewer thermal losses.

So, the energy consumption in Figures 2 and 3 also include energy losses in context of physical

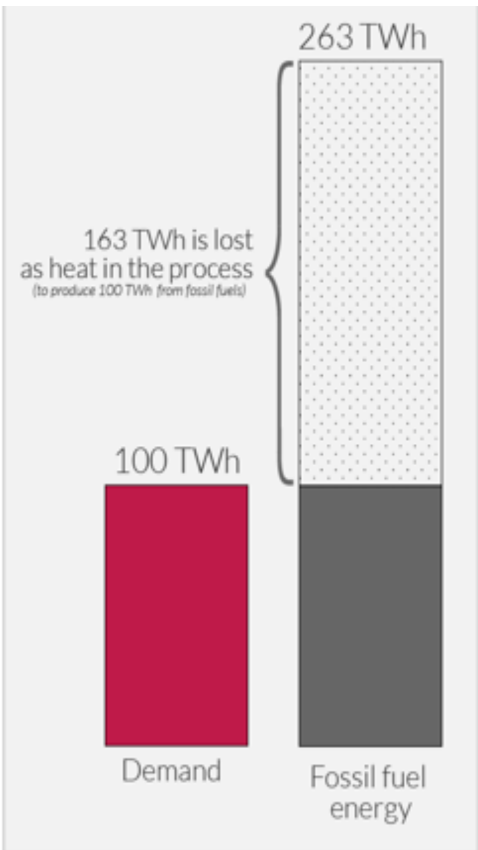

Fig. 4. Energy generation efficiency with the combustion of fossil fuels to generate 100 TWh electricity (Source: Our World in Data 2024, https://ourworldindata.org/energy-production-consumption, Licensed under CC-BY by the author Hannah Ritchie).

work done. Figure 5 shows what tasks where coal was globally consumed by application and Figure 6 shows the same concept for natural gas. Figure 7 shows in what tasks petroleum was globally consumed by application.

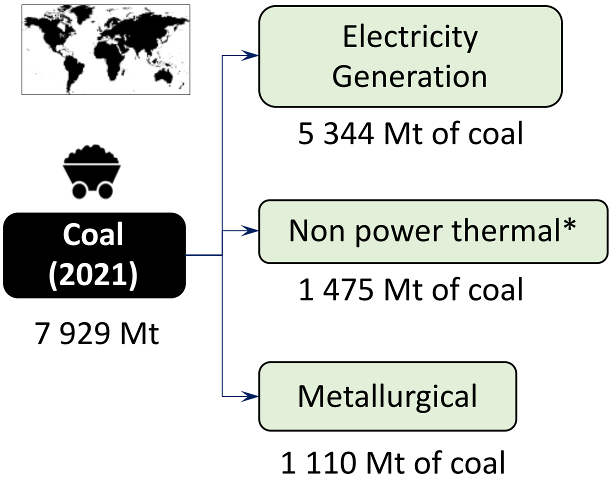

Fig. 5. Global consumption of coal in 2021 by application (Source IEA 2022a).

Figure 5 shows coal consumption for 2021. In 2018, global coal consumption was 7 720 Mt (IEA 2019e).

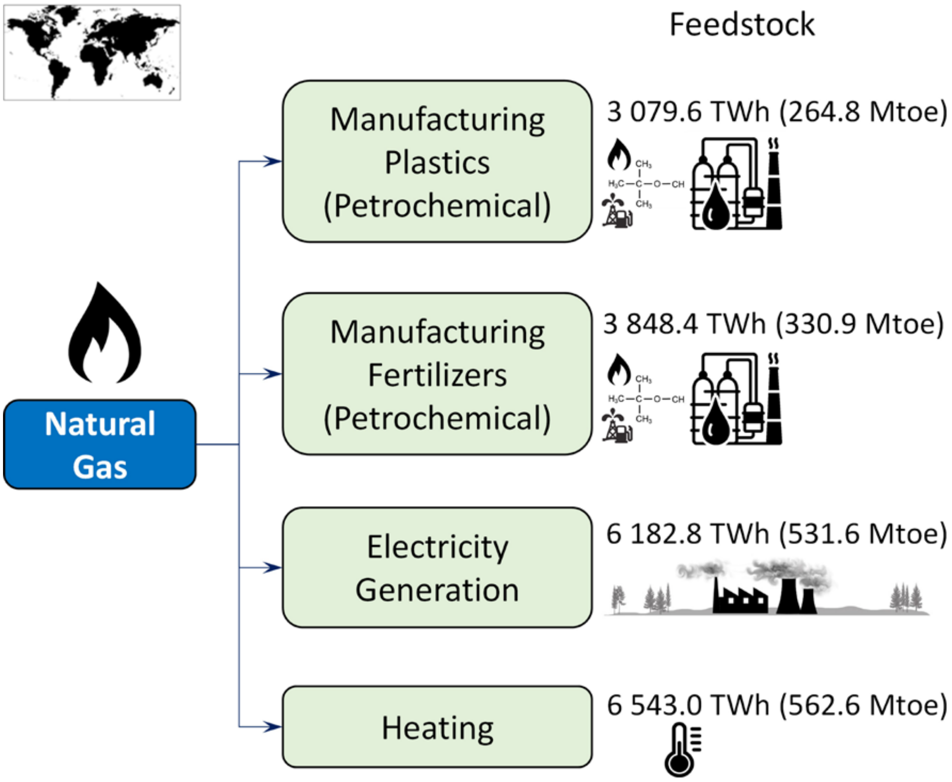

Fig. 6. Global consumption of natural gas in 2018 by application (Sources: BP Statistical Review of World Energy 2019, IEA 2018, International Fertilizer Association IFA databases 2020, EIA 2024a website, EIA 2019b).

Note, Figure 6 does not list how much Natural Gas nor Liquid natural Gas is used for transport.

Table 4. Chemical composition of natural gas (Source: U.S. Department of Energy 2018, EIA 2024a).

Component	Component (mole%)	Component (mole%)
Methane	94,7	87.0 - 98.0
Ethane	4,2	1.5 - 9.0
Propane	0,2	0.1 - 1.5
iso - Butane	0,02	trace - 0.3

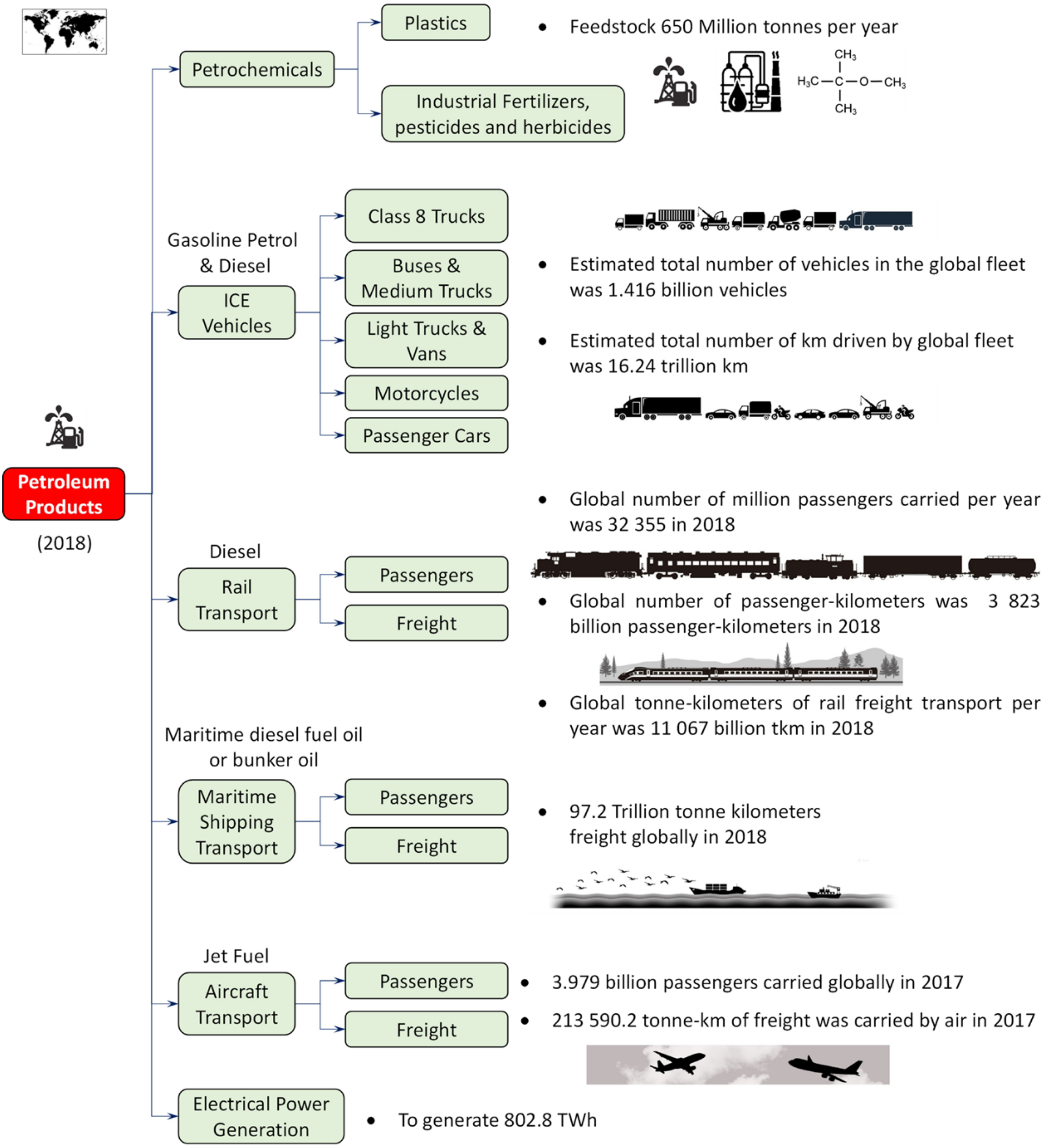

Fig. 7. Global consumption of petroleum products by application (Sources: BP Statistical Review of World Energy 2019, IEA 2019d, UNCTAD 2018, ICAO 2024, IEA 2018, EIA 2019a).

5 MEASURED DISTANCE TRAVELLED BY VEHICLE CLASS IN THE UNITED STATES

Many developments in transport technology as alternatives to ICE vehicles have previously focused on passenger cars. This is inappropriate as passenger cars represent only part of the total number of vehicles on roads and have travelled only a fraction of the kilometers. All vehicle classes need to be quantified in number and physical work done if a substitution system is to be viable. Tables A1 to A6 in Annex A shows a summary of the vehicle transport fleet by nation state.

Assembling the distance travelled by the vehicles in the global fleet proved to be difficult. This kind of data are not routinely collected in many countries. Only one country records the distance traveled, the United States. The United States Department of Transport record and report data on the number of vehicles, by vehicle class and the miles driven by each vehicle class. To estimate the total distance traveled by all the different classes of vehicles in a global context, the patterns and proportions seen in the United States was projected onto a 1.416 billion car fleet, given known proportions in Europe (EU-28) and China (Tables A1 to A6 in the Annex Section).

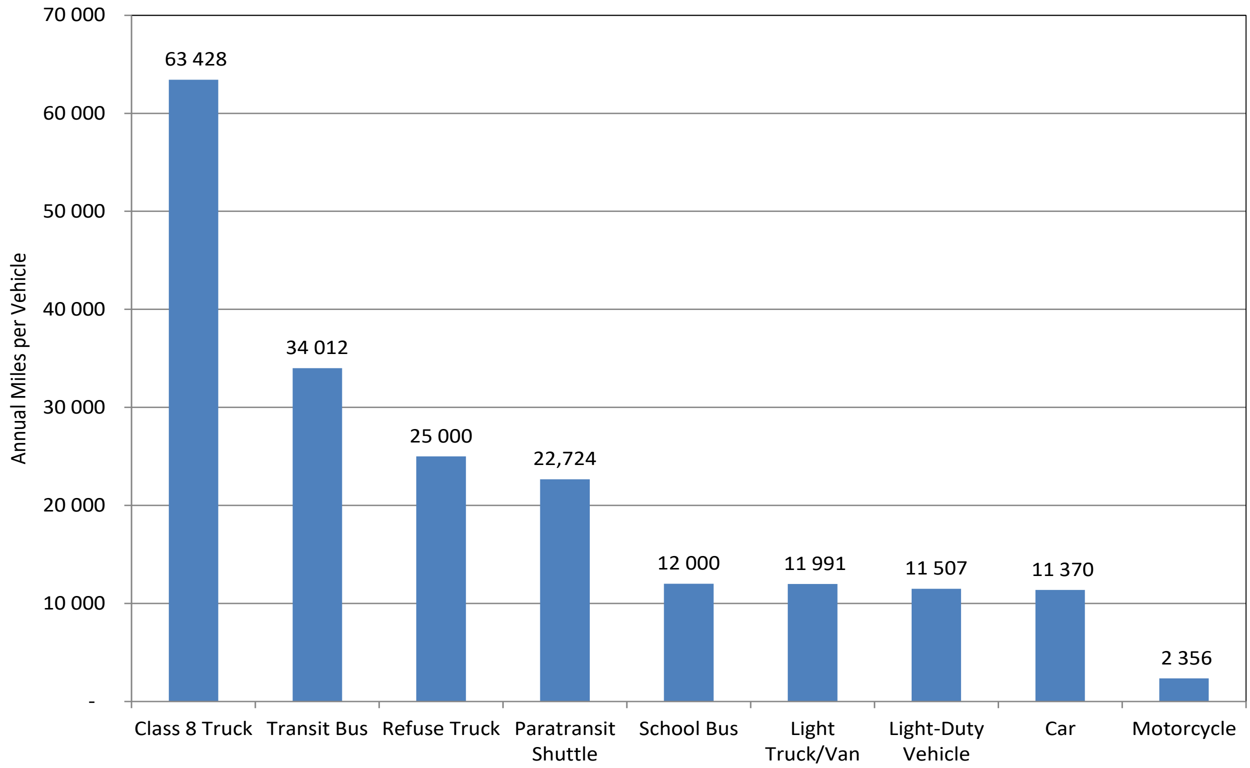

Fig. 8. Average Annual Vehicle Miles Traveled (VMT) by Vehicle Class in the United States (Source: U.S. Department of Energy 2019, Worksheet available at https://afdc.energy.gov/data).

In 2018, the transport fleet in the United States was 269 million vehicles. The U.S. transport fleet was 18.98% of the global transport fleet. Shown in Table 5 is the estimate number of km driven by the different vehicle classes in the United States in 2018.

Table 5. Total number of km driven in the United States in 2018 (Source: U.S. Department of Transportation 2017, Bureau of Transportation Statistics: National Transportation Statistics).

Vehicle Class	**Number of Self Propelled Vehicles**	**Proportion of U.S. Fleet in 2018** (%)	**Average annual km driven by class in 2018** (km)	**Total km driven in 2018** (million km)
Class 8 Truck	4 694 851	1,75%	102 077	479 238
Transit Bus	2 517 520	0,94%	54 737	137 801
Refuse Truck	1 850 465	0,69%	40 234	74 451
Paratransit Shuttle	1 678 668	0,62%	36 498	61 269
Delivery Truck	959 133	0,36%	20 854	20 002
School Bus	888 223	0,33%	19 312	17 153
Light Truck/Van	82 569 993	30,71%	19 298	1 593 406
Light-Duty Vehicle	79 237 170	29,47%	18 519	1 467 371
Passenger Car	78 293 789	29,11%	18 298	1 432 638
Motorcycle	16 223 409	6,03%	3 792	61 513
Total	268 913 221	100,0%		5 344 842
Total	269 million vehicles			5.3 trillion km travelled in 2018

Note: Original data source unit units of miles

6 ESTIMATED DISTANCE TRAVELLED BY VEHICLE CLASSES IN INTERNATIONAL TRANSPORT FLEETS

A number of calculations presented later in this paper require the estimated annual distance travelled by the different vehicle classes in the international transport fleets for the year 2018. This data was collected in the United States only. To resolve this, a set of ratios are required to scale the U.S data to all other ecosystems studied. The following set of calculations were used to estimate a ratio that could be applied to Europe, China and the Rest of the World transport fleets, by comparing them to the United States. These data are shown in Figures 9 to 12. (for a more complete description see Michaux 2021).

1. The average annual gasoline consumption per capita for 151 nations, (the largest consumption rates). This was done only for gasoline, diesel was not included.
2. The human population data for each nation state was collected (Source: UN World Population Data 2018)
3. The number of vehicles in each nation state transport fleet was collected (Tables A1 parts 1 to 3 in Annex A)
4. Steps 1–3 were merged and used to calculate the average annual consumption per vehicle for each nation state. This was used to calculate the annual consumption (Source: Gasoline consumption per capita around the world Global Petrol Gases 2024, https://www.globalpetrolprices.com/articles/52/)

The annual national consumption of gasoline was calculated by multiplying the per capita consumption by the human population. The average gasoline consumed annually per vehicle, for each nation state, was calculated by dividing the total annual gasoline consumption by the total number of vehicles in the national transport fleet (including cars, trucks, buses, etc.).

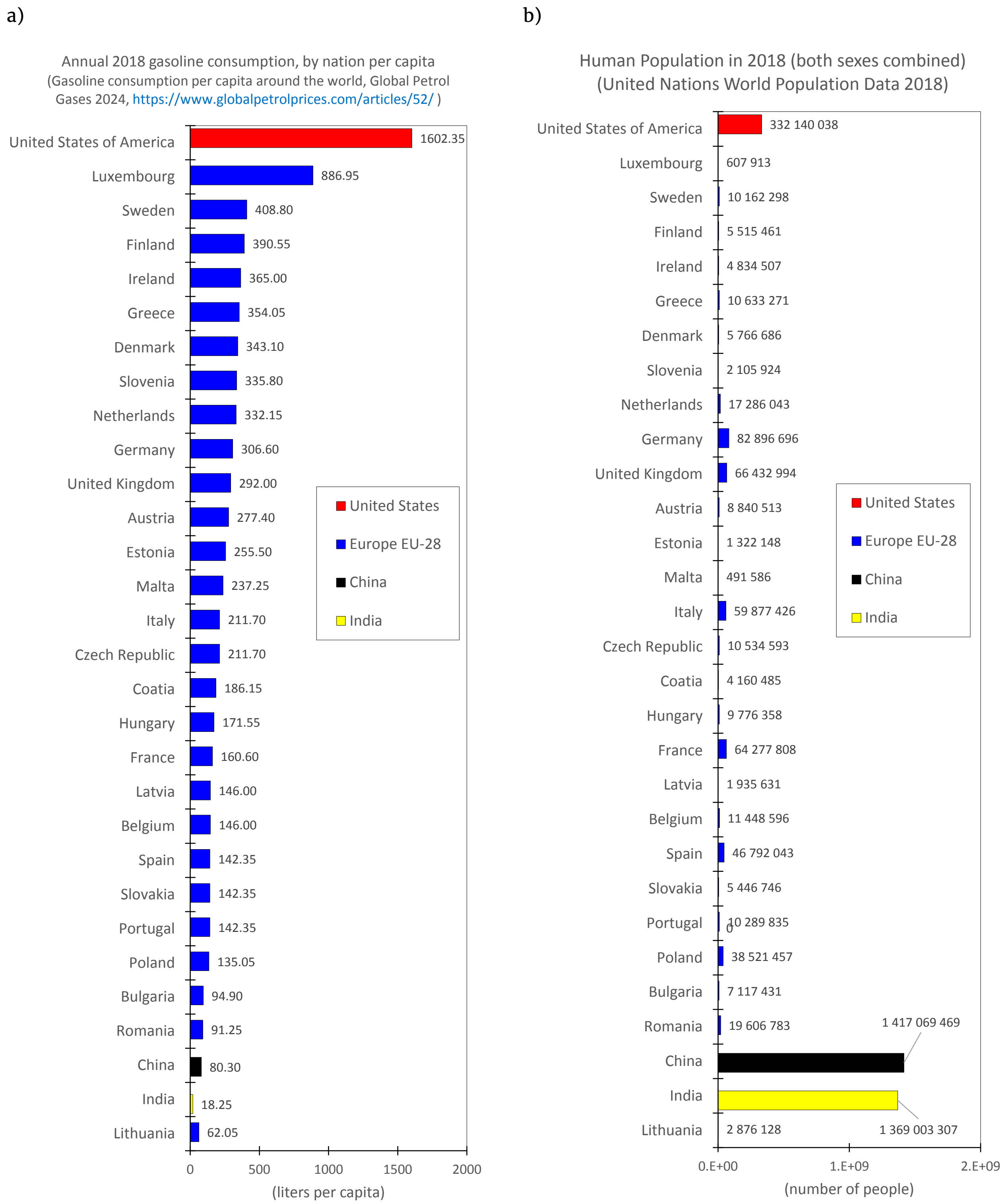

Fig. 9. Annual gasoline consumption per population capita, by nation a), Human population of each nation b) United States, Europe EU-28, China, and India.

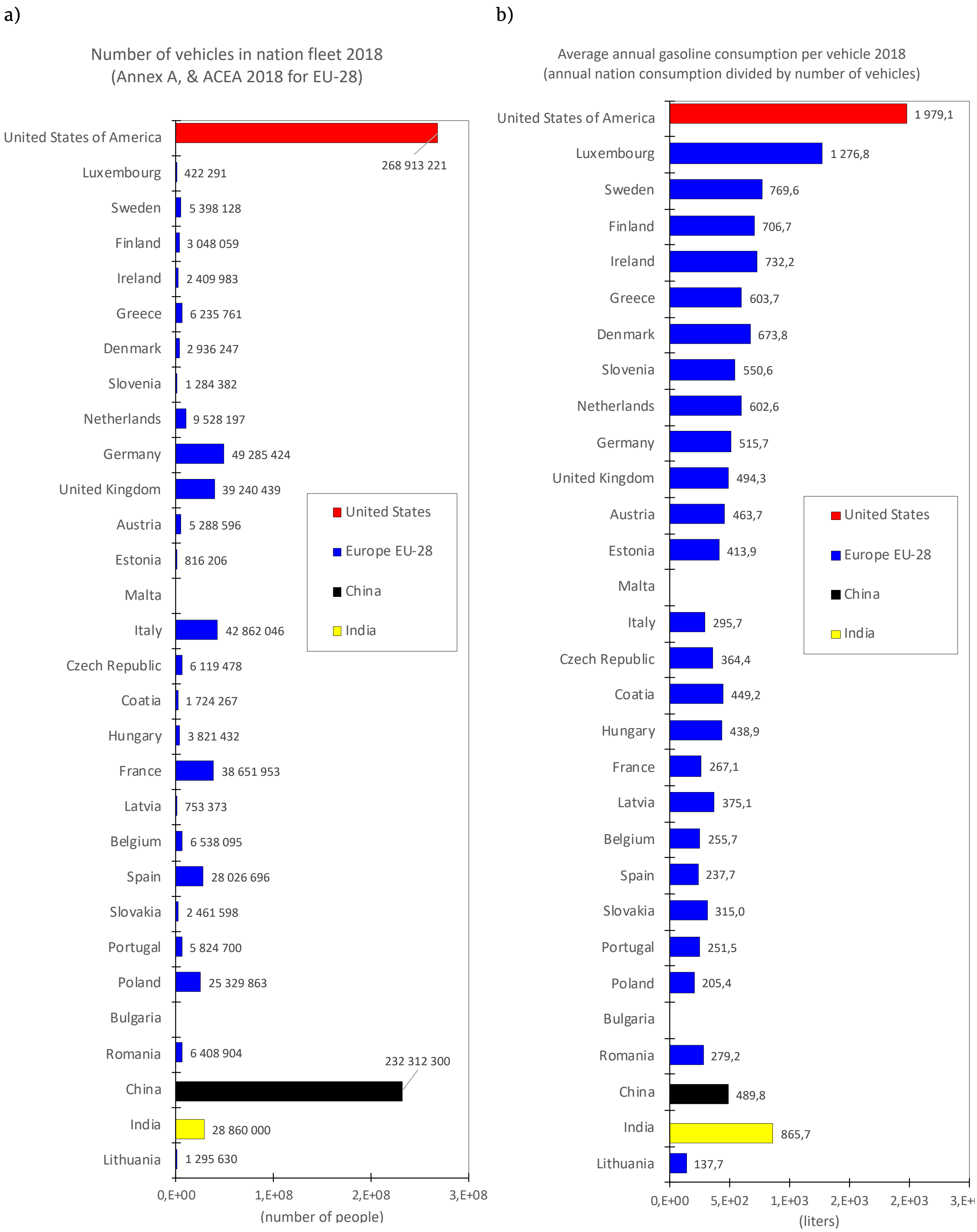

Fig. 10. Number of vehicles in national transport fleet a), Average annual gasoline consumption per vehicle b) United States, Europe EU-28, China, and India.

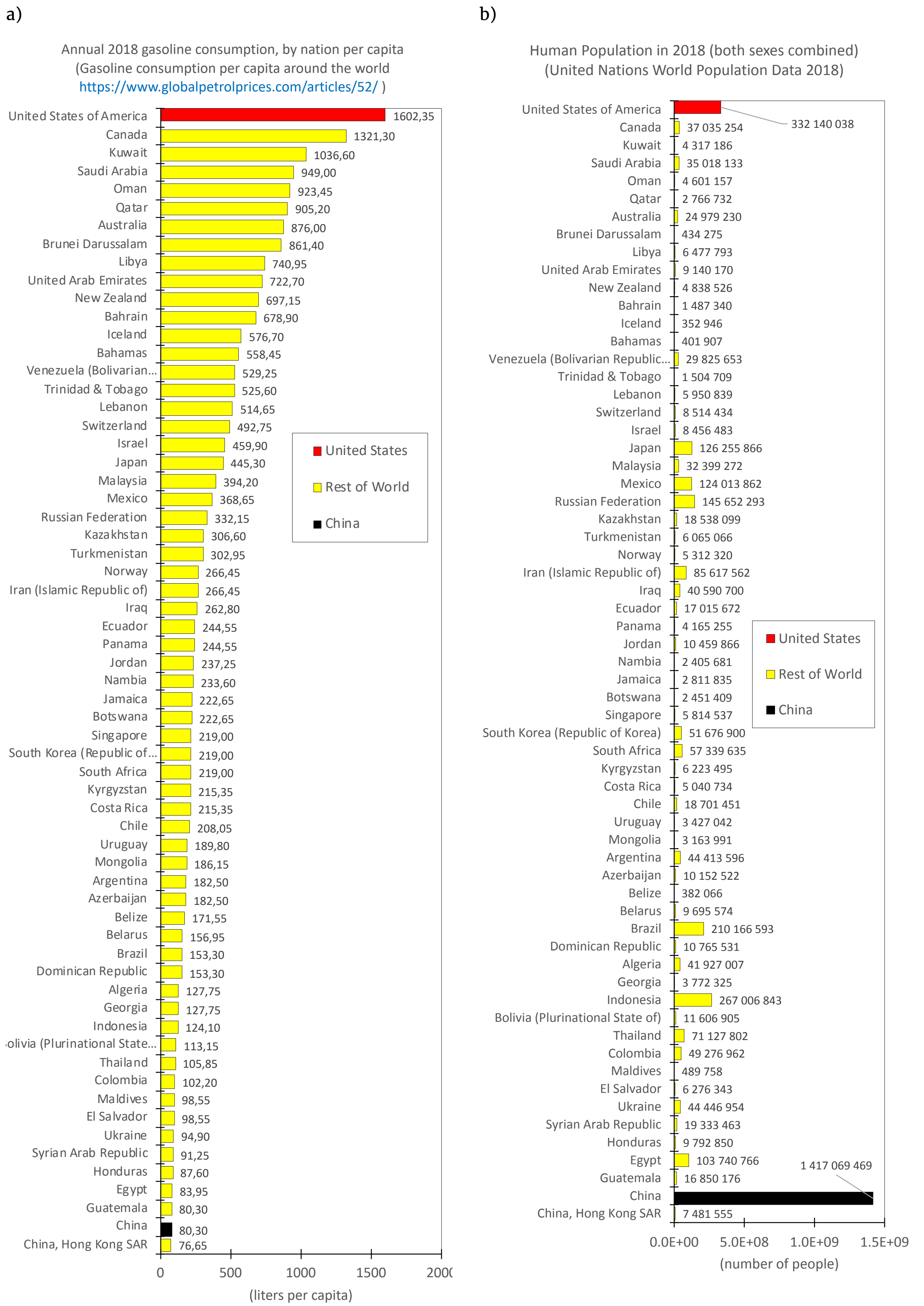

Fig. 11. Annual gasoline consumption per population capita, by nation a), Human population of each nation b) United States, China, and the Rest of World.

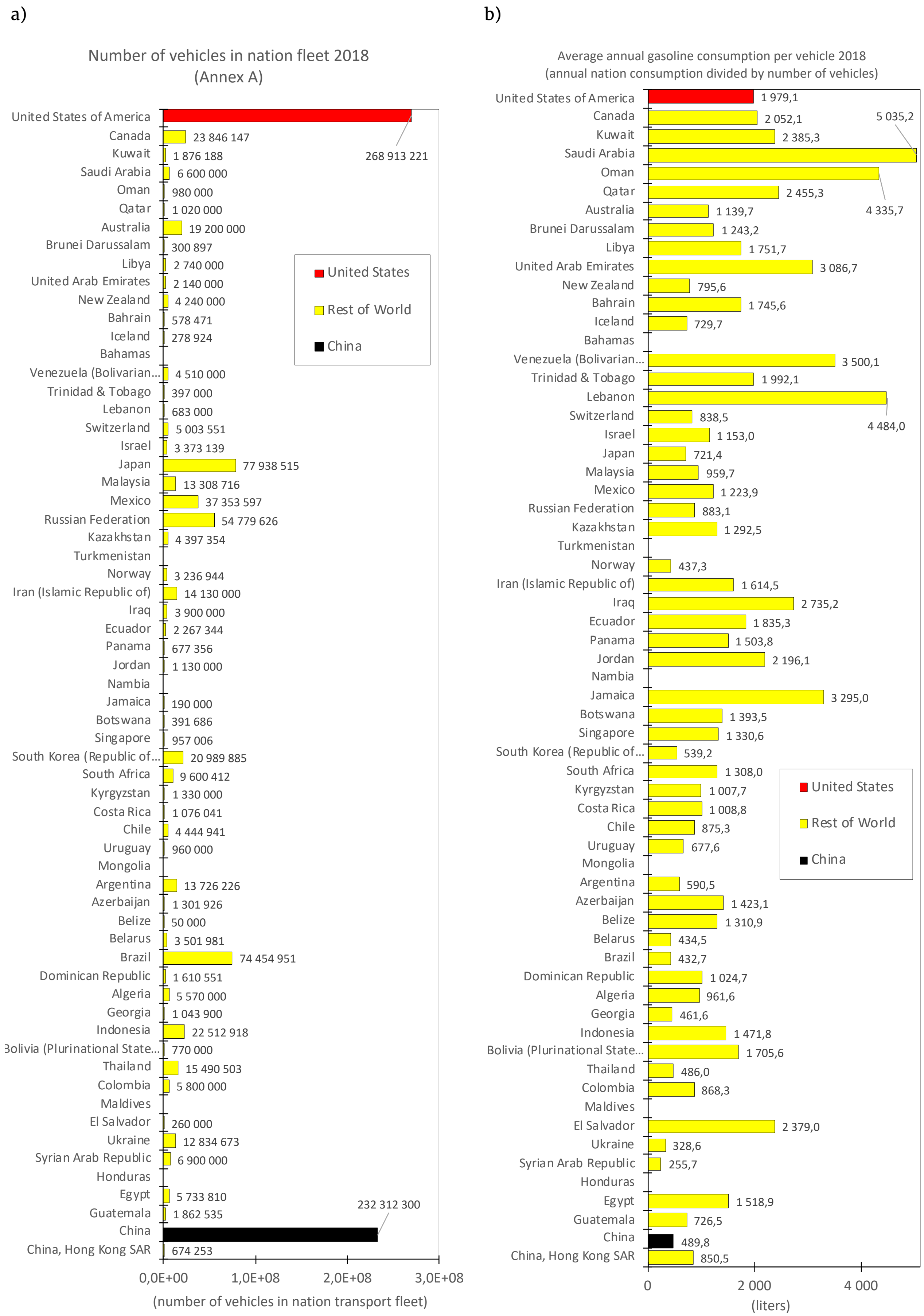

Fig. 12. Number of vehicles in national transport fleet a), Average annual gasoline consumption per vehicle b) United States, China, and the Rest of World.

Using the average vehicle annual consumption of gasoline, for each nation state (Fig. 10b and Fig. 12b) was used to develop a ratio between the United States and Europe (EU-28), China and the Rest of the World transport fleets in order to develop an estimate to compare the activities by vehicles in each of these regions. There are measurements for the United States, but in other regions, an estimated based on the United States is required. The outcome is shown in Table 6. As can be observed, the vehicles of the United States transport fleet travel much further in a calendar year than most (but not all) other nation states. This could be due to the physical size of the United States compared to other nations, and the propensity for the American society to use ICE vehicles instead of communal transport.

Table 6. Estimated ratio between USA and other nations for average annual vehicle consumption (Source: Taken from the average of Figs. 7 to 10).

Nation/Region	**Average annual gasoline consumption per vehicle** (liters)	**Ratio** **(USA:Nation)**
United States of America	1979,1	1
Europe EU-28	467,0	0,24
China	489,8	0,25
Rest of World	1274,9	0,64

These ratios in Table 6 were applied to the number of km travelled by vehicle class in the United States to estimate what those same vehicle classes travelled (on average) in Europe, China, and the Rest of the World (RoW). The outcome of this is shown in Table 7.

Table 7. Estimated average annual distance travelled for each vehicle class in Europe, China, and Rest of World, using the USA and the ratios in Table 6.

Vehicle Class	**Average km driven by vehicle in class in 2018 U.S. Fleet (Ratio 1:1)** (km)	**Average km driven by vehicle in class for 2018 EU-28 Fleet (Ratio 1 : 0.24)** (km)	**Average km driven by vehicle in class for 2018 Chinese Fleet (Ratio 1 : 0.25)** (km)	**Average km driven by vehicle in class for 2018 RoW Fleet (Ratio 1 : 0.64)**
Class 8 Truck	102 077	24 089	25 264	65 757
Transit Bus	54 737	12 917	13 547	35 261
Refuse Truck	40 234	9 495	9 958	25 918
Paratransit Shuttle	36 498	8 613	9 033	23 512
Delivery Truck	20 854	4 921	5 161	13 434
School Bus	19 312	4 557	4 780	12 441
Light Truck/Van	19 298	4 554	4 776	12 431
Light-Duty Vehicle	18 519	4 370	4 583	11 930
Passenger Car	18 298	4 318	4 529	11 787
Motorcycle	3 792	895	938	2 443

While it is recognized that this is a crude assumption, this was the best estimate the author could assemble, for the average distance travelled by each vehicle class, and the total km traveled in the national fleet of these regions. Assembling the number of vehicles in the global fleet proved to be difficult. This kind of data is not routinely collected in many countries. Only one country records the distance traveled. The United States Department of Transport quote up to date information on the number of vehicles, the different numbers by class and the miles driven by each vehicle class. To estimate the total distance traveled by all the different classes of vehicles in a global context, the patterns and proportions seen in the United States were projected onto a 1.416 billion car fleet (Tables A1 parts 1 to 3 in the Annex A). This results in a crude estimate, but it will suffice for the purpose of this paper. Once an overall number of vehicles is established (Table 8), the proportions of vehicle class and the distance traveled by them can be estimated (Table 9).

Table 8. Number of vehicles and estimated km driven in U.S., EU-28, Chinese, RoW and global fleets (Source: Annex A).

Vehicle Class	**Number of vehicles by class in 2018 U.S. Fleet** (number)	**Number of vehicles by class in 2018 EU-28 Fleet** (number)	**Number of vehicles by class in 2018 Chinese Fleet** (number)	**Number of vehicles by class in 2018 RoW Fleet** (number)	**Number of vehicles by class in 2018 Global Fleet** (number)
Class 8 Truck	4 694 851	5 716 322	7 095 300	11 422 874	28 929 348
Refuse Truck + Delivery Truck	2 809 598			6 835 932	9 645 529
Transit Bus + School Bus + Paratransit Shuttle	5 084 411	657 714	1 243 900	12 370 699	19 356 724
Light Truck/Van + Light-Duty Vehicle	161 807 163	27 413 946	18 419 000	393 687 215	601 327 324
Passenger Car	78 293 789	222 683 327	203 689 500	190 493 814	695 160 429
Motorcycle	16 223 409	4 548 655	1 864 600	39 472 597	62 109 261
Total	268 913 221	261 019 964	232 312 300	654 283 130	1 416 528 615

Table 9. Estimated distance travelled by vehicle class in U.S., EU-28, Chinese, Rest of World (RoW) and global fleets (Source: Annex A).

Vehicle Class	**Estimated distance travelled by vehicle class in 2018 U.S. Fleet** (billion km)	**Estimated distance travelled by vehicle class in 2018 EU-28 Fleet** (billion km)	**Estimated distance travelled by vehicle class in 2018 Chinese Fleet** (billion km)	**Estimated distance travelled by vehicle class in 2018 RoW Fleet**	**Estimated distance travelled by vehicle class in 2018 Global Fleet** (billion km)
Class 8 Truck	479,2	137,7	289,3	751,1	1 657,3
Refuse Truck + Delivery Truck	94,5		10,6	148,0	253,1
Transit Bus + School Bus + Paratransit Shuttle	216,2	5,7		338,9	560,8
Light Truck/Van + Light-Duty Vehicle	3 060,8	122,3	86,2	4 797,3	8 066,6
Passenger Car	1 432,6	961,6	922,5	2 245,4	5 562,1
Motorcycle	61,5	4,1	1,7	96,4	163,7
Total	5 344,8	1 231,4	1 310,2	8 377,2	16 263,7

Figure 13 shows the calculation flow chart map to determine the electrical energy requirements to phase out the current global ICE vehicle fleet and replace them with EV's, and the electrical energy required to charge their batteries across an annual 12-month time period.

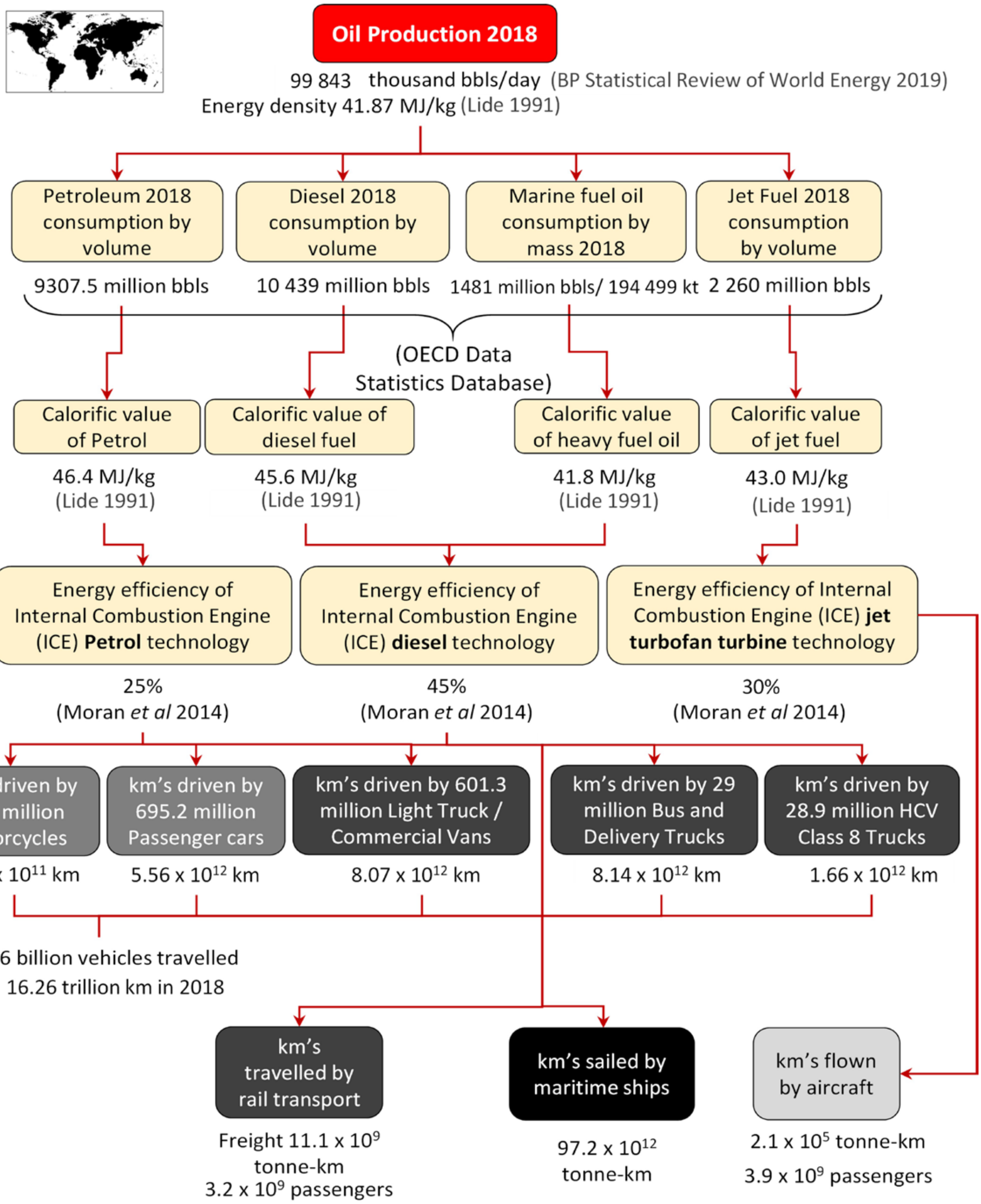

Fig. 13. Calculation flow chart for scope of physical annual work done by global petroleum fueled ICE transport fleet.

7 VEHICLE TRANSPORT FLEET EV TO H_2 CELL SPLIT

This section directly compares the fully electric vehicle for the global transport fleet with a fully hydrogen powered H_2 fuel cell vehicle global transport fleet, in operation across a 365 day time period of activity (as reported in 2018). This comparison was drawn from a previous study (Michaux 2021), which examined the whole transport fleet (passenger cars, trucks, buses, and commercial vans, but also a fully non-fossil fuel rail network and a non-fossil fuel maritime shipping fleet) in context of if all vehicles were Electric Vehicles (EV) with a battery, and in a parallel calculation if those same vehicles were powered with a hydrogen fuel cell. The masses of the EV batteries and the equivalent hydrogen fuel tank mass were calculated. Tables 10 to 12 show this comparison.

As can be observed, the hydrogen solution requires between 2 and 4 times the electricity for it to be implemented. This has important implications. To deliver this extra electricity, 2.2 to 4.7 times the installed capacity in generation needs to be constructed, with an average scalar rate of 3.3. These scalar numbers differ between vehicle classes due to the size and mass of the vehicle. This is not a trivial matter, when the scale of the task is considered.

Table 10. Comparison of the annual electrical energy to be generated to charge a global fleet of pure EV vehicles to the electrical energy to produce the annual mass of hydrogen to fuel a global complete H2 cell vehicle fleet (Michaux 2021).

Vehicle 	**Required annual electrical power to be generated to charge a global fleet of pure EV vehicles *** (TWh)	**Electrical power to produce the annual required mass of hydrogen to fuel a global complete H_2 cell vehicle fleet *** (TWh)	**Ratio of electric power needed to charge a global fleet of EV vehicles to the required power to produce H_2 to power an equivalent fleet of Fuel Cell vehicles**
Class 8 Truck	2 601,9	7 503,7	2,9
Bus & Delivery Truck	1 166,1	3 710,4	3,2
Light Truck & Van	2 181,7	9 203,9	4,2
Passenger Car	1 128,5	2 494,5	2,2
Motor Cycle	19,4		N/A
Maritime Shipping	945,9	2 983,4	3,2
Rail Transport	226,6	1 066,5	4,7
Sum Total	8 270,1	26 962,4	3,3
			Average Ratio

* Includes assumption of a 10% loss in transmission between power station and charging point

There is another comparison of note. The mass of the EV battery compared to the mass of the equivalent system hydrogen fuel tank for each vehicle class shows a very clear pattern. The mass of the required hydrogen tank was assumed to have a storage density for 700 bar compressed hydrogen to be 5.7 wt% (similar to the Toyota Mirai passenger car, Toyota 2014). Table 11 shows this direct comparison across all transport classes. It is clear that the hydrogen fuel cell solution has a much lighter mass energy storage than the EV solution, by an average multiplier of 3.2. Table 12 shows the same comparison as in Table 11, but instead of compressed hydrogen gas, storage is in the form of liquid hydrogen in cryogenic tanks. This has been presented as liquid hydrogen has a much smaller mass and volume of storage system for the same unit of mass of hydrogen fuel. The EV storage system mass ratio to liquid hydrogen storage system is approximately 9:1. This would be important for the large, long-range vehicles like very large ships. The engineering and logistics of liquid hydrogen are much more complex than compressed hydrogen gas. The viability of the system should consider all of these things.

Table 11. Comparison of the estimated mass of energy storage of an EV vehicle (a Lithium-Ion Battery) to the estimated mass of the energy storage of a fuel cell vehicle (compressed H_2 tank at 700 bar pressure).

Vehicle	**EV Vehicles**		**Hydrogen Fuel Cell Vehicles**	**Ratio**
	**Estimated capacity of the EV battery** (kWh)	**Estimated mass of lithium ion battery in vehicle, @230 Wh/kg** (kg)	**Estimated weight of hydrogen storage tank*** (kg)	
Class 8 Truck	450,0	1 957	563	3,5
Bus & Delivery Truck	227,5	896	474	1,9
Light Truck & Van	42,1	183	123	1,5
Passenger Car	46,8	203	70	2,9
Motor Cycle	21,5	80	N/A	N/A
Rail Freight Locomotive	65 000	282 609	75 789	3,7
Maritime Shipping				
Small Vessel	14 269,5	62 041	16 689	3,7
Medium Vessel	358 397,3	1 558 249	419 178	3,7
Large Vessel	4 977 739,7	21 642 347	5 821 918	3,7
Very Large Vessel	11 614 726,0	50 498 809	13 584 475	3,7
			Average:	3,2

* 70 Mpa (700 bar) pressure compressed hydrogen storage tank @5.7 wt% storage density

Table 12. Comparison of the size of energy storage of an EV vehicle (a Lithium-Ion Battery) to the size of the energy storage of a fuel cell vehicle (cryogenic liquid H2 tank) of the same class doing a similar task.

Vehicle 	**Estimated capacity of the EV battery** (kWh)	**Estimated mass of lithium ion battery in vehicle, @230 Wh/kg** (kg)	**Estimated weight of hydrogen storage tank*** (kg)	**Ratio**
Rail Freight Locomotive	65 000	282 609	30 857	9,2
Maritime Shipping				
Small Vessel	14 269,5	62 041	6 795	9,1
Medium Vessel	358 397,3	1 558 249	170 665	9,1
Large Vessel	4 977 739,7	21 642 347	2 370 352	9,1
Very Large Vessel	11 614 726,0	50 498 809	5 530 822	9,1
			Average:	9,1

* Liquid compressed hydrogen storage tank @14 wt% storage density

The data presented so far can now be used to make a crude recommendation for comparing efficiencies of EV systems to Hydrogen fuel cell systems. Considering the implications of the data presented in practical terms, it is then assumed that all short-range vehicle transport should be EV. This includes passenger cars, buses, commercial vans, and delivery trucks. All long-range transport and freight tasks (that would require extra power in application), are recommended to be powered with a hydrogen fuel cell. This includes long range trucking freight (Class 8 HCV), intercity rail transport (passenger and freight) and the maritime shipping fleet. The required physical mass and volume of the battery makes the EV system not practical for maritime shipping and intercity rail freight. Chapter 17 of Michaux (2021) examined what a complete EV maritime fleet would look like. Estimates of fuel consumption, fuel efficiency and distances travelled, for all maritime vessel size classes were all included. The mass of the battery that would be needed to support the EV vessel across the distances travelled by ICE ships of simialr size was calculated. It was found that the mass of the battery took up most and in some cases all the available cargo spaces. Chapter 16 of Michaux 2021) examined an EV rail locomotive to match performance metrics of a standard diesel ICE locomotive. To match performance, an EV locomotive would need a 281.9 tonne battery bank. An alternative H_2-Cell locomotive is discussed in Section 9.4. Class 8 HCV trucks need to travel a very long range, which makes the H_2 Cell system more efficient. This study did not include details like limitations for driving hours for truck drivers. City rail transport internal to the city power grid could be powered with overhead power cables. So, a fuel cell vehicle will be able to have a much greater range and capacity to carry cargo and passengers than an EV, with the same energy mass storage, and thus is more appropriate for long range and cargo transport applications.

8 PHASING OUT SHORT RANGE ICE VEHICLES AND SUBSTITUTION WITH EV'S

To phase out ICE vehicles (and the consumption of petroleum products), a practical substitute is required to be found, that can perform the same vital tasks for the industrial ecosystem. As the 'after oil' solution is needed as soon as possible, a selection of Electric Vehicle (EV's) that are commercially available at the time of writing was assembled. These EV's were grouped according to vehicle class, and the relevant performance specifications were averaged. In doing so, an average estimate for each vehicle class could be used to estimate the annual power requirements to charge the EV batteries for the whole fleet.

The following tables provide a list of current electric vehicles (EV), with battery size, efficiency, average range, and a range of ranges in the city, and out on the open freeway. The range is between driving in sub-zero temperatures with heating on and driving in the warm with no air conditioning. All of the vehicles listed can achieve longer ranges on road trips, if driven economically.

Table B1 in the Annex B Section shows a range of EV units, that on average a passenger car (car) consumes 0.19 kWh/km, or for every kilometer traveled, the vehicle needs 0.19 kWh. Table B2 in the Annex B Section shows the specifications of a series of electric commercial vans. These vehicles are in production and specifications are readily available. An average energy consumption for a Light Truck/Van vehicle to be used is 0.23 kWh/km. Table B3 in the Annex B Section shows the estimated specifications of a range of EV pick-up trucks like the Tesla Cybertruck. None of these vehicles have been released yet and specifications have had to be estimated from manufacture press releases. An average energy consumption for a Light-Duty vehicle to be used is 0.31 kWh/km. Table B4 in the Annex B Section shows the specifications of EV buses to transport lots of people. Only two examples are shown here (7900 Volvo and BYD K9), but these two models represent a large proportion of the current global EV bus fleet. Table B5 in the Annex B shows the specifications for HCV Class 8 trucks if they were EV systems. Specifications are from manufacturer's press releases. An average energy consumption for a Transit Bus, Paratransit Shuttle, or School Bus EV vehicle to be used is 1.32 kWh/km. The electrical energy consumption rates discussed so far in this section assist in estimating how much electric charge would be needed in the vehicle battery. These numbers were used in the calculation flow chart in Figure 13 and Tables 13 and 14.

Table 13. Estimated kWh needed to charge the proposed global EV transport fleet in the same transport scope as 2018.

Vehicle Class 	**Number of Self Propelled Vehicles in 2018 Global Fleet** (number)	**Total km driven by class in 2018 Global Fleet** (km)	**KiloWatt-Hour distance if vehicles were EV** (kWh/km)	**KiloWatt-hours needed to power global transport fleet if all vehicles were EV (assuming no efficiency loss)** (kWh)	**Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point** (kWh)
Refuse Truck + Delivery Truck	9 645 529	2,53E+11	1,01	2,56E+11	2,82E+11
Transit Bus + School Bus + Paratransit Shuttle	19 356 724	5,61E+11	1,32	7,40E+11	8,14E+11
Light Truck/Van + Light-Duty Vehicle	601 327 324	8,07E+12	0,23	1,87E+12	2,06E+12
Passenger Car	695 160 429	5,56E+12	0,19	1,08E+12	1,19E+12
Motorcycle	62 109 261	1,64E+11	0,06	9,21E+09	1,01E+10
Total	1 387 599 267	1,46,E+13		3,96E+12	4,35E+12
Total	1.39 billion vehicles	14.61 trillion km travelled in 2018			4 354.0 TWh

Table 14. Estimated number and power capacity of EV batteries for the proposed Electric Vehicles in the global fleet (2018 scope).

Vehicle Class 	**Number of Self Propelled Vehicles in 2018 Global Fleet** (number)	**Battery Capacity** (kWh)	**Estimated Range** (km)	**Estimated battery capacity needed** (kWh)
Refuse Truck + Delivery Truck	9 645 529	206,0	233	1,99E+09
Transit Bus + School Bus + Paratransit Shuttle	19 356 724	227,5	250	4,40E+09
Light Truck/Van + Light-Duty Vehicle	601 327 324	42,1	206	2,53E+10
Passenger Car	695 160 429	46,8	271	3,25E+10
Motorcycle	62 109 261	12,7	232	7,91E+08
Total	1 387 599 267			6,505E+10
Total	1.39 billion vehicles			65.05 TWh of Batteries

Electric power needed to charge the batteries in the global Electric Vehicle (EV) fleet with the same scope of activities as in 2018 was 4 354.0 TWh. This study did not account for the support infrastructure required to service and support the EV transport fleet. Each EV would need access to a charging port to charge their batteries. A recent study examined this issue in the United States (NREL 2023) and concluded that the projected size of the EV transport fleet in America would be approximately 33 million vehicles by 2030. These 33 million vehicles would need the infrastructure support of approximately 28 million charging ports. If this ration was applied to 1.39 billion Electric Vehicles in the global transport fleet, then 1.2 billion (1 177 356 954) charging ports would be required.

9 THE HYDROGEN ECONOMY

The hydrogen economy is now often promoted as a possible replacement system to phase out fossil fuels (Hydrogen Council 2020, IRENA 2019, IRENA 2018, FCH 2019, COAG 2019, IEA 2019c, ITM 2017). There are many applications for hydrogen that go beyond the transportation. It is hoped that hydrogen could be the fuel to facilitate the decarbonization of:

- Energy intensive industries
- Truck transport
- Aviation
- Maritime shipping
- Heating applications (industrial and building heating)

For the purpose of this study, just the hydrogen needed to fuel a transport grid was included in calculations. Hydrogen is to be manufactured, stored then used as a fuel in a power cell (also called hydrogen fuel cell, or H_2 Cell). A hydrogen fuel cell vehicle is now in competition of the Electric Vehicle as a substitution option to phase out Internal Combustion Engine (ICE) vehicles.

The term Hydrogen Economy refers to the proposed strategy of using hydrogen as a low-carbon energy source – replacing petroleum products as a transport fuel for Internal Combustion Engine (ICE) vehicles. Also, hydrogen could be used as a substitute for natural gas as a heating fuel. Hydrogen is attractive because whether it is burned to produce heat or reacted with air in a fuel cell to produce electricity, where the majority of byproduct is water (there can be some minor emissions like NOx and other radicals).

Hydrogen is not an energy source though, more an energy carrier or storage medium. Traditionally, hydrogen was thought to be not found in its pure form in the natural environment. However, work done over the last few years (Arola 2024, Ball & Czado 2022) has shown that hydrogen does indeed exist in significant quantities in bedrock and that hydrogen can be also found from Pre-Cambrian rocks (Lorrar et al. 2014). For example, Finland's bedrock includes ultramafic and high uranium content rocks which are known to produce natural hydrogen. GTK has research results on geological hydrogen concentrations in different rock types (publication in progress), but not yet comprehensively enough to provide a clear overall picture. A recent discovery in in a deep underground chromite (chromium ore) mine in Albania, has the potential for remarkably high hydrogen outgassing rate of at least 200 tons per year (UGA 2024). This concept is very useful, as extracting hydrogen from the bedrock could be a valuable source in the future, as industrial demand is growing.

When examining what is viable now, it is clear that hydrogen fuel needs to be produced from other compounds such as natural gas, biomass, alcohols, or water. In all cases it takes energy to convert these into pure hydrogen.

One of the most potentially useful ways to use hydrogen is in electric cars or buses in conjunction with a fuel cell which converts the hydrogen into electricity. It is the flexibility that hydrogen offers that makes it so potentially useful within future low-carbon energy systems. It can be produced from a wide variety of resources and can be used in a wide range of applications, such as power generation, as a transport fuel for low carbon vehicles, for the chemical industry, and for low carbon heating. Also, hydrogen is already used extensively in the chemical industry. This means that technology for hydrogen production, handling, and distribution on a large scale, is mature.

To produce 1 kg of hydrogen with electrolysis, it conservatively requires 50 kWh (IRENA 2018, FCH JU 2017, U.S. Department of Energy 2008) and 2.5 kWh to compress it into storage 70.0 MPa (700 bar) tanks (Fig. 14), giving a total energy cost of production of 52.5 kWh/kg. Electricity production with a Proton-Exchange Membrane (PEM) fuel cell with hydrogen required 1 kg for 15 kWh (IRENA 2018, FCH 2019, Michaux 2021). The proposed hydrogen economy is shown in Figure 14. Hydrogen is produced using electrolysis, powered with non-fossil fuel based electricity. That hydrogen is stored and distributed throughout society to be the basic energy of choice in parallel with electricity. Hydrogen is to be used as a fuel source to power vehicles like passenger cars, trucks, and ships with the use of fuel cells (probably PEM cells). Some hydrogen could also be used in turbines (same technology as gas turbines) to generate electricity and heat, which could be used in a variety of applications domestically and industrially.

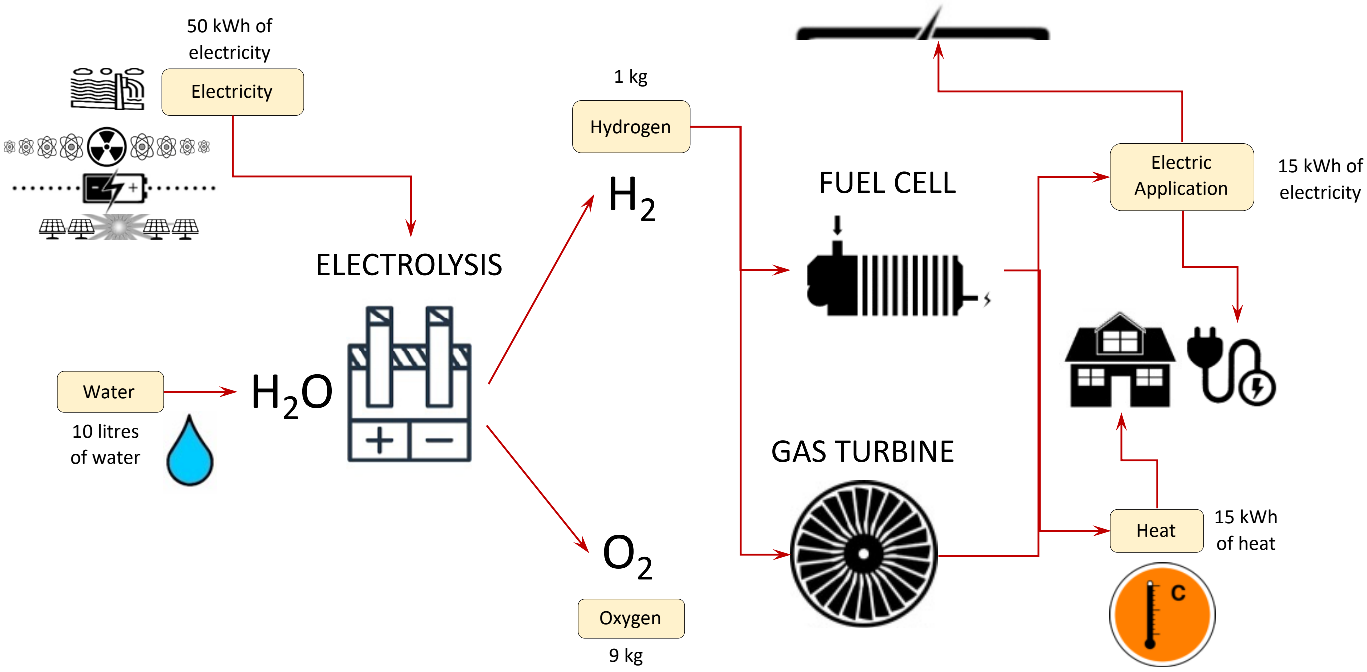

Fig. 14. Production and use of 1kg of hydrogen in the proposed Hydrogen Economy (Source: EIA 2024a, Thomas 2018).

9.1 The use of hydrogen as a combustion fuel in a power generation turbine

It has been proposed (IRENA 2019) to use hydrogen as a combustion fuel to turn a turbine to generate electricity (a direct substitution for natural gas in a re-engineered gas turbine). Consider in a thought experiment how much hydrogen a General Electric model 9F.04 hydrogen gas turbine (288 MW installed power) would annually consume. Also, consider if solar PV power was used to produce that hydrogen, what installed capacity would be needed.

- The General Electric model 9F.04 hydrogen gas turbine has an installed power of 288 MW (Goldmeer 2019). If this turbine was configured in a combi cycle which would have 60.4% efficiency and in simple cycle 38.7%. This would make this set up more efficient.
- Assuming a 58.5% annual avialability (similar to the average natural gas turbine), this turbine would operate at 5 124.6 hours a year.
- This turbine in combi cycle would then produce 2 355.2 GWh of electricity a year
- The General Electric model 9F.04 hydrogen gas turbine consumes 21 886 kg (243 500 m^3) of hydrogen an hour to output power at 288MW (Goldmeer 2019)
- Thus, the annual consumption of the 9F.04 hydrogen gas turbine operating for 5 124.6 hours would be 112 157 tonnes of hydrogen
- Given it requires 50 kWh to produce 1kg of hydrogen with electrolysis and 2.5 kWh to compress it into storage 70 MPa tanks (Fig. 14), it would require 5 888 GWh of electrical energy supplied annually to produce hydrogen for this single turbine.
- The average size solar PV power station (installed power of 33.1 MW) produced 33.04 GWh (33 040 663 kWh) in the year 2018 (Source: Global Energy Observatory 2020, and Tables 34 to 36)
- Thus, it would require 178 average sized PV stations (each 33.1 MW installed power) to annually produce 5 888 GWh.
- The installed power capacity for 178 solar PV stations would be 5 888.2 MW

In order to support a 288 MW hydrogen turbine that would annually produce 2 355.2 GWh, a solar PV installed capacity of 5 888.2 MW would be required, to deliver 5 888 GWh to manufacture the hydrogen. Alternatively, the 2 355.2 GWh could be delivered with solar PV power directly, with 2 355 MW installed capacity. The difference between a hydrogen turbine supported with solar panels to deliver 288 MW compared to delivering 288 MW directly with solar PV power is a multiplier of 2.5. It is not sensible to consider using hydrogen as a combustion fuel in direct power generation.

9.2 The use of hydrogen as a power storage

It has been proposed to use hydrogen as a store of energy (Zhang et al. 2016), where power generation in excess to demand load could be used to produce hydrogen with electrolysis (Menton 2022). Given it requires 52.5 kWh to produce 1 kg of hydrogen, but that 1 kg of hydrogen can only deliver 15 kWh of electricity, hydrogen as an energy storage would be 28.6% efficient. While the use of excess available power is a useful task, it is recommended that other power storage methods are considered.

9.3 Hydrogen Fuel Cell Heavy Duty Trucks

It has previously been concluded that all long-range vehicles such as trucks should be hydrogen fuel cell powered (Section 6, Michaux 2021). For each vehicle class, a commercially available model was used to represent the whole class as an average in the calculation of the required scope of the hydrogen economy. The Hyundai Motor Company have produced and commercialized a heavy duty hydrogen fueled truck (FuelCellsWorks 2020). The first 50 manufactured units are being sent to Switzerland in Q3 of 2020 with a planned total of 1600 XCIENT trucks to be manufactured by Hyundai by 2025.

The XCIENT H_2 Cell fueled truck is powered by a 190 kW hydrogen fuel cell system with dual 95 kW fuel cell stacks (FuelCellsWorks 2020). Seven large hydrogen fuel tanks offer a combined storage capacity of 32.09 kg of hydrogen. The driving range of the XCIENT truck is quoted by Hyundai as being 400km (assuming the 4 x 2 model with refrigerated up-fit configuration while operating 34 tonne truck + trailer). This provides a hydrogen fuel consumption efficiency of 8.02 kg/100km. These specifications were developed based on a balance between the optimal requirements from the potential commercial fleet customers. Refueling time is approximately 8-20 minutes. Table 15 shows the estimated quantity of hydrogen for the number of vehicles in each class to travel the same number of kilometers as what was done in 2018. An estimate the total mass of hydrogen is summed together.

Table 15. Estimated required volume of hydrogen to be consumed by all self-propelled vehicles in the global fleet in 2018, as if they were all hydrogen fuel cells.

Vehicle Class 	**Number of Self Propelled Vehicles in 2018 Global Fleet** (number)	**Total km driven by class in 2018 Global Fleet** (km)	**Consumption of hydrogen if vehicle was a FCEV** (kg/100 km)	**Consumption of hydrogen if vehicle was a FCEV** (kg/km)	**Quantity of H_2 for all global vehicles in that class to travel the same distance as was done in 2018** (kg)	**Quantity of H2 for all global vehicles in that class to travel the same distance as was done in 2018** (tonnes)
Class 8 Truck	28 929 348	1,66E+12	8,02	0,0802	1,33E+11	1,329E+08
Total		1.66 trillion km				132.9 million tonnes

9.4 Hydrogen Fuel Cell Rail Transport Network

A proportion of the rail transport system is already electric EV based. Diesel fuel locomotives pull 45% of passenger rail transport and 85% of rail freight (IEA 2019a). To phase out the remainder of these petroleum fueled ICE diesel engines in the global rail network, and phase in electric motor propulsion, it was recomended that all new locomotives be electrical propulsion systems, powered by hydrogen fuel cells. The extra electrical energy needed to produce the hydrogen across the year 2018 was undertaken. In this calculation, the extra power requirement to be delivered to the electric motors on board each train locomotive, is to be generated by H_2 supplied fuel cells splitting water. As shown in Figure 14, a PEM fuel cell can generate 15 kWh from 1 kg of hydrogen, with a waste output of water and heat (Thomas 2018).

Thus, to generate 2.27 x 10^{11} kWh of electrical energy, the global rail system (at the same scope as 2018) would require 1.85 x 10^{10} kg (18.47 million tonnes) of hydrogen to be manufactured, stored, and then carried on trains as they operate.

To estimate how much each train would be required to carry in a hydrogen tank, a freight train running an average distance is used. This example does not account for extra hydrogen consumption due to the extra torque required to pull such a heavy load but will use the average distance (Michaux 2021). According to the Association of American Railroads (AAR 2024), an average example, a train might haul 3 000 tonnes of freight 804.6 km (500 miles) and consume approximately 11 541 liters (3,049 gallons) of diesel fuel. Given that the mass of diesel fuel is 0.85 kg/l (Annex G, Table G1), and its energy density if 12.67 kWh/kg, then 11 541 liters of diesel contains 124. 3 MWh of energy. If a Diesel ICE unit is 38% efficient, then 47.2 MWh of energy is useful work done. So, a hydrogen fueled PEM cell fueling an electric motor would have an approximately 73% energy efficiency (IEA 2019b). To do the same amount of useful physical work, it would require 64.7 MWh. So, this Hydrogen fueled electric train system would require from an energy source of 64 699 kWh.

If a PEM fuel cell produces approximately 15 kWh (Thomas 2018) from 1 kg of hydrogen, then the estimated mass of hydrogen required to be stored in a tank aboard a locomotive train pulling 3 000 tonnes of freight 804.6 km, would be 4 313.4 kg, or 4.3 tonnes.

So, for an EV freight train to replace a diesel locomotive, it would need to have a 65 000 kWh battery bank (estimated). Using an estimated energy density for a lithium-ion battery technology of 230 kg per Wh of capacity (IEA 2019b), a 65 000 kWh battery would have a mass of 281 963 kg, or 281.9 tonnes.

This means that the energy store load carried by a freight locomotive, if it were a pure EV system, would be a 281.9 tonne lithium-ion battery, whereas if this system was a hydrogen fuel cell, then the energy store would be 4.32 tonne. This difference in mass makes the hydrogen fuel cell system useful for any long-range transport distance. The industrial ecosystem is underpinned by the transport of goods and people. Rail has been a very effective method to transport large quantities of freight and large numbers of passengers over long distances. A large proportion of rail transport (both passenger and freight) is powered by diesel fueled ICE engines. To phase out fossil fuel systems, the size and scope of those diesel fueled rail locomotives would need to be quantified some numbers collected. Also, if urban planning would become more reliant on rail as ICE vehicles are phased out, then the scope of electrification of the existing diesel fueled rail networks would need to be understood.

Passenger rail transport activity comprises urban and non-urban passenger movements and is typically measured in passenger-kilometers per year. Such activity has increased significantly over the past twenty years, but is concentrated in a few regions, China, India, Japan, European Union, and Russia together account for more than 90% of passenger rail activity worldwide (IEA 2019a). A summary of rail transport statistics in 2018 is (IEA 2019a):

- The energy intensity for passenger rail transport as an estimated global average is 112 kJ/passenger-km
- The energy intensity for passenger rail transport in Europe is 340 kJ/passenger-km
- Global number of million passengers carried per year was 32 355 in 2018
- Global number of passenger-kilometers was 3 823 billion passenger-kilometers in 2018
- The energy intensity for freight as an estimated global average is 108 kJ/tonne-km

- The energy intensity for freight in Europe is 166 kJ/tonne-km
- Global tonne-kilometers of rail freight transport per year was 11 067 billion tkm in 2018
- Global tonnes carried in rail freight transport per year was 12 545 tonnes in 2018

To phase out diesel fuel, all rail activity would have to become EV-based technology. In a global context, 45% of passenger rail transport and 85% of rail freight is driven by diesel fuel locomotives (IEA 2019a). If the number of million passengers carried per year in diesel fueled trains, on a global scale was 45%, then 1 720 billion passenger-kilometers was in trains powered by diesel (45% of 3 823 billion passenger-kilometers = 1 720 billion passenger-kilometers). With an energy intensity for passenger rail transport as an estimated global average is 112 kJ/passenger-km, 1.92 x 10^{14} kJ of energy would need to be added to the electric grid in extra capacity to transport all rail passengers. Converting from kJ to kWh, this would require 5.35 x 10^{10} kWh of extra power draw capacity.

Given that diesel fuel Internal Combustion Engine (ICE) technology is 45% efficient, this means that 2.4 x 10^{10} kWh of useful work would be done (45% of 5.35 x 10^{10}kWh = 2.4 x 10^{10} kWh). If these systems were replaced with Electric Vehicle technology, which have an efficiency of 73%, then then the required extra power draw capacity to transition the remainder of the global rail passenger transport system would be 3.30 x 10^{10} kWh (2.4 x 10^{10} kWh/73% = 3.30 x 10^{10} kWh).

If the number of tonne-kilometers of rail freight transport per year in diesel fueled trains, on a global scale was 85%, then 9 407 billion tkm were transported by locomotives powered by diesel. With an energy intensity for freight as an estimated global average is 108 kJ/tonne-km, 1.02 x 10^{15} kJ of energy would need to be added to the electric grid in extra capacity to transport all rail freight. This would require 2.82 x 10^{11} kWh of extra power draw capacity.

As diesel fuel Internal Combustion Engine (ICE) technology is 45% efficient, this means that 1.27 x 10^{11} kWh of useful work would be done (45% of 2.82 x 10^{11} kWh = 1.27 x 10^{11} kWh). If these systems were replaced with Electric Vehicle technology, which have an efficiency of 73%, then then the required extra power draw capacity to transition the remainder of the global rail passenger transport system would be 1.73 x 10^{11} kWh (1.27 x 10^{10} kWh/73% = 1.73 x 10^{11} kWh). So, the work done by a complete EV rail network of the scope and size of the 2018 would be:

3.30 x 10^{10} kWh + 1.73 x 10 ^{11}kWh = 2.06 x 10^{11} kWh

Table 16 shows the electricity required to produce the hydrogen if the above power was provided with a hydrogen fuel cell.

Table 16. Hydrogen production for rail transport (Annex C, Table C8).

Energy Consumed by electric propulsion system for rail transport fleet that is currnetly diesel locomotive (2018 scope) (kWh)	Hydrogen Required given 1kg produces 15 kWh (kg)	Electricity required to produce hydrogen @50 kWh/kg (kWh)	Electricity to compress H2 into 700 bar tanks @2.5 kWh/kg (kWh)	Electricity requried to produce hydrogen (kWh)	Required annual electric power generation assuming 10% grid transmission loss between power station and electrolysis unit and compression unit (kWh)
2,06E+11	1,37E+10	6,87E+11	3,43E+10	7,21E+11	7,93E+11

Assuming a 10% loss in output power between the power station and the point of application, of extra power will need to be supplied (7.21 x 1.1 = 7.93).

This would be:

7.93 x 10^{11} kWh or 793.1 TWh

9.5 International Maritime Shipping Fleet 17% Hydrogen Fuel Cell Powered

The maritime transport shipping fleet delivers a vital service to the global industrial ecosystem. The movement of goods and commodities internationally cannot happen in the needed quantities without shipping. As raw materials are typically extracted on one continent (for example Africa, Middle East, South America, South Africa, etc.), used for manufacture on another continent (for example China in Asia), and then used and consumed on yet other continents (for example Europe, North America, etc.). These material flows are so large, that they can only be transported in bulk volumes by large maritime shipping. It will be a challenge to phase out fossil fuels in the maritime industry. The volumes of cargo and commodities moved are truly vast and the distances travelled are longer than any other transport system currently in use (Table 17). Multiple options to phase out fossil fuels have been proposed (EFTE 2018), ranging from fully EV, to sail assisted and nuclear propulsion (currently used in large military vessels like aircraft carriers).

Table 17. Number of ships in global maritime fleet by size and their fuel consumption.

Size Classification	**Number of ships in Global Fleet**	**Ship Size**	**Gross Tonnage**
	(Source: The World Merchant Fleet in 2018 Statistics from Equasis)	(TEU)	(GT)
Small (100 GT to 499 GT)	53 854		300
Medium (500 GT to 24 999 GT)	44 696	1000	12 300
Large (25 000 GT to 59 999 GT)	12 000	4000-5000	54 000
Very Large (>60 000 GT)	6 307	10000+	196 000
Total	116 857		262 600

For the purpose of this study, it is assumed that the post fossil fuel maritime shipping will be fueled by ammonia (46%), hydrogen (17%), and bioenergy (37%). This has been based on a projection from Table 3 (IEA 2021a).

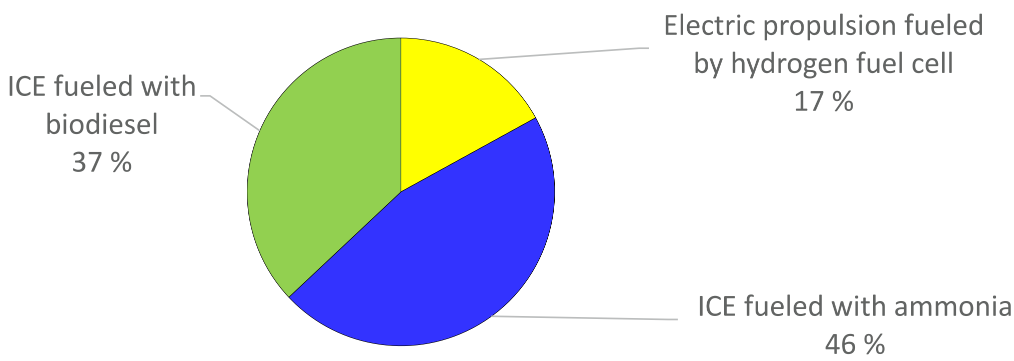

Fig. 15. Proportion of global maritime shipping by fuel, using the 2018 scope (Source: split taken from IEA 2021a).

Annex C shows the full calculation to estimate the electrical energy required to produce enough hydrogen to fuel 17% of the global shipping fleet (based on the 2018 scope of physical work done). The results are as follows. Given that the electrical energy of 1kg of hydrogen produced is 15 kWh (Thomas 2018), 1.46 x 10^{10} kg of hydrogen would be needed. If it is assumed that hydrogen production in a PEM cell is 50 kWh/kg (this is conservative at the time of writing this paper), and to compress that hydrogen into a 700 bar storage fuel tank was 2.5 kWh/kg, then a total of 7.68 x 10^{11} kWh of electricity is required (Table 18).

Table 18. Electrical energy needed to produce hydrogen for the H_2-Cell powered maritime fleet (17% of the global fleet, 2018 scope) (Table B17).

Size Classification 	**(TEU)** (kWh)	**Hydrogen mass required @15 kWh/kg** (kg)	**Power required to produce hydrogen @50 kWh/kg** (kWh)	**Power required to compress hydrogen in 700 bar storage tanks @2.5 kWh/kg** (kWh)	**Total energy required to produce hydrogen for 17% of maritime shipping fleet** (kWh)	**Electrical power generated at station to account for 10% loss in transmission** (kWh)
Small (100 GT to 499 GT)	2,19E+09	1,46E+08	7,32E+09	3,66E+08	7,68E+09	8,45E+09
Medium (500 GT to 24 999 GT)	3,73E+10	2,49E+09	1,24E+11	6,22E+09	1,31E+11	1,44E+11
Large (25 000 GT to 59 999 GT)	7,24E+10	4,83E+09	2,41E+11	1,21E+10	2,53E+11	2,79E+11
Very Large (>60 000 GT)	1,08E+11	7,17E+09	3,58E+11	1,79E+10	3,76E+11	4,14E+11
Total	2,19E+11	1,46E+10 14,6 (million tonnes)			7,68E+11	8,45E+11 844,9 (TWh)

Electrical energy required to produce the hydrogen to fuel 17% of the global shipping fleet is 7.68 x 10^{11} kWh. To produce the electrical energy at the power station, assuming a 10% transmission loss, 8.45 x 10^{11} kWh, or **844.9 TWh** would need to be generated.

9.6 Steel manufacture

The global steel industry consumed 13.9% of coal in 2018, where 71% of steel was made using coal (World Coal Association 2024, World Steel Association 2019). About one-quarter of the world's steel is produced by the Electric-Arc Furnace method (EAF), which uses high-current electric arcs to melt steel scrap and convert it into liquid steel of a specified chemical composition and temperature (World Steel Association 2019). Annex D shows a more complete discussion of how the numbers in Table 19 were calculated.

Table 19. Energy consumption in steel production across whole process (Source: Fruehan et al. 2000) (Table D2).

Steel Production Process	**Average Energy Requirement to Produce Steel** (billion Joules / metric ton)	**Average Energy Requirement to Produce Steel** (kWh/metric tonne)
Liquid Metal "Pig Iron"	13,5	3 750
Liquid Hot Metal: Basic Oxygen Furnace	11	3 056
Liquid Hot Metal: Electric Arc Furnace	2,25	625
Hot Rolling Flat	2,2	611
Cold Rolling Flat	1,2	333
Process path Pig Iron + Basic Oxygen Furnace + Hot Rolling Flat + Cold Rolling Flat	27,9	7 750
Process path Pig Iron + Electric Arc Furnace + Hot Rolling Flat + Cold Rolling Flat	19,2	5 319

Note: 1 billion joules = 277.777778 kilowatt hours

Taking data from Table 19, it requires between 7 750 and 5 319 kWh to produce a single tonne of steel, depending on what conventional process path is used. A non-fossil fuel alternative could be the use of hydrogen to produce steel. In Sweden, an initiative which endeavors to revolutionize steel making is being developed called HYBRIT, a collaboration between SSAB, LKAB and Vattenfall (HYBRIT 2019). HYBRIT aims to replace coking coal, traditionally needed for ore-based steel making, with hydrogen. The result will be the world's first fossil-free steel-making technology, with virtually no carbon footprint. According to the HYBRIT website, a tonne of steel could be produced with just 3 488 kWh (in addition to 560 kWh of bio torrefied biomass and 42 kWh of coal) (Fig. 16). Natural gas is also required to make high quality steel carbon, where 25% of the energy required for reduction. This lower energy consumption could be due to the use of an Electric Arc Furnace, which processes mostly un oxidated steel, it would need less energy to meet the same performance targets.

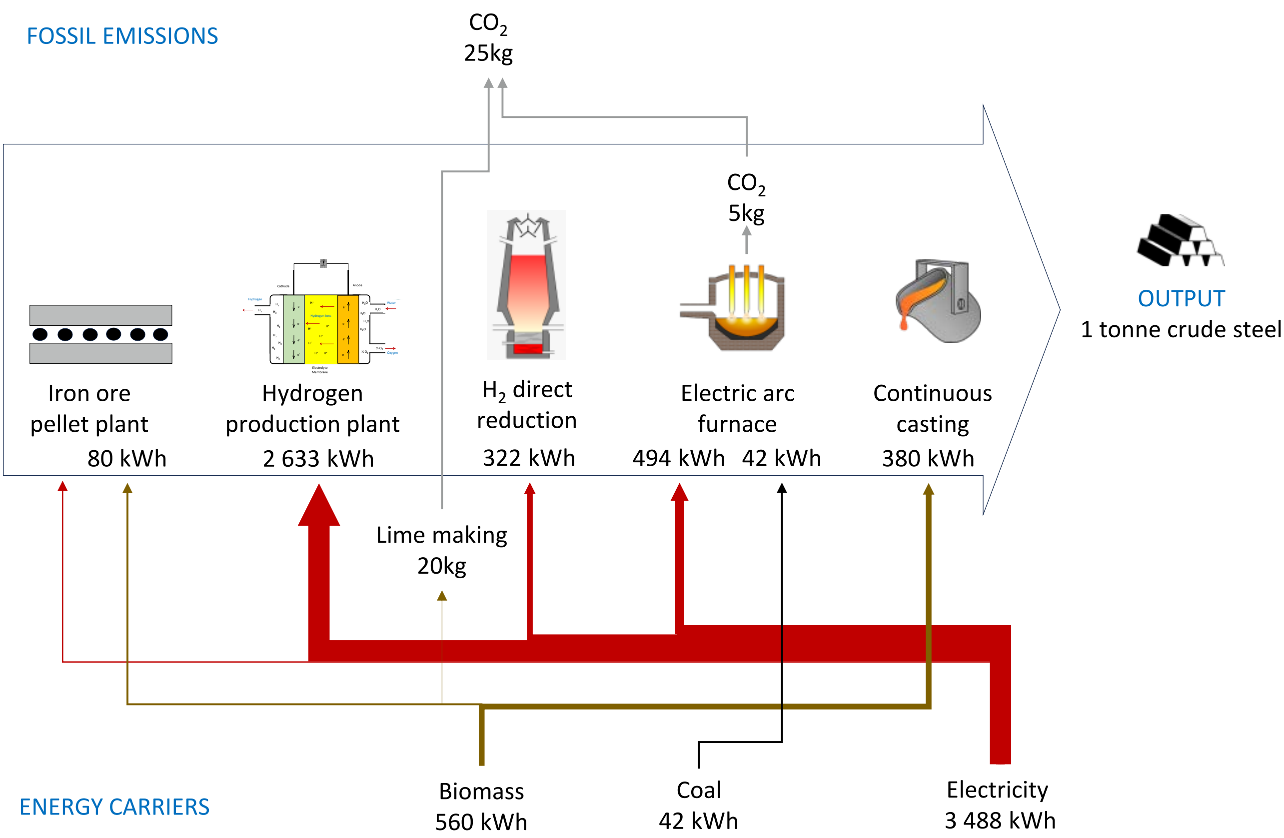

Fig. 16. Production of steel through reduction in a hydrogen atmosphere (Source: Drawn from HYBRIT 2019).

For the purposes of this study, it is assumed that the HYBRIT system works as shown (where production is much more energy efficient than the conventional process path at 3 488 kWh/tonne), and all steel production is transferred away from conventional coal fired production and using the hydrogen atmosphere process proposed by HYBRIT instead. The additional needed feedstocks of coal, bio torrefied biomass and gas were not included in this report for simplicity.

Global crude steel production reached 1 808.6 million tonnes (Mt) for the year 2018 (World Steel Association 2019). If it requires 3 488 kWh/tonne to produce steel, then 6 308.4 TWh of electrical energy is needed to be generated annually to deliver this needed quantity of steel ([1.81×10^9 tonne] x [3.488×10^3 kWh/tonne] = [6.308×10^{12} kWh]). To produce the electrical energy at the power station, assuming a 10% transmission loss, 6.94×10^{12} kWh, or 6 939.2 TWh would need to be generated.

10 PRODUCTION OF AMMONIA

A proposed alternative to hydrogen fuel is ammonia, which would be used in a form of Internal Combustion Engine (ICE) engine. Slight engineering changes to a conventional ICE system would be needed to cater to the different properties of ammonia. This compatibility means existing fleets may be retrofitted with ammonia-based technology without significant alterations. There are a number of technical challenges to be overcome for this to be safe to operate, have a manageable environmental impact and be economically viable.

Ammonia has different ignition and combustion properties in comparison to traditional fuels. It requires a higher ignition temperature, about 651°C, and the flame speed is considerably slower. Modifications to the engine's ignition system and control of the air-fuel mixture are necessary to optimize performance (Wang et al. 2023a). Ammonia's lower energy density than traditional fuels may require additional considerations for storage and efficiency, especially for applications requiring high power output. There are many safety hazards to be overcome with technological development for ammonia to be a useful fuel.

Ammonia has an energy density, at 12.7 MJ/L, than even liquid hydrogen (8.5 MJ/L) (Zamfirescu & Dincer 2009). Liquid hydrogen has to be stored at cryogenic conditions of −253 °C, whereas ammonia can be stored at a much less energy-intensive −33 °C. At temperatures below −33°C ammonia turns liquid at atmospheric pressure. Increasing the pressure by itself suffices to liquefy the gas: at 20°C a pressure of 7.5 bar is adequate. Ammonia, although hazardous to handle, is much less flammable than hydrogen. Ammonia is considered toxic, corrosive and a high health hazard because it is corrosive to the skin, eyes, and lungs. Exposure to 300 parts per million (ppm) is immediately dangerous to life and health. Ammonia is also flammable at concentrations of approximately 15% to 28% by volume in air (CDC 2024 https://www.cdc.gov/niosh/topics/ammonia/default.html).

Ammonia (NH_3) is one of the most important and widely produced inorganic chemicals in the world, which can be used:

1. to produce agricultural fertilizers like ammonium nitrate, ammonium phosphate, and urea (Khademi & Sabbaghi 2017, IEA 2021b)
2. as a capturing agent in acid gas removal (AGR) processes (Akbari et al. 2018, IEA 2024a),
3. for large scale refrigeration and air-conditioning for buildings and industrial processes (Egenhofer et al. 2014, IEA 2021b),
4. to manufacture explosive materials, fibers, plastics, polymers, papers, and acids (Khademi & Sabbaghi 2017), and
5. as a potential fuel for internal combustion engines (ICE) due to a high octane rate of 110–130 (Zamfirescu & Dincer 2009) and fuel cells (e.g., solid-oxide fuel cells) for power generation with or without reforming (Aziz et al. 2017, Fuerte et al. 2009).

There are research and development projects under way to make an ammonia ICE economically viable and to overcome these challenges in working with this potential fuel. For example, a two-stroke ammonia engine is being developed for maritime vessels (Lindstrand 2023). Toyota corporation have announced they are developing a passenger car ICE fueled by ammonia (Toyota 2023). When using pure ammonia, high boost pressure and compression ratio are required to compensate for the low ammonia flame speed. In spark-ignition engines, adding hydrogen to ammonia helps in speeding up the flame front propagation and stabilizing the combustion. In compression-ignition engines, ammonia can be successfully used in dual-fuel mode with diesel. A serious issue to overcome is the escape of unburnt ammonia in gases form, and high nitrous oxide (N_2O) emissions in the exhaust. There have been innovations of the installation of apposite aftertreatment systems to manage this. How successful these mitigation measures are, remain to be seen.

Ammonia is produced by using heat to force the combining of nitrogen (sourced from the air, and sometimes sourced from gasifying coal) with hydrogen to produce ammonia (NH_3), as shown in Equation 1. Ammonia is currently produced at an industrial scale through the synthesis of nitrogen and hydrogen, through the use of the Haber-Bosch process (Appl 1982), which is an artificial nitrogen fixation process and is the main industrial procedure for the production of ammonia. The hydrogen is sourced from natural gas, with the majority content being methane. The reaction is reversible, and the production of ammonia is exothermic.

$$N_2 + 3H_2 \xrightarrow{\text{yields}} 2NH_3 \quad \text{Equation 1}$$

At each pass of the gases through the reactor, only about 15% of the nitrogen and hydrogen converts to ammonia (Appl 1982). Gases are cooled and ammonia turns into liquid. Liquid ammonia is separated, and rest of the gas is recycled. By continual recycling of the unreacted nitrogen and hydrogen, it is possible to produce ammonia from about 97 to 98% of the feedstock. This conversion requires to be conducted at pressures above 10 MPa (is often much higher for efficiency of output) and between 400 and 500 °C. The ammonia is then used to create other forms of nitrogen including ammonium nitrate and urea (ammonia + CO_2). This is explained more completely in Annex E.

The hydrogen used in commercial-scale ammonia synthesis processes comes mainly from natural gas, coal, and other fossil fuels (IEA 2021b). Two-thirds of ammonia are currently synthesized from natural gas-derived hydrogen worldwide; while in China, 97% of ammonia is synthesized from coal-derived hydrogen (Xiang & Zhou 2018). However, to reduce fossil fuel consumption and greenhouse gas

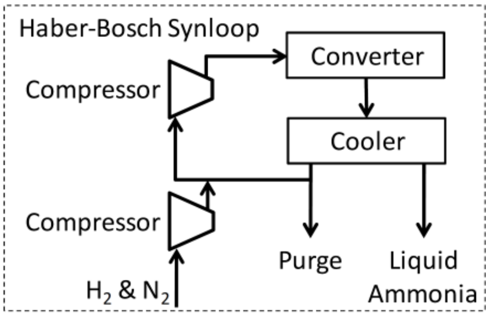

Fig. 17. Flow diagram of Haber-Bosch synthesis loop showing major components (Bartels 2008).

emissions, renewable energy derived green hydrogen is being promoted for ammonia production (IEA 2021b). Considering the application scale, potential alternatives for green hydrogen are biomass gasification and water electrolysis via renewable power, namely biomass-to-ammonia (BtA) and power-to-ammonia (PtA). Ammonia has a relatively low calorific value, and on top of that, characteristics like low cetane number and low flame speed make it difficult to apply in combustion engines. Ammonia's fuel properties are challenging when used in internal combustion engines (Table 20).

Table 20. Comparison of fuel properties (Table E1) (Source: IEA 2024a, fuel information Ammonia, https://www.iea-amf.org/content/fuel_information/ammonia).

	Energy content (LHV) (MJ/kg)	Energy content (LHV) (MJ/L)	Density (kg/m^3)	Octane (RON)	Flame-velocity (m/s)	Flammability-limits (vol/%)	Minimum Ignition Energy (mJ)
Cooled Ammonia	18,6	12,69	682	>130	0,067	15-28	680
(Liquefied)		(1 atm, -33°C)					
Compressed Ammonia	18,6	11,65	626	>130	0,067	15-28	680
(Liquefied)		(300 bar, 25°C)					
Cooled Hydrogen	120	8,5	70,85	>130	3,25	4.7-75	~0.016
(Liquefied)		(1atm, -253°C)					
Compressed Hydrogen (gaseous)	120	2.46 (300 bar, 25°C)	20,54	>130	3,25	4.7-75	~0.016
Diesel (n-dodecane)	44,11	32.89 (1 atm, 25°C)	745.7[12]	<20	~0.80	0.43-0.6	~0.23
Gasoline (iso-octane)	44,34	(n-octane) 30,93 (1 atm,25°C)	(n-octane) 697,6	100	0.41 ~0.58 (RON 90-98)	0.95-6 0.6-8 (RON 90-98)	1.35 ~0.14 (RON 90-98)
Methanol	19.90	15.65 (1 atm,25°C)	786,3	108,7	0,56	6.7-36	~0.14
Ethanol	26,84	21.07 (1 atm,25°C)	785,1	108,6	0,58	3.3-19	0,6

Note: 1 MJ = 0.2778 kW*h

10.1 Production of ammonia for 46% of the global maritime shipping fleet

In this study, it was assumed that 46% of the maritime shipping fleet would have ICE propulsion systems fueled with ammonia (Fig. 17), as per the prediction for 2050 (IEA 2021b) and as shown in Table 3. As such, of the 2.63 x 10^{11} liters (Table 21) of marine bunker fuel oil annual consumption in 2018 (OECD 2024 Data Statistics Database), 1.21 x 10^{11} liters of that bunker fuel oil would be replaced by an equivalent quantity of ammonia. Table 21 shows the fossil fuel petroleum product consumption. It is this fuel quantity that global annual ammonia production will be required to replace.

Table 21. Petroleum product consumption in the year 2018 (Source: OECD 2024 Data Statistics Database).

Fossil Fuel	Fuel consumed in 2018	
	(bbls)	(Liters)
Petrol	9 307 500 000	1,48E+12
Diesel	10 439 000 000	1,66E+12
Marine fuel *	194 499 000 (tonne)	2,63E+11
Jet fuel	2 260 000 000	3,59E+11
	Annual total	3,76E+12

* Units of tonnes were converted to liters where:
1 tonne = 8.5 barrels
1 Barrel volume unit is equal to 158.98 Liters
Thus, scalar to convert tonne to liters = 1351.39

As it is a liquid at room temperature and pressure, ammonia does not have the same storage and transport logistical problems that hydrogen does. Annex E shows a how the numbers in Tables 22 to 24 were developed.

The production of hydrogen requires 50 kWh/kg (or 50 MWh/tonne). To produce 177 kg of hydrogen would require 8 850 kWh (50 x 177), which is the hydrogen feedstock to produce 1 tonne of ammonia.

Table 22. Estimation of the energy to produce hydrogen to produce ammonia fuel for 46% of global shipping fleet (2018 scope) (Table E6).

Size Classification 	Mass of ammonia given energy density of ammonia = 5.167 kWh/kg (tonnes)	Quantity of hydrogen given 1 tonne ammonia requries 177 kg of H_2 (kg)	Energy consumed to produce hydrogen @50 kWh/kg (kWh)	Electrical power generated at station to account for 10% loss in transmission (kWh)
Small (100 GT to 499 GT)	2,21E+06	3,91E+08	1,95E+10	2,15E+10
Medium (500 GT to 24 999 GT)	3,75E+07	6,64E+09	3,32E+11	3,65E+11
Large (25 000 GT to 59 999 GT)	7,29E+07	1,29E+10	6,45E+11	7,09E+11
Very Large (>60 000 GT)	1,08E+08	1,91E+10	9,57E+11	1,05E+12
Total	2,21E+08	3,91E+10	1,95E+12	2,15E+12
Total	220,8 (million tonnes)	39,1 (million tonnes)		2 149,2 (TWh)

The electrical energy to produce 39.1 million tonnes of hydrogen, to in turn produce 220.8 million tonnes of ammonia to annually power 46% of the maritime shipping fleet (based on 2018 scope) is 1.95 x 10^{12} kWh. To produce the electrical energy at the power station, assuming a 10% transmission loss, 2.15 x 10^{12} kWh.

If it takes a further 7 222.2 kWh/tonne to produce the ammonia (Rouwenhorst et al. 2021) in the Haber-Bosch process (Appl 1982), then the full energy cost to produce ammonia would be:

1 tonne ammonia = 16 072.2 kWh (8850 + 7222.2)

Table 23. Estimation of the energy required to produce ammonia fuel in addition to hydrogen production (Table E7).

Size Classification 	**Mass of ammonia required to fuel 46% of maritime shipping** (tonnes)	**Electrical power generated to produce hydrogen** (kWh)	**Energy consumed to produce ammonia @7222.2 kWh/ tonne** (kWh)
Small (100 GT to 499 GT)	2,21E+06	2,15E+10	1,75E+10
Medium (500 GT to 24 999 GT)	3,75E+07	3,65E+11	2,98E+11
Large (25 000 GT to 59 999 GT)	7,29E+07	7,09E+11	5,79E+11
Very Large (>60 000 GT)	1,08E+08	1,05E+12	8,59E+11
Total	2,21E+08	2,15E+12	1,75E+12
Total	220,8 (million tonnes)	2 149,2 (TWh)	1 753,9 (TWh)

Table 24. Estimation of the energy required to produce ammonia fuel for 46% of the global shipping fleet (2018 scope) (Table E8).

Size Classification 	**Mass of ammonia required to fuel 46% of maritime shipping** (tonnes)	**Electrical power generated to produce hydrogen** (kWh)	**Energy consumed to produce ammonia @7222.2 kWh/tonne** (kWh)	**Total energy required to produce Ammonia** (kWh)
Small (100 GT to 499 GT)	2,21E+06	2,15E+10	1,75E+10	3,90E+10
Medium (500 GT to 24 999 GT)	3,75E+07	3,65E+11	2,98E+11	6,64E+11
Large (25 000 GT to 59 999 GT)	7,29E+07	7,09E+11	5,79E+11	1,29E+12
Very Large (>60 000 GT)	1,08E+08	1,05E+12	8,59E+11	1,91E+12
Total	2,21E+08	2,15E+12	1,75E+12	3,90E+12
Total	220,8 (million tonnes)	2 149,2 (TWh)	1 753,9 (TWh)	3 903,1 (TWh)

So, to produce the needed quantity of 220.8 million tonnes of ammonia, the 2 149 TWh of electrical energy generated to produce 39.1 million tonnes of hydrogen is added to the 1 753.9 TWh of electrical energy generated to produce the ammonia in the Haber Bosch process. This means that to produce ammonia to fuel 46% of the global maritime shipping fleet (using the 2018 scope of activity and fleet size), 3.90 x 10^{12} kWh or **3 903.1 TWh** would need to be generated.

10.2 Production of ammonia for agricultural fertilizer

In the late 1990's, the energy consumed to produce fertilizer accounts for 28% of the global energy consumed for industrial agriculture (Heller & Keoleian 2000). This is mainly the consumption of natural gas (methane) to produce ammonia, where approximately 9% of global gas demand is used to produce ammonia for the manufacture of fertilizer (Martinez-Alier 2011). Petroleum products like diesel are critical inputs for the functioning of the industrial production of food (most agricultural equipment vehicles are diesel ICE fueled).

Currently, the average human consumes about 2 800 kcal per day (increasing from an average of 2 360 kcal/day in the mid-1960's, https://www.fao.org/). It is convenient to remember that 2400 kcal equals 10 MJ (megajoules), so that per year we consume endosomatically about 3.6 GJ (gigajoules). The exosomatic use of energy in rich countries per person per year reaches 150 or 200 GJ on average, reflecting the fact that most energy (from fossil fuels, biomass, hydroelectricity, nuclear fission, wind) goes to production and consumption processes different from those directed to basic food needs (Martinez-Alier 2011).

Petrochemical technology applied to the processing of phosphorous (sourced from phosphate rock), nitrogen and potassium developed a spectrum of capabilities that accelerated the ability to manufacture food (NPK fertilizer and pesticides) (NPK = Nitrogen-Phosphorus-Potassium). A common phosphorus-based fertilizer on the global market is DAP (diammonium phosphate). Petrochemical fertilizers are another name for the synthetic products because they are produced using large quantities of petroleum, gas, and coal. Some common examples include ammonium nitrate, superphosphate, and potassium sulfate.

Nitrogen is a key component of most synthetic fertilizers, as plants require it for photosynthesis. The use of industrially produced nitrogen fertilizers has expanded significantly in the last few decades. Currently, 70% of the world's agricultural land requires nitrogen to become productive and produce food crops. More than half of the synthetic nitrogen fertilizers ever produced globally, have been used since 1985 (UNFAO 2015, Friedemann 2021).

The element phosphorus underpins the ability to produce food. It is second to nitrogen as the most limiting element for plant growth on 40% of the world's arable land. With too little phosphorus, plants are stunted with low yields. With enough phosphorus, crop yields can increase by 50% (UNFAO 2015). At the time of writing this report, there is no element that can substitute for phosphorus, nor can it be manufactured. The closest element to phosphorous in the same family of the periodic table is arsenic. Due to toxicity to living organisms, the substitution of arsenic into fertilizers is unlikely.

In 2018, the global consumption of ammonia was 144 million tonnes, while consumption was 184 million tonnes in 2021 (IndexBox 2023) (Fig. 18).

Table 25. Estimation of electrical energy required to produce hydrogen to produce ammonia to produce fertilizer (Table E10).

Mass of ammonia required to produce fertilizer (million tonnes)	**Quantity of hydrogen given 1 tonne ammonia requries 177 kg of H_2** (kg)	**Energy consumed to produce hydrogen @50 kWh/kg** (kWh)	**Electrical power generated at station to account for 10% loss in transmission** (kWh)
144,0	2,55E+10	1,27E+12	1,40E+12
	25,5 (million tonnes)		

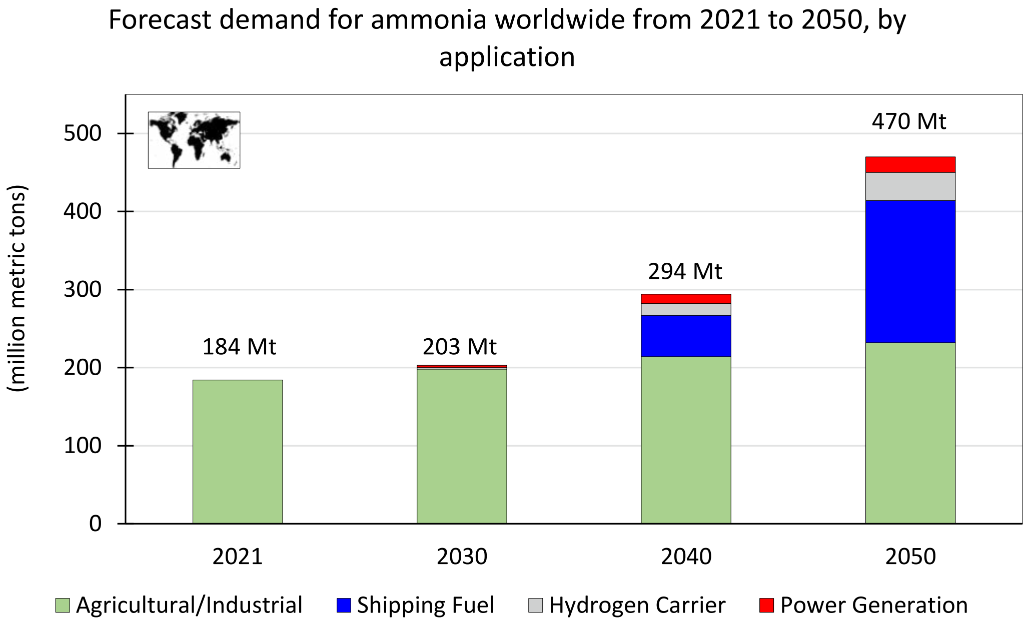

Fig. 18. Forecast demand for ammonia worldwide from 2021 to 2050, by application (Source: IndexBox 2023).

Ammonia is produced from a combination of nitrogen and hydrogen (Equation 1), where to produce 1 tonne of ammonia, 177 kg of hydrogen is combined with 823 kg of nitrogen. The energy consumed to produce 1 tonne of ammonia using a Haber-Bosch process is 26 GJ (7 222.2 kWh) (Rouwenhorst et al. 2021).

In 2018, the global consumption of ammonia was 144 million tonnes, while consumption was 184 million tonnes in 2021 (IndexBox 2023). Using Equation 1, it requires 177 kg of hydrogen and 823 kg of nitrogen (which can be sourced from the air) to produce 1 tonne of ammonia. So, 25.5 million tonnes of hydrogen are needed as feedstock to produce 144 million tonnes of ammonia (Table 25). This hydrogen would require 1.40 x 10^{12} kWh of electricity for production in PEM fuel cells.

Once the required hydrogen feedstock is produced, it requires a further 7 222.2 kWh of energy to produce 1 tonne of ammonia (Rouwenhorst et al. 2021). So, to produce 144 million tonnes of ammonia, 1.14 x 10^{12} kWh of electricity needs to be produced.

Table 26. Electrical energy required to produce ammonia given hydrogen feedstock (Table E11).

Mass of ammonia required to produce fertilizer (million tonnes)	**Energy consumed to produce ammonia @7222.2 kWh/tonne** (kWh)	**Electrical power generated at station to account for 10% loss in transmission** (kWh)
144,0	1,04E+12	1,14E+12

Table 27. Estimation of the energy required to produce ammonia for fertilizer production for 2018 global consumption (Table E12).

Mass of ammonia required to produce fertilizer (million tonnes)	**Electrical power generated to produce hydrogen** (kWh)	**Energy consumed to produce ammonia @7222.2 kWh/tonne** (kWh)	**Total energy required to produce Ammonia** (kWh)
144,0	1,40E+12	1,14E+12	2,55E+12
		Total	2 545,8 (Twh)

Adding the outcomes of Tables 25 and 26 together, to produce 144 million tonnes of ammonia would require 2.55 x 10^{12} kWh or **2 545.8 TWh** of electrical energy (Table 27).

11 PRODUCTION OF BIOFUELS

The substitution of petroleum fuels with biofuels has been proposed as a sustainable solution in the task before us. Bioenergy is often considered to be a genuinely sustainable and renewable energy source and has been promoted in many studies as the most effective solution to phase out fossil fuels (U.S. Department of Energy 2016). Bioenergy is defined as energy made from a natural biomass or biofuel. Biomass is any organic material which has absorbed sunlight and stored it in the form of chemical energy. Examples are wood, energy crops and waste from forests, yards, or farms (EIA 2024b). As a fuel it may include wood, wood waste, straw, manure, sugarcane, and many other by-products from a variety of agricultural processes. Biomass and bioenergy are promoted as useful in that the feedstock can be sustainably replenished without harming the environment or depleting finite nonrenewable resources. The sustainably available biomass is approximately 100 EJ (25–250 EJ) (IEA 2024b).

A biofuel is a fuel that is produced through contemporary processes from biomass, rather than a fuel produced by the very slow geological processes involved in the formation of fossil fuels, such as oil. Since biomass technically can be used as a fuel directly (e.g. wood logs), alternatively the terms biomass and biofuel are often used interchangeably. Usually, the word biomass simply denotes the biological raw material the fuel is made of, or some form of thermally/chemically altered solid end product, like pellets or briquettes. Biofuel is defined as liquid or gaseous fuels, used for transportation, that is manufactured from biomass resources. Some of the biofuels are termed 'Drop-in biofuels' which are functionally equivalent to petroleum fuels and fully compatible with the existing petroleum infrastructure (Karatzos et al. 2014). These drop-in biofuels require no ICE engine modification of the vehicle (U.S. Department of Energy 2024). The global production of biomass from the planetary environment in 2008 was 170 billion metric tonnes (Shen et al. 2009). The global human population has been harvesting only 3.5% of this, which is in turn split up into food production, lumber/wood products and feedstock for chemicals.

Most of biofuel currently produced is sourced from oil seed crops soy and corn. Soy feedstock has shown to be the most effective to produce biodiesel, and corn has been shown to be most effective in producing ethanol. Ethanol has been used to blend into gasoline, and it has the capacity to fuel Internal Combustion Engine (ICE) technology directly if required. Cellulosic ethanol is not commercial (Friedemann 2021). Biofuel is considered a drop in fuel, that can be used with existing infrastructure and existing ICE vehicles. Algae from aquaculture has also been a proposed feedstock for biofuels, with work done to produce bio diesel and jet fuel.

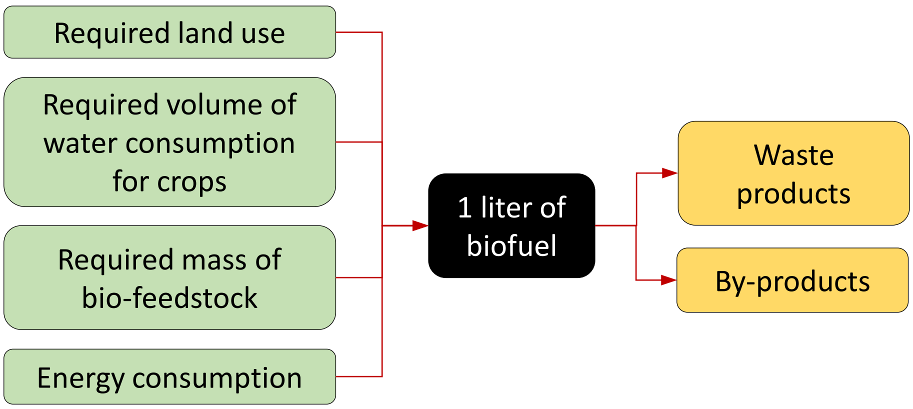

Fig. 19. Calculation inputs and outputs for biofuels.

Using a form like Figure 19, calculations will be made to estimate the scale of production of corn and soy as feedstock to produce biodiesel and ethanol to meet 2018 global demand for gasoline, diesel, marine bunker fuel and jet fuel. The mass of feedstock will be used to estimate the area of needed arable land, water consumption in production. These numbers will be compared to a relevant global parameter like global scale of crop lands. Annex F shows how these tables were calculated.

11.1 Biofuels for 37% of the maritime shipping fleet

In this study, it was assumed that 37% of the maritime shipping fleet would have ICE propulsion systems fueled with ammonia (Fig. 15), as per the prediction for 2050 (IEA 2021a) and as shown in Table 3. As such, of the 2.63 x 10^{11} liters (Table 21) of marine bunker fuel oil annual consumption in 2018 (OECD 2024 Data Statistics Database), 9.73 x 10^{10} liters of that bunker fuel oil would be replaced by an equivalent quantity of biodiesel.

Table 28. Biodiesel to fuel 37% of the global shipping transport fleet (based on 2018) (Table E6).

Liters of biodiesel to be produced (liters)	**Biomass feedstock of soybean seeds @4.91 kg/ liter of fuel produced** (kg)	**Ferlizer @74g per liter of fuel produced** (kg)	**Waste biomass @3.59 kg/liter of fuel** (kg)	**Glycerine produced @106 g per liter of fuel produced** (kg)
9,73E+10	4,78E+11	7,20E+09	3,49E+11	1,03E+10
	477,5 (million tonnes)	7,2 (million tonnes)	349,1 (million tonnes)	10,3 (million tonnes)

Table 29. Energy consumed in production of soybean feedstock biodiesel for 37% of the global aviation industry (Table E7).

Liters of biodiesel to be produced (liters)	**Electricity consumed** (kWh)	**Steam consumed in production** (kWh)
9,73E+10	1,81E+10	2,44E+11
	18,1 (TWh)	244,1 (TWh)

To produce 1 liter of soy based biodiesel, 4.91 kg of soybean seed is required, resulting in 477.5 million tonnes of soybean biomass feedstock, and 1 361.5 km^3 of fresh water to annually produce enough biodiesel for 37% of the shipping fleet. It takes approximately 14 000 liters of water to produce enough soybeans to make a 1 liter of biodiesel (Gerbens-Leenes et al. 2009). The land use to grow soybeans can be quantified, where 53 317 liters of biodiesel could be produced on 1 km^2 of arable land used to grow soybeans (data taken from Sadaka 2013, then converted from imperial units to standard SI units).

Table 30. Water consumed and arable land required in production of biodiesel for 37% of the global shipping transport fleet (Table E8).

Liters of biodiesel to be produced (liters)	**Potable water consumed to produce soybean biodiesel @14 000 liters per liter of fuel** (liters)	**Arable land needed given 1 km^2 of soybean production produces 53 317.6 liters of biodiesel** (km^2)
9,73E+10	1,36E+15	1 824 021,1
	1 361,5 (km^3)	1,82 (million km^2)

Note: 1 km^2 of soybean land produces about 53 317.6 liters (57 gallons per acre) of biodiesel

This was then adjusted to estimate the area of arable land required to grow soybeans, assuming for every 1 km^2 of soy growing land produces 53 317 liters/km^2 of bio-ethanol. This resulted in a needed 1.82 million km^2 needed in the global system to produce soy for biofuels.

11.2 Ethanol bio jet fuel for 62% of Aviation Transport

In this study, it was assumed that the aviation industry would contract in activity by 38%, as per the prediction for 2050 (IEA 2021a), as shown in Table 3. As such, the 3.59 x 10^{11} liters of jet fuel annual consumption in 2018 (OECD 2024 Data Statistics Database) would contract to 2.23 x 10^{11} liters of jet fuel.

The aviation industry is a vital part of the international transport network. Jet turbines represent a very sophisticated application of high-quality refined petroleum. The majority of the physical work done in the commercial aviation fleet is conducted by turbojet powered aircraft, which consumes jet fuel. The remaining small portion is conducted by turboprop aircraft, which consume petroleum gasoline. The global scope of transport by air was determined by accessing World Bank data. In summary (Source: World Bank Group 2019):

- 3 979 billion passengers carried globally in 2017
- 213 590.2 million tonne-km of freight was carried by air in 2017

The viability of a non-fossil fuel system that could replace a jet fueled turbine was not as maturely developed as other transport technologies. There were several systems that were described in theory but establishing engineering performance metrics that could be used in context of this study was difficult.

Developing a battery powered EV aircraft was possible on a small scale, but due to the mass of the batteries would be relatively short range and carry a small cargo or relatively few passengers (Spaeth 2023). A hydrogen powered system would need a large hydrogen fuel tank of specific geometry, which would have to fit inside the cabin, not the wing. Then there is the question of energy density of hydrogen in context of the aircraft being able to carry enough fuel. These issues reduced the cargo and/or number of passengers. However, it was possible to produce jet fuel from biomass, in a fashion where jet aircraft can perform to specification (Michaux 2021, Section 21), (EIA 2024b).

Table 31. Land use and water consumption in the production of ethanol biofuel for the aviation industry (Table E3).

Liters of jet fuel to be produced from ethanol biofuel (liters)	Biomass feedstock dry corn to produce ethanol biofuel @2.08 kg/liter of fuel (kg)	Potable water consumed to produce ethanol biofuel @2 575 liters per liter of fuel (liters)	Arable land needed given 901 127 kg/km^2 of corn production (km^2)	Soil erosion (3kg per litre of fuel produced assumed) (kg)
2,23E+11	4,64E+11	5,74E+14	515 445,3	6,68E+11
	464,5 (million tonnes)	573,6 (km^3)		668,3 (million tonnes)

Note: 1 km^2 of corn growing land can produce about 901 127 kg (or 901.13 tonne) of corn
1 liters = 1.0 × 10-12 cubic kilometers

This biofuel technology solution could make jet aviation viable after fossil fuels are phased out (this is described more fully in Annex E). However, in its current state of readiness, it is not viable to consider this as a full replacement of petroleum-based aviation jet fuel as a fuel. Also, biofuels are in direct competition with the production of food, at a time when food shortages are observed around the world (FAO 2015). For the purposes of this study, it is assumed that biofuels become viable in the market conditions in 2050. Annex F shows how these tables were calculated.

12 FOSSIL FUEL SUPPORTED INDUSTRIAL TASKS OTHER THAN TRANSPORT

Currently, our industrial systems are completely dependent on non-renewable natural resources for energy sources. Over the last 100 years western society has evolved into a petroleum-driven economy. Economic activity correlates strongly with the transport of goods. All industrial activity, energy use in general, and economic indicators such as GDP, all correlate strongly with energy consumption (Heinberg 2011, Martenson 2011), with oil in particular.

If fossil fuels are to be phased out, then these fossil fuel energy systems, and the industrial ecosystem dependency on them, need to be understood.

12.1 Fossil fuel powered electricity generation

In the year 2018, the global power station fleet generated 26 614.8 TWh of electricity, where the use of fossil fuels accounted for 64.19% (17 086.1 TWh) (BP Statistics 2020). To generate electrical energy globally in 2018, by fossil fuel source:

- 66% of coal was globally consumed to generate 10 100.5 TWh
- 41% of gas was globally consumed to generate 6 182.8 TWh
- 3.02% of oil was globally consumed to generate 802.8 TWh

This annual consumption of **17 086.1 TWh** will now have to be generated by non-fossil fuel power systems.

12.2 Fossil fuel heating of buildings

Heating of buildings is required in around 40% of households globally for several months of the year (IEA 2022b). In some parts of the world (Northern parts Europe, United States, Canada, and China in particular), this not a convenience comfort but a survival requirement for human habitation. There are five main types of heat pumps:

1. **Air to Air Heat Pumps**, Electricity Usage: Moderate
   Source heat from the air on the load side, then transfers it to a refrigerant which travels through a coil inside the ductwork. Air blowing across the coil heats the air inside the house. This is the most common type of heat pump.
2. **Ground Source (Geothermal)**, Electricity Usage: Low
   Use geological heat reservoirs under the ground as the source of heat. They use a buried loop of pipe (known as a ground loop) that is filled with a water and antifreeze mixture. The heat from the ground is absorbed into the fluid in the ground loop and then is brought inside to a heat exchanger. This heat is then transferred to the refrigerant, which cycles through the heat pump to heat the air or water in the house. This type of heat pump is considered a highly efficient and cost-effective option for heating and cooling.
3. **Water to Water**, Electricity Usage: Low
   A type of geothermal heat pump that uses water as the source of heat. They require drilling into the earth and then using a heat exchanger to transfer that heat to the water that runs through the heating system.
4. **Water to Air**, Electricity Usage: Low
   Use a geothermal drilling to source heat from the earth's surface. However, instead of transferring heat to water, the hot water runs through a coil in a duct, and when air blows across that coil, it heats up.
5. **Air to Water**, Electricity Usage: Moderate
   Source heat from the air on the source side and transfer it to a refrigerant. The refrigerant then cycles through a heat exchanger where it can heat the load side water to be pumped through the house. This type of heat pump is less common than the others.

Table 32. Typical electricity usage for standard air source heat pump sizes.

Air Source Heat Pump Size (Joules)	Heated Area / Space* (m^2)	Electricity Usage (kWh)
9 495 503	27,87	2,6
12 660 670	37,16	3,5
15 825 838	46,45	4,4
18 991 005	55,74	5,3
21 101 117	61,87	5,8
23 738 757	69,67	6,6
26 376 396	77,38	7,3
31 651 676	92,9	8,8
47 477 513	139,35	13,2
63 303 351	185,8	17,6
79 129 189	232,25	22
94 955 027	278,7	26,3

*Maximum area or space during mild winters. Reduce the coverage by ~30% for colder climates and by ~50% for extreme winters with prolonged sub-freezing conditions.
Source: Source Heat Pump,
https://learnmetrics.com/heating-btu-calculator/

The relative efficiencies of each type of heat pump varies with system size and air temperature (Table 32). The seasonal variation in climate temperature is very complex and beyond the scope of this study to map effectively. To estimate energy usage in heating, it was assumed all heat pumps were type one and used electricity as an energy source to heat buildings.

In 2018, 17% of gas was used globally for heating applications (Source: U.S. Department of Energy 2018). These applications will have to be done with electric heaters and be powered off the electric power grid. If that fraction of gas 483.9 bcm (562.6 Mtoe) of the 2018 global consumption of 3848.9 bcm (3309.4 Mtoe) was converted to electricity, it would produce an estimated 2 560 TWh (Source: U.S. Department of Energy 2024, EIA 2024a, BP Statistics 2019).

If that electricity was then converted to a heating application, the conversion from electric power to heating application is approximately 92%, because almost all purchased energy is converted to building heat (Source: U.S. Department of Energy 2018). The extra power draw this will require is to be an estimated 2 780 TWh in extra capacity. Assuming 10% of grid transmission loss, **2 816 TWh** would be required to be delivered annually. This is assuming solar and geothermal cannot directly replace heating applications. There are low-enthalpy domestic heating technologies using heat exchange pumps. The scale-up potential of these technologies is not clear. Nevertheless, they would not be able to substitute all industrial-scale heating applications.

12.3 Plastics manufacture

Plastics and petrochemicals are made using oil and gas feedstock (among other things). Globally, over 8.1 trillion kilograms of plastics have been produced from about 14% of the annual global oil and 8% of annual global gas consumption (IEA 2018). About 10% of total world refinery output, or around 650 million tonnes per year, is used by the plastics industry for its feedstock and energy needs. Countless numbers of manufactured products are either made from plastics or contain plastic components. Very few consumer products in today's marketplace contain no plastic parts at all. It could be argued that our current technology now depends on plastics to operate.

Currently, petrochemicals are the first link in a chain of industries that ultimately use hydrocarbons as raw materials. Chemicals produced from oil and gas make up around 90% of all raw materials to make petrochemicals, which are known as feedstocks; the rest comes from coal and biomass. About half of the petrochemical sector's energy consumption consists of fuels used as raw materials to provide the molecules to physically construct products.

Bioplastics could be a substitution technology for petrochemical based plastics (U.S. Department of Energy 2004, Shen et al. 2009). This technology is promising and could be the way to replace much of the existing plastics industry. However, it is not clear how much biomass would be needed to be harvested from the natural environment to do this, and the question of whether this is sustainable is beyond the scope of this study. While it is clear that bioplastics are not as sophisticated in material properties performance compared to petrochemical plastics, bioplastics may be the solution to phase out the use of petrochemicals. Bioplastics could be used in applications that do not need high performance material properties. A small number of plastic applications that do require high performance material properties could continue to be petrochemical based. This hybrid solution would phase out the majority of oil, gas and coal consumption currently tasked to plastics manufacture, but would also maintain industrial requirements.

For this study, it was assumed that the existing oil and gas consumption to produce plastics was substituted with the use of bioplastics technology, where the source raw material was biomass. What annual quantity of biomass harvesting would be sustainable was beyond the scope of this work. For this reason, biomass for bioplastics was not estimated.

13 THE POST FOSSIL FUEL GLOBAL INDUSTRIAL SYSTEM

The following Figures 20 to 26 map out the global industrial system in context of what the Green Revolution would look like. This was done in a fashion to try and summarize all of the various different kinds of data developed in this study. Figure 20 maps out the global self-propelled vehicle fleet in context of the required electrical energy required to service its operation. Table 33 and Figures 21 and 22 map out the size of the proposed hydrogen economy.

Table 33. The size of the proposed hydrogen economy in terms of required annual mass of H_2 (based in 2018 scope).

Consumption Task 	**Hydrogen** (million tonnes)	**Hydrogen** (kg)	**Required Electric power to manufacture H_2 with electrolysis (@50kWh/kg)** (kWh)	**Required Electric power to compress H_2 into tanks at 700 bar pressure (@2.5 kWh/kg)** (kWh)	**Required annual electric power generation assuming 10% grid transmission loss between power station and electrolysis unit and compression unit** (kWh)
Existing hydrogen global annual demand for industrial applications (73.9 Mt -refining applications)	35,7	3,57E+10	1,79E+12	N/A	1,96E+12
Hydrogen required to fuel the global fleet of Class 8 Heavy Duty trucks 	132,9	1,33E+11	6,65E+12	3,32E+11	7,68E+12
Hydrogen required to fuel the global fleet rail transport 	13,7	1,37E+10	6,87E+11	3,43E+10	7,93E+11
Hydrogen required to fuel 17% the global maritime shipping fleet 	14,6	1,46E+10	7,32E+11	3,66E+10	8,45E+11
Hydrogen production to produce ammonia to fuel 46% of maritime fleet 	39,1	3,91E+10	1,95E+12	NA	2,15E+12
Hydrogen production to produce ammonia to produce fertilizer	25,5	2,55E+10	1,27E+12	NA	1,40E+12
Steel production in hydrogen atmosphere (HYBRIT) 	94.0 (estimated 52 kg of H_2 per tonne of steel)	9,40E+10	4,70E+12		5,17E+12
Total	355,5 million tonnes of H_2				2,00E+13 20 001.1 TWh

The estimated annual hydrogen required to support the proposed global H_2-Cell transport fleet and hydrogen supported global industry was 355.5 million tonnes, which would require annual production of 20 001.1 TWh of electricity.

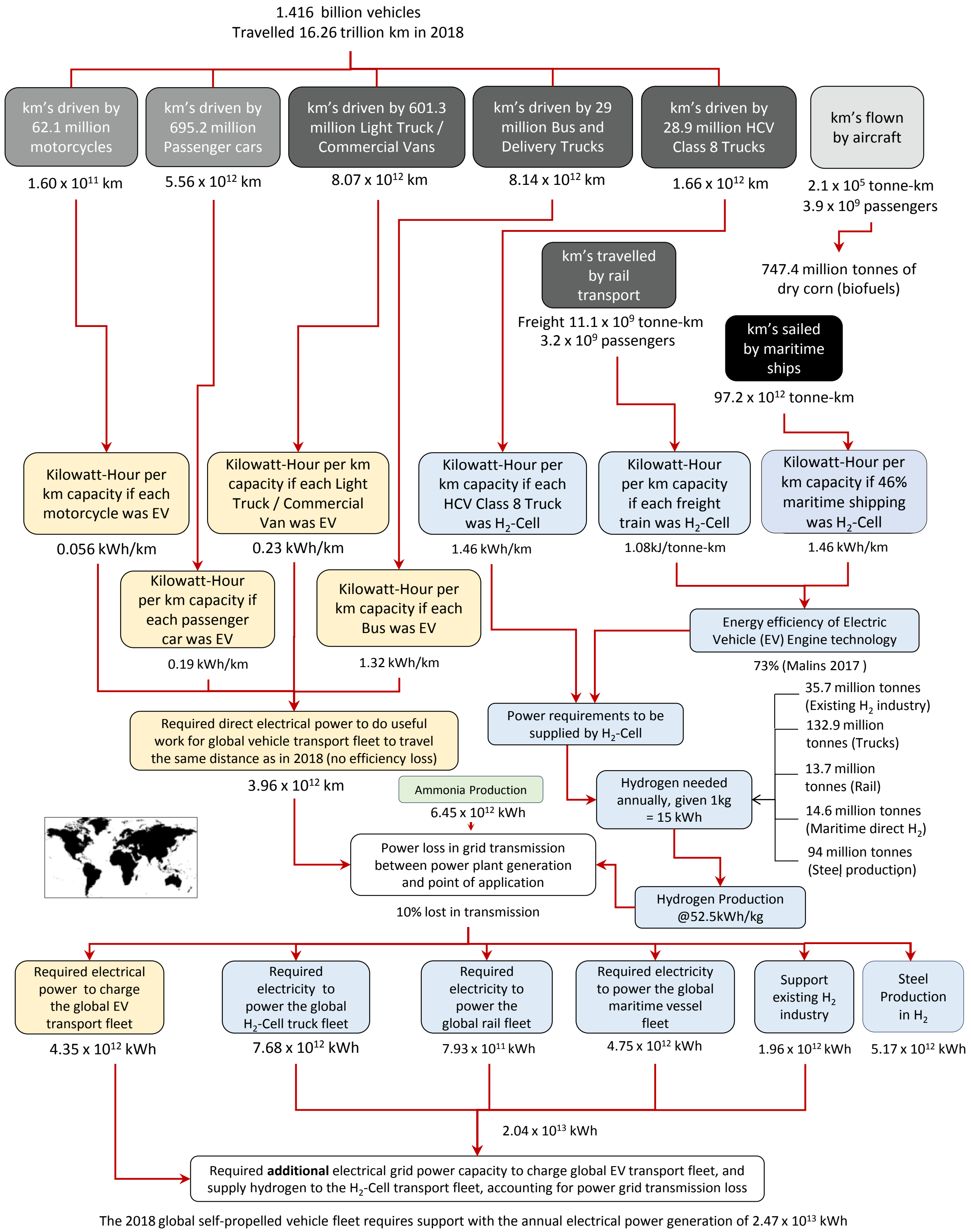

Fig. 20. The annual electrical energy generation to support the 2018 global self-propelled vehicle transport fleet.

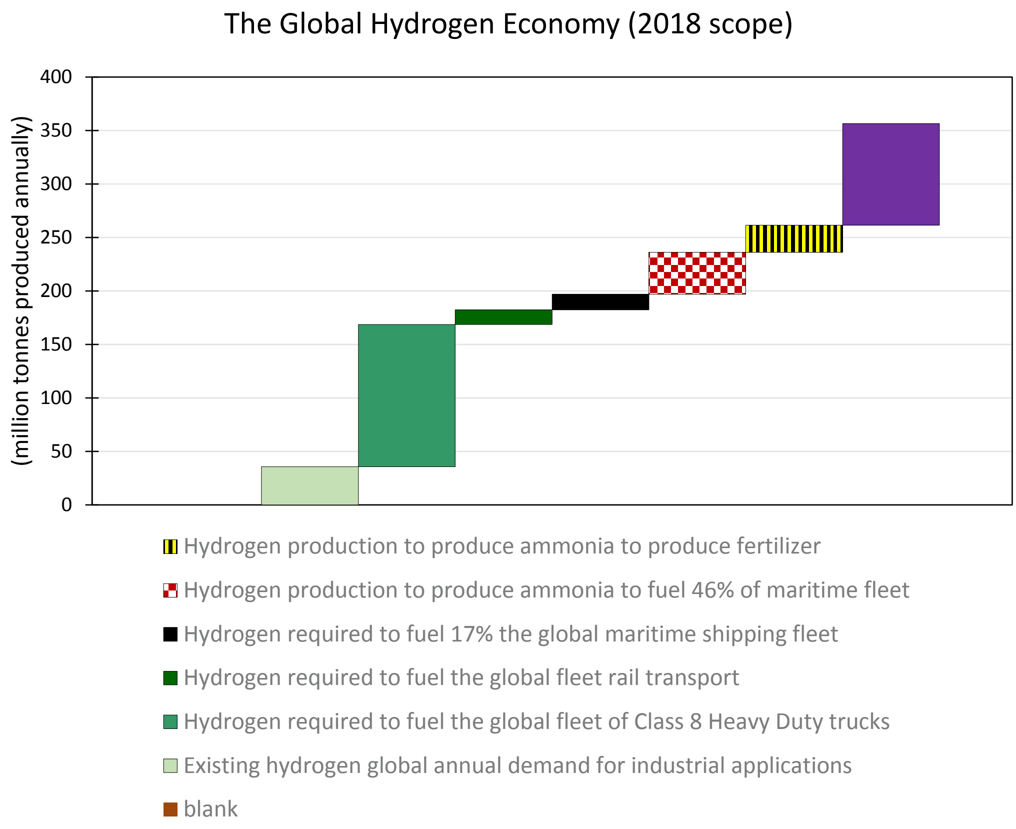

Fig. 21. Size of the proposed global hydrogen economy – million tonnes of hydrogen annually produced.

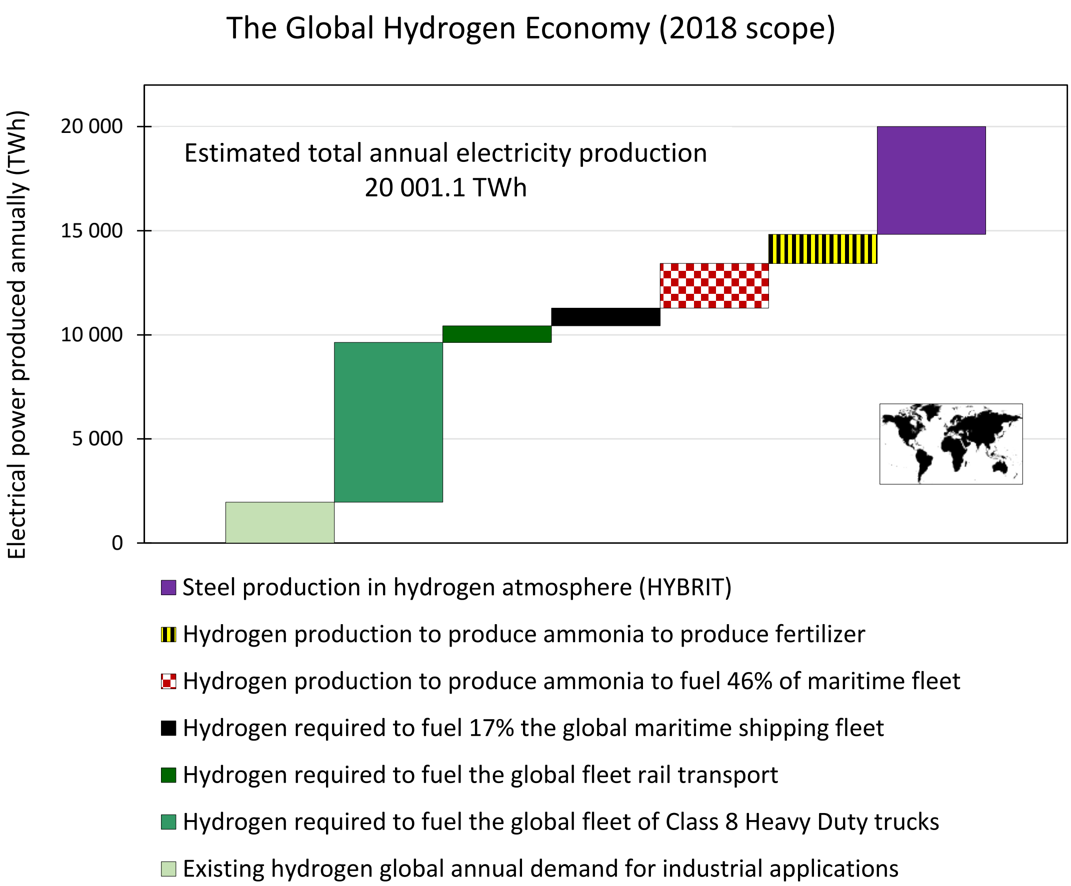

Fig. 22. Size of the proposed global hydrogen economy – TWh of electricity annually produced.

Figures 23 to 26 compare the numbers developed to produce biofuel to global food production, available arable land, and world freshwater consumption. Biodiesel is produced from soybean biomass feedstock. Ethanol based jet fuel is produced from corn biomass feedstock. Like many other non-fossil fuel technology examples, biofuels work perfectly well on a small scale. It is when each system is scaled up to be made available to the global population in a fashion where it replaces a widespread system (like gasoline fueled ICE's), that practical bottlenecks become apparent.

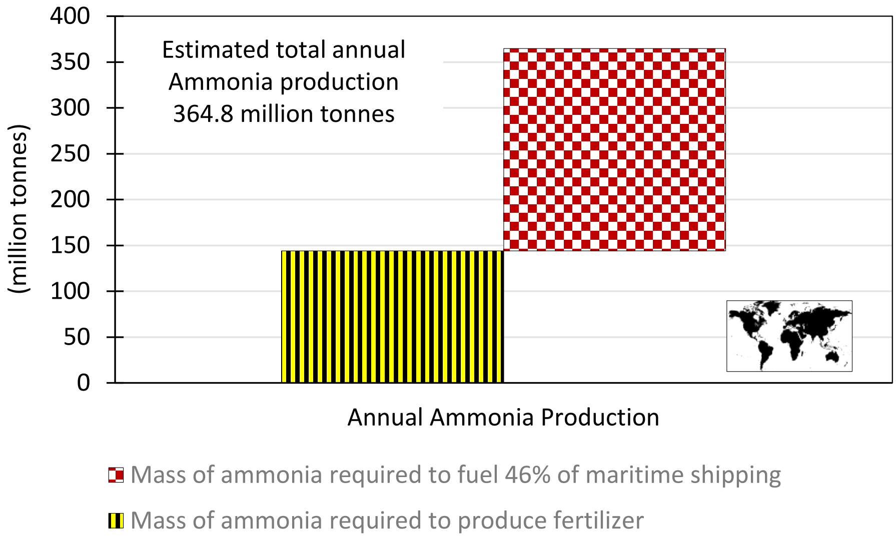

Fig. 23. Proposed global ammonia economy.

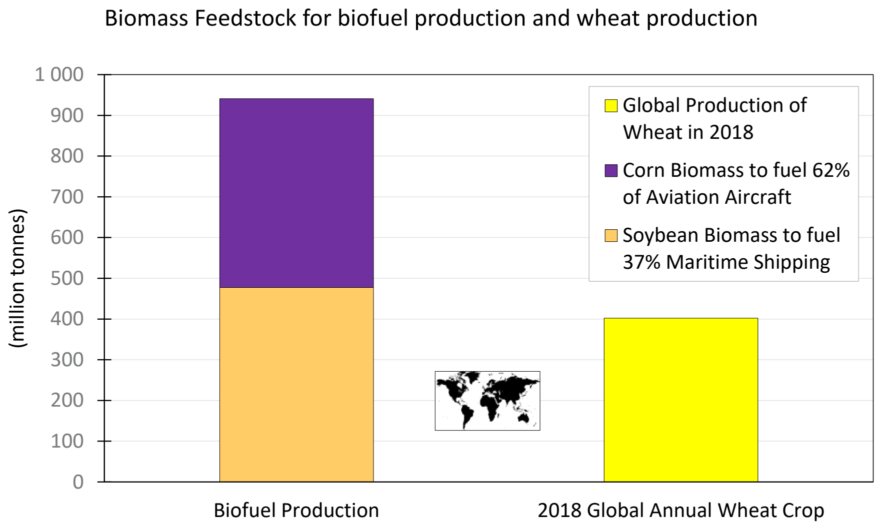

Fig. 24. Global production of biomass feedstock to produce biofuels compared to the 2018 global wheat crop (Source: USDA 2019).

The estimated mass of biomass feedstock for biofuels, where only a 37% of the total 2018 maritime shipping and 62% of 2018 aviation aircraft are examined, is projected to be 2.34 times the size of the global 2018 annual wheat crop (Fig. 24). That same biomass for biofuels would need 2.66 million km^2 of arable land, which would be 24.1% of 11 million km^2 available arable land on the planet surface (FAO 2015) (Fig. 25). Both biofuels (corn and soy) together would need 1 935.2 km^3 of fresh water in irrigation. This would be 48.5% of the 2018 global water withdrawal for the global human society, from the planetary hydrological freshwater cycle was 3 990 km^3 (UNESCO 2019, WWAP 2019) (Fig. 26).

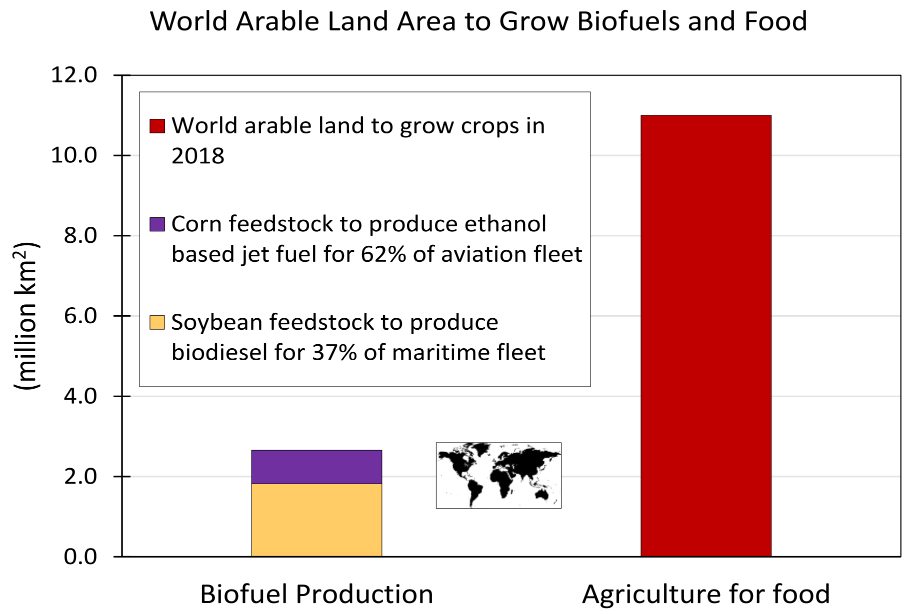

Fig. 25. Arable land area to grow biomass feedstock for biofuels compared to global proportion of arable land in 2018 (Source: FAO 2015).

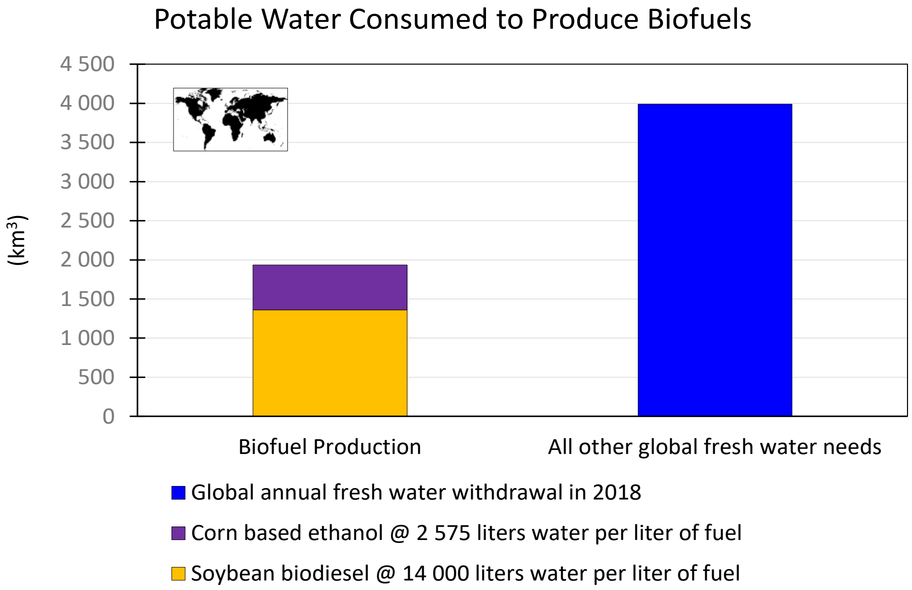

Fig. 26. Potable freshwater consumption to produce biofuels compared to the global freshwater withdrawal in 2018 (Source: UNESCO 2019, WWAP 2019).

All components of this study can now be assembled to determine the sum total extra electrical energy required to completely phase out fossil fuels and maintain the existing industrial ecosystem specifications.

SUMMARY	
	(TWh)
Electrical power required to charge EV batteries	4 354,0
Electric power required to produce hydrogen	
for existing applications (excluding hydrogen used to refine petroleum products)	1 963,5
Production of hydrogen for a H2-Cell HCV Class 8 truck fleet	7 676,0
Production of hydrogen for a H2-Cell rail network	793,1
Production of hydrogen for a H2-Cell in 17% of maritime shipping	844,9
Electric power to produce steel in a hydrogen atmosphere	6 939,2
Electric power required to produce ammonia production	
To fuel 46% of the maritime shipping fleet*	3 903,1
To produce agricultural fertilizer	2 545,8
Electrical power required to produce biodiesel for 37% of maritime shipping	18,1
Electrical power required to phase out coal, gas, oil power generation**	17 086,1
Electrical power required to power heat pumps for building heating	2 816,0
Total	48 939,9

* Includes produced hydrogen feedstock and Haber Bosch process to produce ammonia

** Source BP Statistics 2020, Michaux 2021

This is the required extra capacity of power generation compared against global electrical energy consumption in 2018. Figures 27 and 28 map out the components that make up this number. What is required is the construction and commissioning of an expansion of the electrical energy plant fleet that is 1.83 times the capacity of the existing system, but with non-fossil fuel power systems, which are generally not as effective, due to a generally lower Energy Returned on Energy Invested ratio (ERoEI) (Hall et al. 2014, Michaux 2021). Figures 26 and 27 show a required extra 48 939.8 TWh of electrical energy generation capacity to be constructed globally in addition to the existing 9 528.7 TWh (in 2018) of non-fossil fuel power generation systems.

These numbers, while large, does not account for the fossil fuel energy used to generate heat in manufacture. Steel production using coal was included, but consistent data for all other heating applications (for example the production of silicon wafers for solar panels) was unavailable. This could the subject of future work. For example, to manufacture a high purity silicon wafer as a component in a solar photovoltaic panel, the metallurgical grade silica needs to be heated with the combustion of coking coal (Troszak 2020). The manufacture of the hyper-pure silicon for photovoltaics occurs in two stages. The oxygen is removed to produce metallurgical grade silicon. It is further refined to produce semiconductor grade silicon. An intermediate grade with impurity levels between metallurgical silicon and semiconductor grade silicon is often termed solar grade silicon. The silica is reduced (oxygen removed) through a reaction with carbon in the form of coal, charcoal, and heating to 1500-2000 °C in an electrode arc furnace (Pizzini & Calligarich 2013).

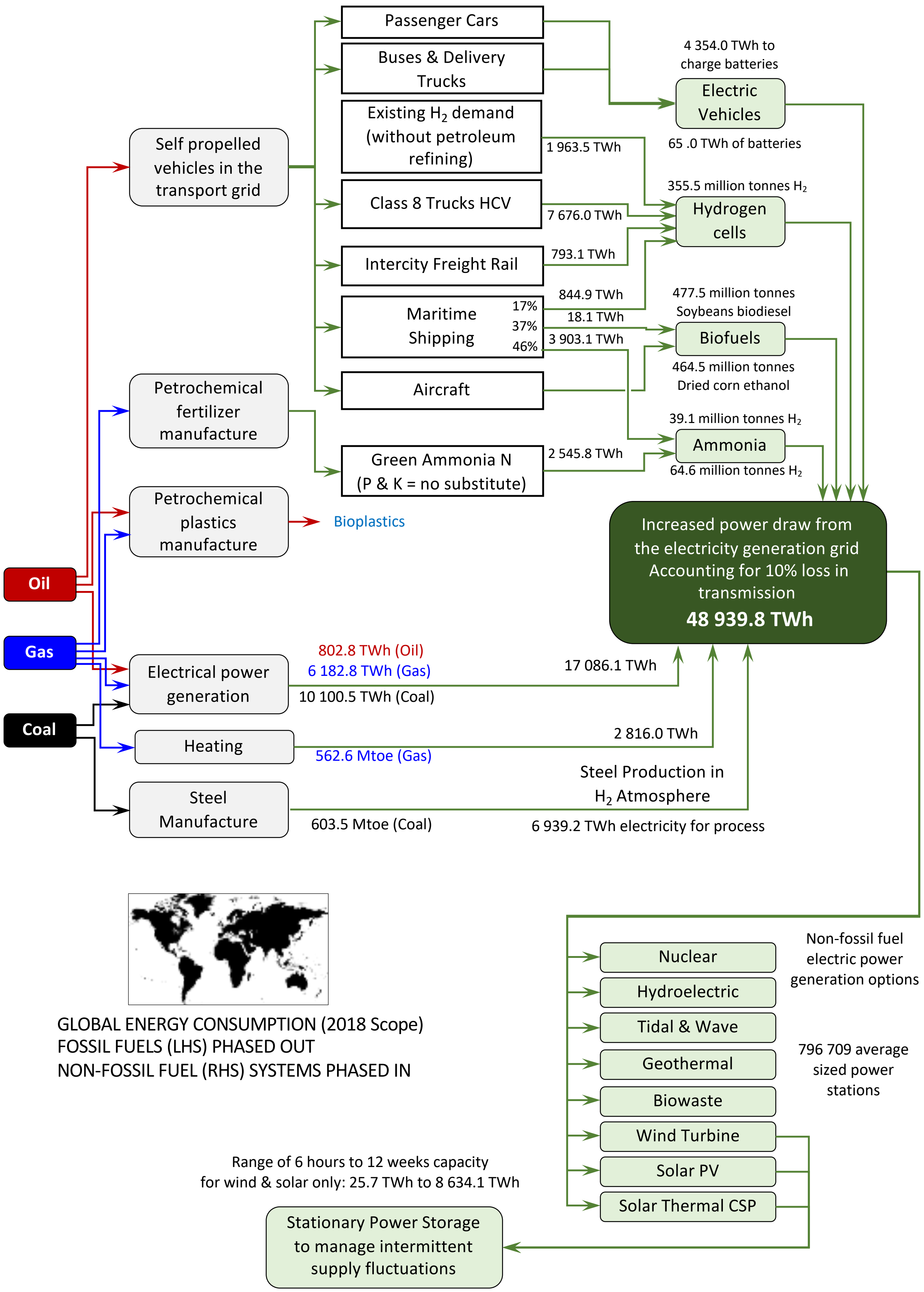

Fig. 27. Fossil fuel energy consumption by application and proposed substitution systems.

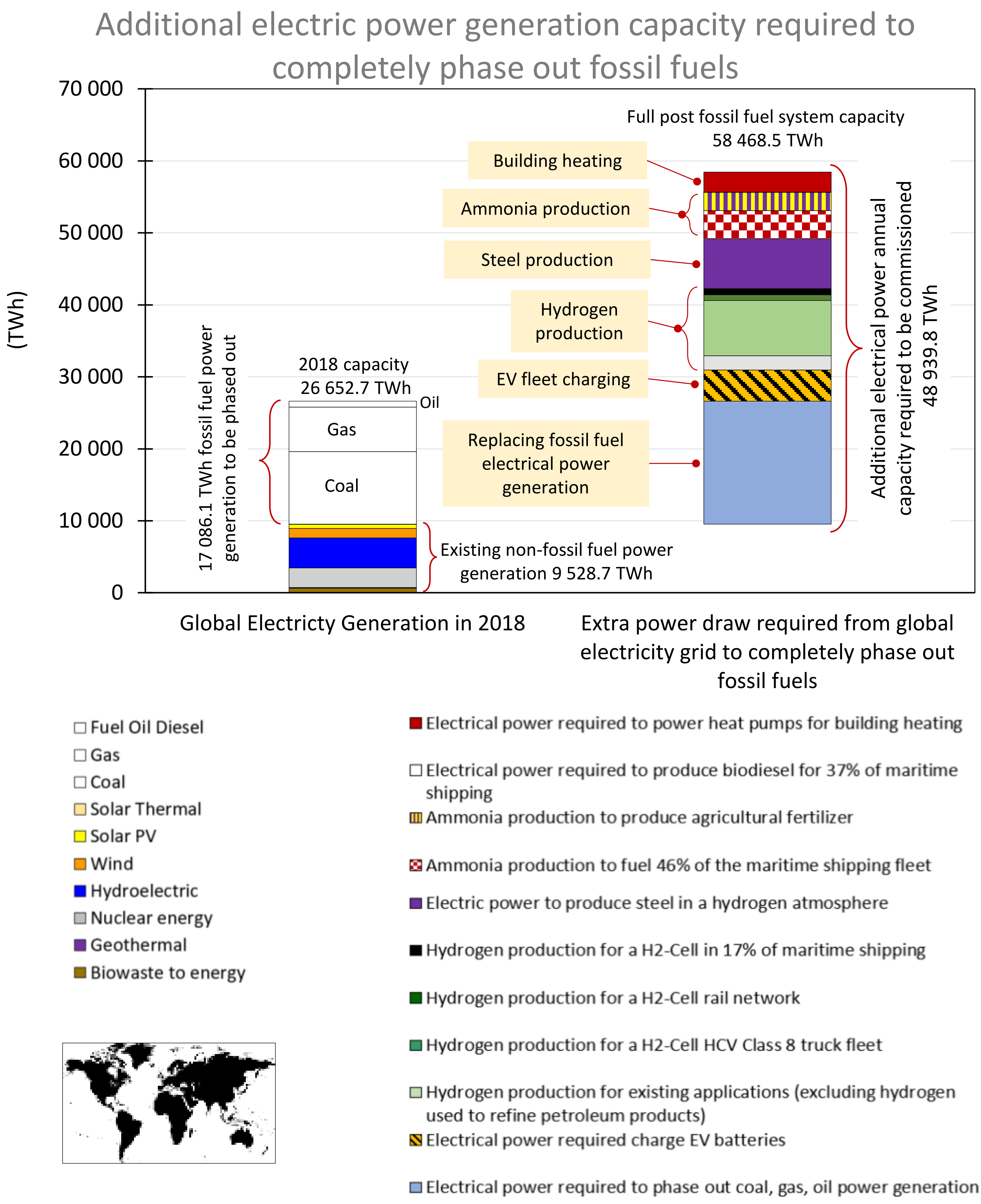

Fig. 28. The estimated additional electrical energy required globally to phase out fossil fuels.

A large proportion of coal and gas is used by manufacture in applications that consume fossil fuel products as direct feedstock. It was beyond the scope of this study to map and model this energy stream. Also, most of the proposed electrical non-fossil fuel support system was not dependent on the combustion of an energy source. As such, it does not have the same inefficiencies that the current fossil fuel system does. Figure 2 shows that in 2018, the global primary energy consumption was 172 884 TWh, and Figure 4 shows that most of that energy is lost due to heat dissipation. Thus, when fossil fuels are burned, a large proportion of energy is lost. Renewable energy systems do not have this inefficiency.

14 PERFORMANCE OF EXISTING FLEET OF ELECTRICITY GENERATION POWER STATIONS

The extra electricity generation capacity to completely phase out fossil fuels was estimated to be 48 939.8 TWh, using a combination of EV's and H_2 Cell transport systems. This extra capacity would have to come from non-fossil fuel electric power generation systems. Part of this task is to phase out 17 086.1 TWh of fossil fuel power generation and replace them with non-fossil fuel power systems. To this end, the performance of each system in terms of power delivered and full operating hours across a 365 day time period is required to be understood. This would allow the calculation of the number of new non-fossil fuel stations that would be needed to substitute for the phased out fossil fuel power stations. Tables 34 to 36 shows the global number and performance of electrical energy stations, by fuel source as they were in 2018. Each of the power generation systems was examined where the specifications of each individual station were collected, and statistical analysis was conducted on each fuel source system.

Table 34. Maximum and minimum capacity of electrical energy stations by source in 2018.

Power Generation System 	**Global Electricty Production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019)** (TWh)	**Global Number Power Plants in 2018 (Global Energy Observatory)** (number)	**Installed Global Capacity in 2018 (Global Energy Observatory)** (GW)
Coal	10 100,5	1 437	1237.7 GW
Gas	6 182,8	2 781	1207.5 GW
Nuclear	2 701,4	438	431.8 GW
Hydroelectric	4 193,1	3 163	712.9 GW
Wind	1 303,8	16048 (est)	597 GW
Solar PV	579,1	17526 (est)	580.14 GW
Solar Thermal	5,5	52	5.5 GW
Geothermal	93,0	108	14.6 GW
Biowaste to energy	652,8	3 800	55 GW
Fuel Oil Diesel	802,8	1 069	225.8 GW
Total (TWh)	2,66E+07 26 614,8	46 423	5067,9

Note: data quoted for wind and solar was incomplete. Some stations were not connected to the grid due to late commissioning, some were taken offline earlier than planned due to maintenance issues. So, the true numbers of operating solar and wind plants in 2018 was not consistently quantified.

These numbers would have to be balanced against the physical size, and capital cost of each kind of plant. Constructing a solar panel array farm is an entirely different matter to constructing and commissioning a nuclear power plant (EIA 2020). It is to be remembered that the operating life after commission of these plants is also different, where a wind turbine and solar panel has a useful working life of approximately 20 years (WWEA 2019), whereas a coal-fired power plant is assumed to be 30 years (Spath et al. 1999). A nuclear power plant's operating life is assumed to be 40 years (Generation II Plant) to 60 years for a Generation III+ plant (World Nuclear Association 2019).

Table 35. Number and capacity of electrical energy systems by source in 2018.

Power Generation System 	**Maximum Installed Plant Capacity Found in Data for 2018 (Global Energy Observatory & Agora Energiewende and Sandbag 2019)** (MW)	**Power Produced by a Single Average Plant in 2018** (kWh)	**Minimum Installed Plant Capacity Found in Data in 2018 (Global Energy Observatory)** (MW)	**Standard Deviation of Installed Plant Capacities for 2018 (Global Energy Observatory)** (MW)
Coal	6 600 MW	7 028 812 030	0.9 MW	926.6
Gas	5 040 MW	2 223 247 834	1 MW	560.2
Nuclear	8 212 MW	12 803 184 576	20 MW	1339.4
Hydroelectric	22 500 MW	1 325 746 584	0.005 MW	703.5
Wind	610 MW	81 241 809		
Solar PV	850 MW	33 040 663		
Solar Thermal	392 MW	76 970 000	0.25 MW	73.78
Geothermal	1273 MW	603 226 027	0.05 MW	163
Biowaste to energy		34 581 818		
Fuel Oil Diesel	5 523 MW	850 797 343	0.7 MW	520.5

Table 36. Availability and power produced by average sized stations by source in 2018.

Power Generation System Source 	**Full operating hours in practice of existing installed capacity in 2018 (Global Energy Observatory)** (h)	**Availablity across the year** (%)	**Average Installed Plant Capacity in 2018 (Global Energy Observatory)** (MW)
Coal	8 161	93,2%	861,3
Gas	5 120	58,5%	434,2
Nuclear	6 256	71,4%	2046,5
Hydroelectric	5 882	67,1%	225,4
Wind	2 184	24,9%	37,2
Solar PV	998	11,4%	33,1
Solar Thermal	1 000	11,4%	77,0
Geothermal	6 370	72,7%	94,7
Biowaste to energy CHP	1 091	12,5%	31,7
Fuel Oil Diesel	3 555	40,6%	239,3

Table G2 in Annex G shows the relative efficiency of the different energy generation systems. Figures 29 and 30 shows a comparison between the different power generation plants, in context of how many average sized plants would be required to deliver 1000 TWh of electricity on an annual basis. As can be observed, to replace a single average sized coal or gas fossil fuel powered electricity generation plant would require many average sized renewable power plants. This reflects the relative effectiveness of each of these power systems.

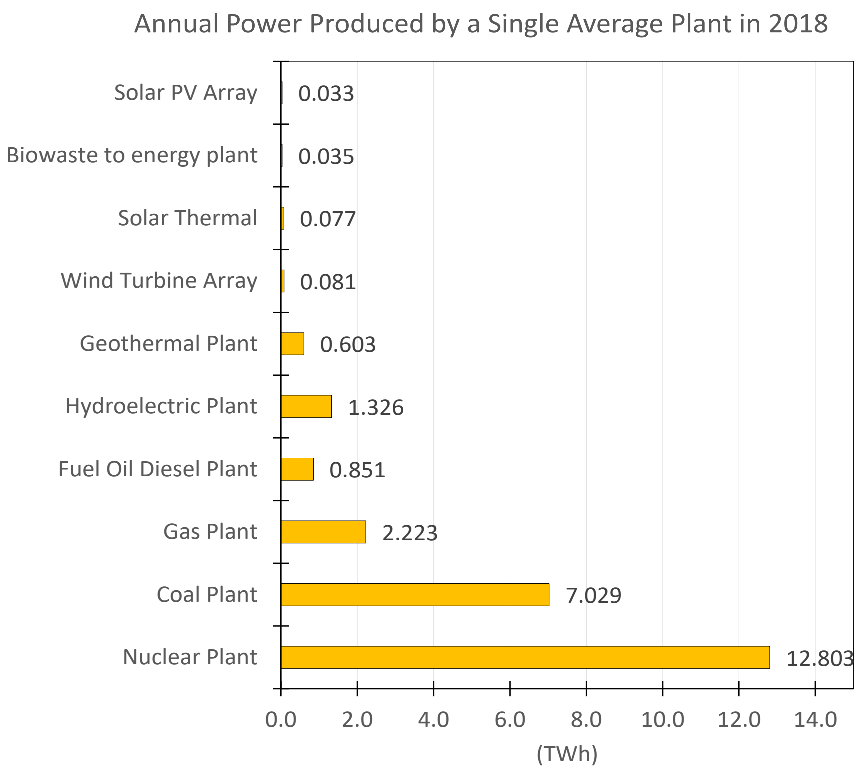

Fig. 29. Annual Power Produced by a Single Average Plant in 2018 (Source: Agora Energiewende and Sandbag 2019, Global Energy Observatory 2020).

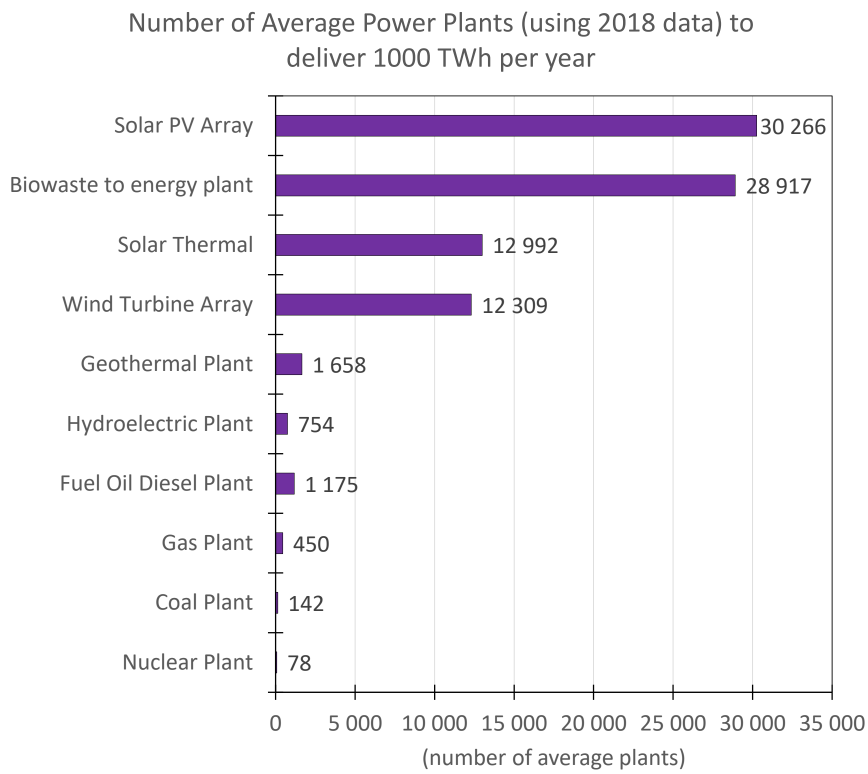

Fig. 30. Number of Average Power Plants (using 2018 data) to deliver 1000 TWh per year (Source: Agora Energiewende and Sandbag 2019, Global Energy Observatory 2020).

Electrical energy is required to be delivered to the point of charging in many places in the electric power grid. Electricity must be transmitted from large power plants to the consumers via extensive networks. The transmission over long distances creates power losses. A major part of the energy losses comes from Joule effect in transformers and power lines. The energy is lost as heat in the conductors, which is included in the energy efficiency of the power generation source (Grigsby 2006). Once the power has been generated, it must be transmitted through the transmission and distribution network.

Considering the main parts of a typical Transmission & Distribution network, here are the average values of power losses at the different steps:

- 1 - 2% – Step-up transformer from generator to Transmission line
- 2 - 4% – Loss in energy due to resistance of transmission wires and electrical equipment
- 1 - 2% – Step-down transformer from Transmission line to Distribution network
- 4 - 6% – Distribution network transformers and cables

In addition, a further 7-10% electrical energy can be lost, which could be caused by congestion, which occurs when the normal flow of electricity is disrupted by device constraints or safety regulations (Singh 2014). The true impact of this would vary considerable between different electrical grids around the world, where collecting this information was beyond the scope of this study. As such this was not included in calculations reported in the present study.

The overall losses between the power plant and consumers are then in the range between 8 and 15% (IEC 2007). For the purposes of this report, an **average value of 10% in power loss** during transmission will be used. This conservative value could account for future efficiency gains in some instances.

The selected 10% loss in transmission has been based on observations on the existing fossil fuel-based power grid. If the energy mix is made up of a larger proportion of wind and solar, this number would probably be too conservative (Schernikau & Smith 2023). Transmission losses on land are different to undersea power cable transmission losses. For example, the Euro-Asia Interconnector Project 18, was proposed to transport 2 TW of power from the Northern Territory in Australia to Singapore, a distance of 4 500 km (EuroAsia Interconnector 2017). If this project was constructed, it would require long distance undersea power transmission. This project has modeled and accounted for a 60% power loss between the point of generation and the point of consumption. To deliver the 2 TW of power, 3.3 TW would have to be generated at the source power stations.

For a wind turbine, electrical energy is generated in in the form of alternating current (AC) and is generally not produced in a stable enough voltage, frequency or phase to input directly into the electrical energy grid (Grigsby 2006). The electrical energy must by converted or conditioned in a process called being rectified. Typically, a substation rectifies and sums the current from individual wind turbines and then the wind farms rectified output is converted to the correct voltage, frequency, and phase, before inserting into the grid. Rectifier and subsequent inverter losses result in a round trip loss of approximately 30% of the (on and offshore) wind farms raw electrical output (Schernikau & Smith 2023). From this point, a further transmission loss of usually 8 to 10% happens depending on the distance. If wind is to take up a major part of the energy mix, then this extra loss of power in transmission will have to be accounted for (this is not accounted for in this paper).

15 PROPOSED ENERGY SPLIT

To deliver the needed extra power, the existing non-fossil system power station network would be developed. Predicting how future industrial sites would develop, and what market share for each technology type would be extraordinarily complex and impractical. For the purpose of this study, an energy mix prediction for 2050 shown in an IEA report (IRENA 2022) was used (Fig. 31). Note that the IEA predicts that the size of the global annual electricity generation to be nearly 90 000 TWh, three times the capacity of 2018 and approximately two times the value estimated here for replacement of fossil fuels completely from 2018 energy requirements. The energy mix predicted for 2050 on the LHS chart of Figure 31 shows an energy mix that is approximately 68.2% wind and solar.

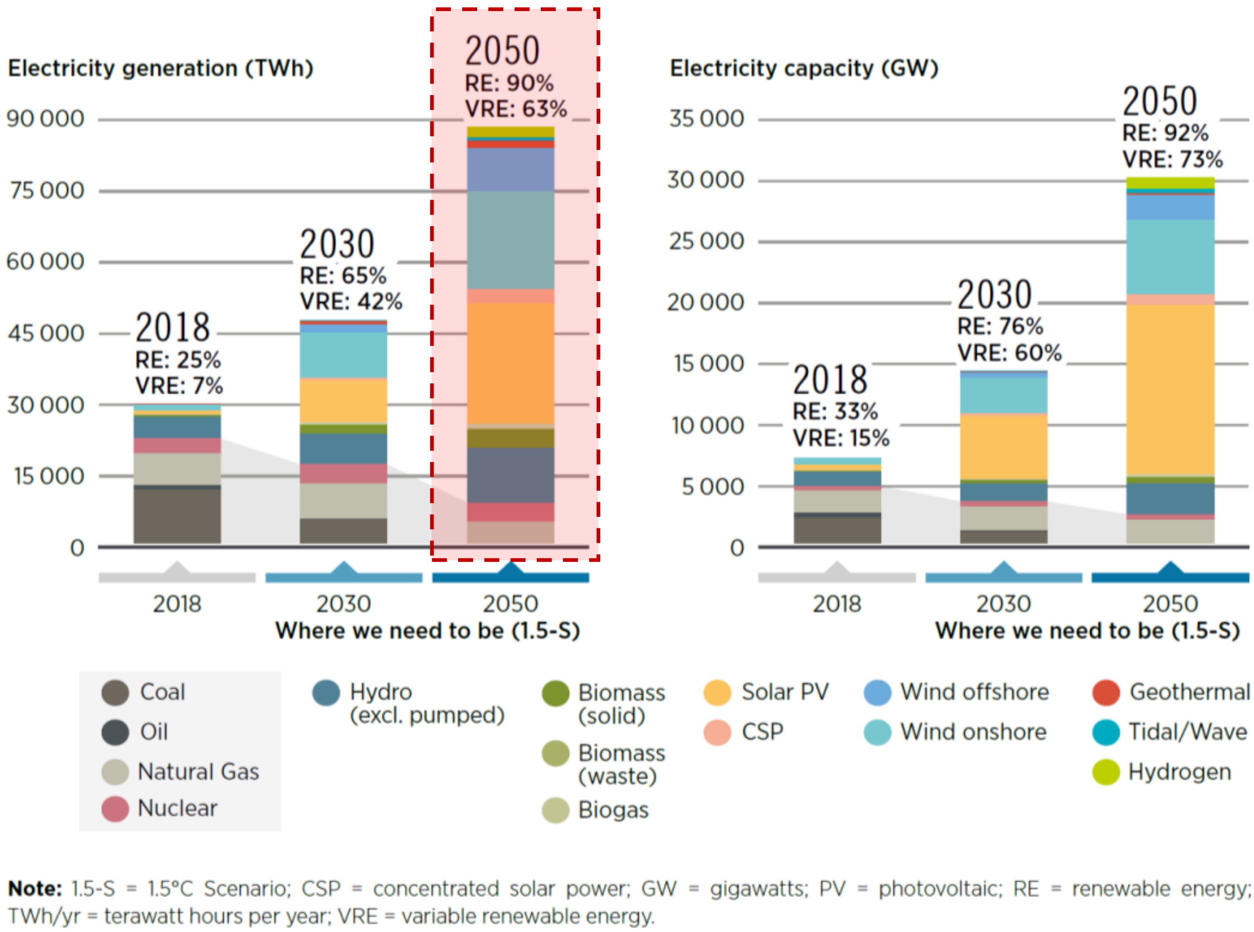

Fig. 31. Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050 (Source: IRENA 2022, Fig. 2.3, pg 61).

Table 37 shows the predicted energy split for 2050 in Figure 31 (inside the red rectangle with the dotted border), which in conjunction with learnings from previous work (Michaux 2021) became the developed energy split for this study. This was used to estimate what extra capacity of new power systems and what type would be required to phase out fossil fuels. The energy split in Figure 31 has some assumptions which were not used in this study. Figure 31 and Table 36 show that natural gas still is part of the energy mix. While this may be sensible in that gas power generation could be used as a power buffer, senior policy makers who develop strategic plans in Europe prefer to phase out fossil fuels completely (personal observation by the author in strategic development meets held in Brussels). So, this paper assumes gas, like all other fossil fuels will be removed entirely.

Table 37. Proposed energy split electrical energy generation systems in 2050 (IRENA 2022, Fig. 2.3).

Power Generation System 	**Proposed energy split electrical power generation systems in 2050 (IRENA 2022, Fig. 2.3)** (%)
Gas	5,0%
Nuclear	3,8%
Hydroelectric	12,9%
Biomass (solid)	4,0%
Biomass (biogas)	1,3%
Solar PV	30,0%
Solar Thermal	2,7%
Wind onshore	24,8%
Wind offshore	10,7%
Geothermal	1,3%
Tidal/Wave	0,7%
Hydrogen	2,7%

It was assumed in this study that biowaste to energy systems cannot be expanded beyond what it is now, as planetary environmental sustainability limits may be exceeded. What is considered a sustainable harvest rate from the environment compared against what might be demanded for consumption should be the subject of future work to be done. Work done in Finland shows that the Finnish forestry industry is close to the sustainable limits of what should be harvested, and expansion of that harvest could be challenging (Michaux et al. 2022). Any extra biomass harvest capacity should be tasked to generate biofuel for the aviation industry, feedstock for bioplastics and feedstock for the organic fertilizer industry. So, for this study, the biowaste power generation (Combined Heat and Power CHP) was to stay as it was in 2018.

A simulation to expand the nuclear power plant (NPP) fleet was conducted (Scenario E in Michaux 2021). It was found that the logistics to expand nuclear value chain could not happen fast enough (assuming a net increase of 25 new plants a year from 2025, and a 5 year build time) to fully replace fossil fuel systems. It was postulated that the industrial system could not expand the nuclear fuel cycle infrastructure so quickly, assuming if done appropriately. That being stated, nuclear power could well become the power source that keeps heavy industry viable. Nuclear power should be expanded but valued much more highly than it is now.

The potential for geothermal power is good, but dependent on scientific breakthroughs. Low temperature geothermal could be used for building heating if heat reservoirs were available (shallow enough to access). A breakthrough in deep well drilling could revolutionize this power source. Available geothermal resources in the desired quantities could be a bottleneck though. Most known heat resources are not mapped to the level of precision that could be used for geothermal power. It is proposed that geothermal power will expand in capacity. Consistent data was not available for wave or tidal energy systems in a form that could be used in this study, so it was not included. Hydroelectricity will expand in a similar proportion to shown in Figure 31.

It was assumed that wind and solar power would become the primary electric power source for the global industrial system, with an energy mix proportion of approximately 70% in context of the previous assumptions. Proportions of onshore/offshore wind turbines were taken directly from the IEA (IRENA 2022) where onshore wind turbines were 70% of the fleet, and offshore turbines were 30% of the fleet. Proportions of solar PV/solar CSP systems were also taken directly from the IEA (IRENA 2022) where solar PV systems represent 90% of the solar capacity and solar CSP thermal systems represent 10%. Using the proportions shown in Figure 31, Table 37, and the assumptions just stated, the energy mix used in this paper were developed and listed below (shown in Table 38). Each of these assumptions were developed by the author through a combination of the prediction of the 2050 market split and insights learned from (IEA 2021a).

- All fossil fuels will be completely phased out
- Hydro will expand by adding 115% capacity compared to 2018 production rates
- Nuclear will double in capacity from 2018 production rates
- Biowaste to energy was to remain the same in energy split proportion
- Geothermal power generation will triple in producing capacity compared to 2018 production rates
- After the above calculations, all remaining new required capacity will be split equally between wind and solar
- New wind capacity will be a split between 70% onshore wind turbine site to 30% offshore wind turbine
- New solar power capacity will be split between 90% solar PV and 10% solar thermal

Table 38. Energy split used and number of new power stations in this study.

Power Generation System	Proposed Energy Split non-fossil fuel electrical power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (TWh)	Power Produced by a Single Average Plant in 2018 (GWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)	Estimated Installed capacity (GW)
Nuclear	7,50%	3 670,5	12 803,2	287	587
Hydroelectric	13,36%	6 538,4	1 325,7	4 932	1 112
Wind	38,33%	18 758,7	81,2	230 899	8 589
Solar PV	34,50%	16 884,3	33,0	511 015	16 915
Solar Thermal	3,83%	1 874,4	77,0	24 352	1 874
Geothermal	0,74%	362,2	603,2	600	57
Biowaste to energy	1,74%	851,6	34,6	24 624	781
Total	100,00%	48 939,9		796 709	29 914

Tables 34 to 36 shows the existing non-fossil fuel power station fleet as it was in 2018, and the proposed extra non-fossil fuel power stations required to phase out fossil fuels is shown in Table 38. Tables 39 and 40 shows the full capacity of the completely non-fossil fuel power station fleet if fossil fuels were completely phased out.

Table 39. Size and scope of the existing non-fossil fuel power station fleet and the proposed expansion extra power stations.

Power Generation System	Exsiting Non-Fossil Fuel Power Station Fleet		Proposed Additional Expansion of Fleet	
	Existing global non-fossil fuel electricity production in 2018 (Agora Energiewende and Sandbag 2019) (TWh)	Existing Global Number Non-Fossil Fuel Power Plants in 2018 (Global Energy Observatory) (number)	Expanded extra required annual capacity to phase out fossil fuels (TWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	2 701,4	438	3 670,5	287
Hydroelectric	4 193,1	3 163	6 538,4	4 932
Wind	1 303,8	16 048	18 758,7	230 899
Solar PV	579,1	17 526	16 884,3	511 015
Solar Thermal	5,5	52	1 874,4	24 352
Geothermal	93,0	108	362,2	600
Biowaste to energy	652,8	3 800	851,6	24 624
Total	9 528,7	41 135	48 939,9	796 709

Table 40. Total size and scope of the electrical energy station system if fossil fuels were completely phased out.

Power Generation System 	**Proposed Full System Annual Power Generation** (TWh)	**Total Number of Powers Stations (existing non-fossil fuel + new plants)** (number)
Nuclear	6 371,9	725
Hydroelectric	10 731,5	8 095
Wind	20 062,5	246 947
Solar PV	17 463,4	528 541
Solar Thermal	1 879,9	24 404
Geothermal	455,2	708
Biowaste to energy	1 504,4	28 424
Total	58 468,6	837 844

16 DAILY FLUCTUATIONS OF POWER DEMAND AND THE CAPACITY FOR OFF PEAK CAPACITY

How one would build this new and expanded power grid is not entirely understood. Managing the day-to-day fluctuations in both power generation supply and demand load has been the focus of technology development and engineering management for many years. Peak demand is typically characterized as annual, daily, or seasonal and has the unit of power (Torriti 2016). Peak demand, peak load or on-peak are terms used in energy demand management describing a period in which electrical energy is expected to be provided for a sustained period at a significantly higher than average supply level.

This happens today all over the world and is a fundamental characteristic of how human society uses electrical energy and this is related to how society uses electrical energy during the day and night, across the four seasons of the yearly cycle. Peak demand fluctuations may occur on daily, monthly, seasonal, and yearly cycles (Smil 2016a,b).

Different kinds of power demand each have different cycles. In industrialized regions of China or Germany, the peak demands mostly occur in daytime. In a more service-based economy such as Australia, the daily peak demands often occur in the late afternoon to early evening time (e.g. 4pm to 8pm) (Liu et al. 2017). During the night there is a noticeable reduction in demand as most economic activity ceases (as shown in Fig. 33). Residential and commercial electricity demand contributes a lot to this type of network peak demand (Liu et al. 2017). Power demand also varies with the winter season, as more heating of buildings is required (Landsberg & Stewart 1980), resulting in an increase in power demand across the winter months.

To keep the electrical generation grid delivery system stable, consumer demand and supply generation must be consistent at every moment. The total power system generation must follow the same pattern as the demand. So as demand fluctuates, power generation and power demand must be in balance (Fig. 32).

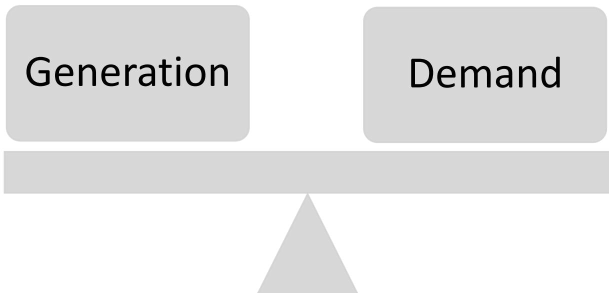

Fig. 32. To keep the system stable, demand and generation must be identical a every moment, and in balance.

Existing power systems currently rely on changing the generation of fossil fuel-based and hydro plants to cope with the fluctuations in the demand (Grigsby 2006). Intermittent power supply from wind and solar generation systems is also balanced up in the same manner, with most variation mitigation coming from gas power-fired systems (shown in Fig. 33). One strategy to ensure supply and demand balances was to shut down production delivered to the grid to curb excessive wind and solar electricity production.

Figure 33 shows the electrical energy generation portfolio of various technologies in Ontario, Canada for the time period February 17–22, 2021. As can be seen demand follows a well-established peak and trough pattern, of variable amplitudes. What is interesting to note, was how the different power generation systems changed production to meet those changes. Nuclear power provided a stable base load that did not really change, probably because it currently is the cheapest form of electricity generation.

The different power systems are capable of changing power delivery quantity, but some systems are more flexible than others in doing so. Nuclear and coal can change output, but work best when the power output is kept as stable as possible. Natural gas is the most flexible power generation system in operation and is often the preferred system to manage short range balances in supply vs. demand.

The maximum wind generation happened to occur in a demand valley on the 22^{nd} of 2021. Solar did not deliver consistent power across each day, and then stopped overnight. Canada has a strong capacity for hydroelectricity. In the time period shown in Figure 33, hydroelectrical energy supply was able to vary with demand, but only within a relatively narrow amplitude range (about half of the range needed). Hydroelectricity can vary power output but is heavily influenced by the volume of water in in its associated reservoir, which makes it vulnerable to changes in weather patterns. So, hydro can only be part of the fluctuating variability mitigation to ensure balance of supply to demand. This could be changed if hydro power share of the energy mix compared to other systems was very large.

Figure 33 shows that gas powered electricity generation was highly flexible in what it was able to deliver. Gas power formed a buffer between changing demand across the day/night cycle and contributions of wind and solar. Without gas power generation as a source, keeping the power grid stable in context of supply and demand would be challenging. This is something to consider as gas power generation is being phased out. The extra power generation capacity also must be non-fossil fuel in operation. This excludes the use of oil, gas or coal fired power stations. Solar power cannot operate at night (an electrical energy demand trough happens overnight, from approximately 2200 hours to 600 hours the following day. A peak in

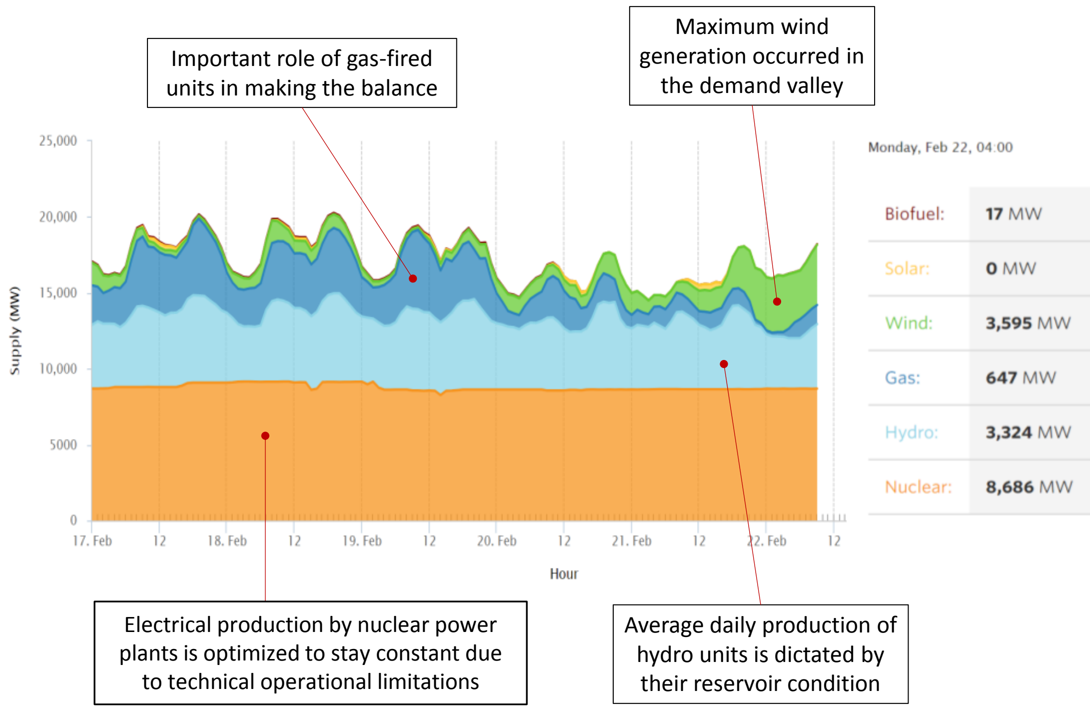

Fig. 33. Electrical energy generation portfolio of various technologies in Ontario, Canada (February 17–22, 2021) Copyright © 2001–2020 Independent Electricity System Operator, all rights reserved. This information is subject to the Terms of Use set out in the IESO's website (www.ieso.ca).

demand for electrical energy also happens around 1800 hours, associated with the last meal of the day in domestic households). Wind power is too intermitent and variable in operation to be reliable enough as a buffer system. Hydroelectric power generation can vary in output but only in a limited range. Biofuel power systems could form a buffer to replace gas systems if they were optimized to do so and operating plants were commissioned in large enough numbers. It is suggested that to replace gas as a variable mitigation system, extra systems of wind (buffered by power storage banks), biofuel/ biomass power generation, geothermal, tidal, and hydro systems (where possible) be constructed. Due to the difference in flexibility, these systems will have to be larger in capability, where some capacity is simply idle for periods of time. While this idea has been proposed, it is not clear how a very large wind and solar power plant fleet (e.g. 68.2% of the global energy mix) could balance supply and demand without the support of a fossil fuel power generation in external power grids. This topic has been studied extensively in the literature, but a universal agreed upon solution does that covers all practicalities does not yet exist thus far. This issue of power storage buffer to smooth out intermittent power supply from wind and solar systems is discussed in Sections 17 and 18 in this paper.

One of the strategies for future energy management of the incoming electric vehicle fleet, might be to charge EV batteries only in off peak electricity production (off-peak hours when power demand is usually low). That is, charge EV batteries only at night. This concept was developed to allocate electrical energy consumption to an off-peak time period. If this was viable, then power storage would be not needed (or at least much less would be required). Figure 33 shows an approximate variation of power demand/supply between 15 000 MW and 20 000 MW, or a range of 5 000 MW. This was just an approximate 25% variation across the day/ night cycle. While this efficiency measure will help smooth supply and demand, the enormous amount of electrical energy needed to charge EV's will probably exceed this spare capacity.

17 LONG TERM FLUCTUATIONS OF SOLAR POWER GENERATION

This paper assumes that power storage will be needed only for wind and solar supply mitigation and smoothing. The purpose of Sections 17 and 18 was to examine some of the issues that contribute to the need for power storage for buffer applications. There is discussion in the literature that propose a wide range of power storage sizes, which is discussed in Section 20.

Solar PV and solar CSP systems, like wind, are highly intermittent in supply of electrical energy generation (EIA 2019d). The nature of this variable intermittency has longer term aspects in comparison to the day-to-day fluctuations of power generation. Photovoltaic cell efficiency has an upper limit of power generation, termed the Schockley-Queisser Limit for monocrystalline silicon (Grigsby 2006, Schernikau & Smith 2023). This states that a maximum of 33% of incoming photons can be converted into electrons in silicon photovoltaic cells. Existing state of the art single layer solar PV cells have an efficiency of 26% conversion. Multilayer solar PV systems have reached 45% conversion but are not as durable as silicon monocrystalline systems. The overall efficiency of solar PV systems on an annual basis, is approximately 12% as a general average, and is considerably less than this on a daily basis according to weather conditions.

It is important to understand that whilst solar is intermittent, it does not have a random generation pattern. Solar resource for power generation is very predictable. Solar radiance suitable for power generation varies in a day/night cycle that is highly predictable. It also varies in a seasonal fashion. In northern Europe in particular, solar radiance in summer months (June, July, and August) is much stronger than in winter months (December, January, and February). Figure 34 shows solar radiance for the year 2015 in Germany in 2015. This section shows examples from Germany, Spain, and Switzerland. Solar radiance does not vary as much as in Figure 34 closer to the planetary equator. However, most of the human population is in the Northern Hemisphere.

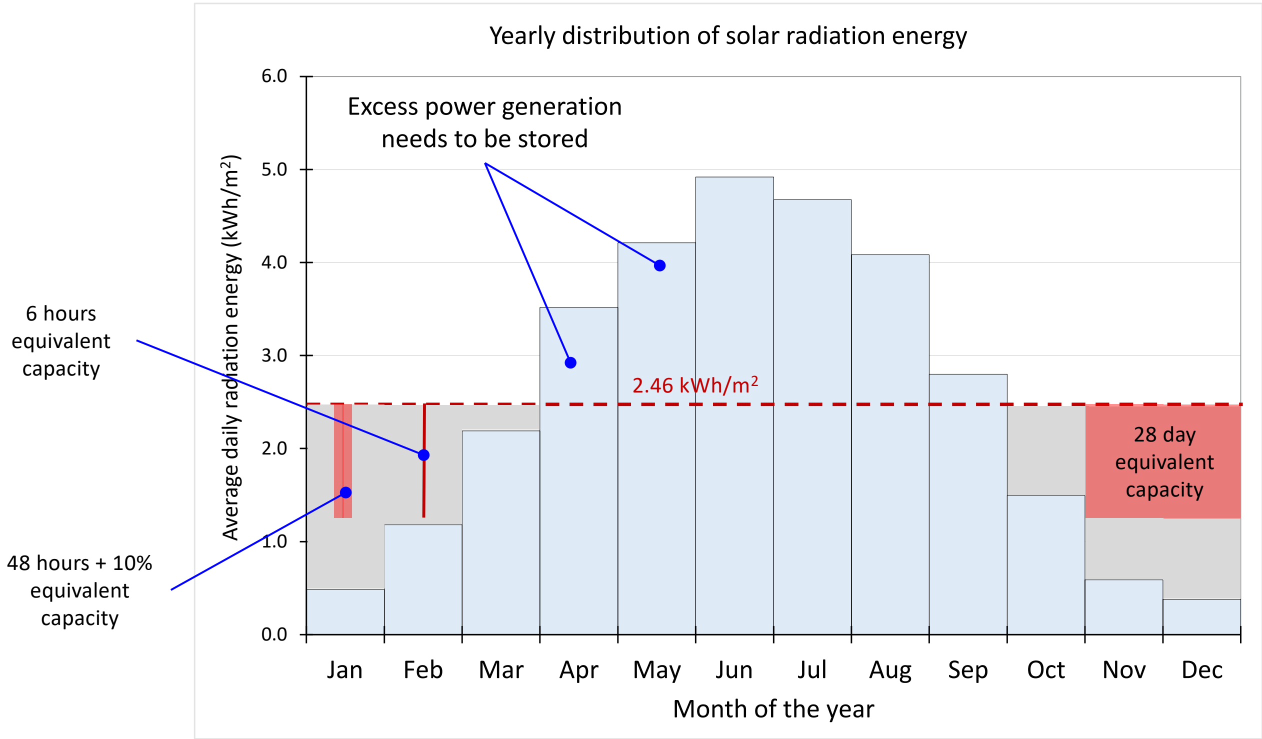

Fig. 34. Distribution of the sun's radiation energy over the year in Germany (Wesselak & Voswinckel 2016).

Consider another thought experiment, whereby solar photovoltaic systems were to generate electrical energy in Germany, using this solar radiance shown in Figure 34. Table 38 shows that solar power generation must now account for 34.5% of the energy mix. Such a large proportion of the energy mix would now have to be internally self-sufficient in terms of capability to stabilize supply and demand in contrast to how solar PV systems are currently managed. As such, it would have to deliver electrical energy at a constant capacity, represented by the dotted red line (at 2.46 kWh/m²) in Figure 34. For the warmer 6 months of the year (from April to September), there would have been an excess of generation capacity, which would be required to be collected and stored for at least for 6 months. Then, for the remaining colder 6 months, the available power generation capacity would be less than which is required by the red dotted line. For these 6 months, the power generated previously would have to be released gradually from storage. The required storage buffer for this thought experiment system, is shaded in grey in Figure 34. A red rectangle representing a 28 day equivalent storage buffer is shown (Right Hand Side). Two more red rectangles, representing a 48 hour +10% storage buffer and a 6 hour storage buffer are shown in Figure 34 (Left Hand Side). As can be seen, all three red rectangles are not even close to having enough capacity to function as a buffer storage (colored grey). This thought experiment supports the proposal that the size of a power storage buffer (at least in Germany) should be 12 weeks (Ruhnau & Qvist 2021).

Now consider how power demand in winter would be much higher than in summer due to heating demand requirements. Heating of buildings is often delivered using natural gas power systems. If fossil fuels were phased out, then that power would have to be delivered from another source. This study assumes this task of heating will be delivered using heat pumps (Section 12.2), requiring electricity to function.

Figures 35 and 36 show the results for January (winter) and July (summer) from a simulation of electricity generation in Switzerland in the year 2050, based on the Swiss 2050+ energy plan (Mearns & Sornette 2022).

The Energieperspektiven 2050+ plan (BFE 2020) had the following targets:

- Net zero CO_2 emissions by 2050
- To improve energy efficiency in all sectors
- Replace petroleum powered transport with electric vehicles

- Replace gas-and oil-powered heating with electric heating, mainly from heat pumps
- To not replace nuclear power plant (NPP) at the end of safe operating lives
- To substitute lost nuclear power production, mainly with solar PV
- To smooth intermittency with storage from batteries
- To be energy independent across the annual cycle by 2050

In this simulation (Mearns & Sornette 2022), demand load for power in each month in 2050 was 37% more than corresponding month in 2017. It was assumed that solar PV capacity in 2050 was 20 times the 2017 Swiss capacity. Nuclear power was removed from the energy mix. It was assumed that pumped hydro storage (PHS) was greatly expanded in 2050 (3.8 GW capacity, 520 GWh storage) compared to 2017 (1.4 GW capacity, 369 GWh storage). Figure 35 shows the power generation and demand load for the simulated month of January 2050. Figure 36 shows the power generation and demand load for the simulated month of July 2050. The difference between these two figures can be explained with the months shown in Figure 34.

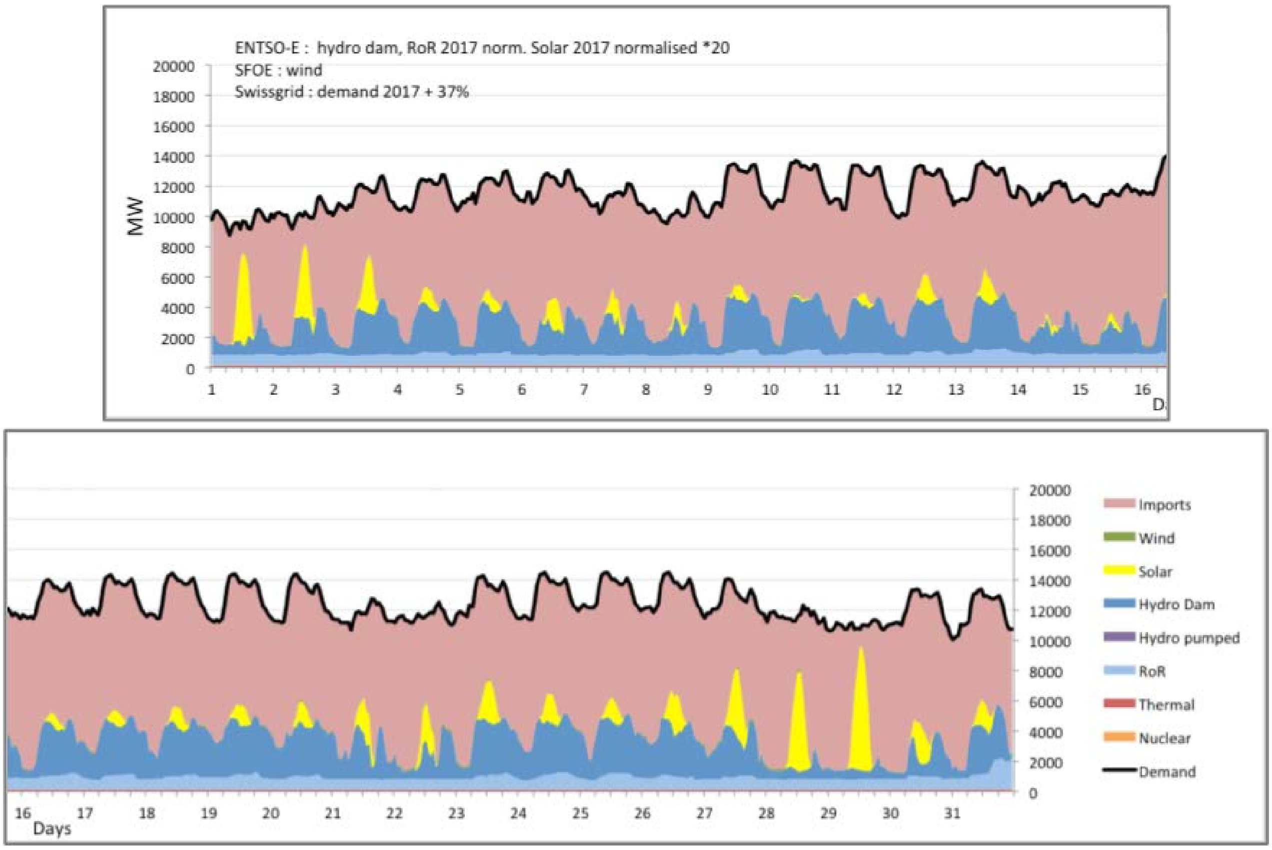

Fig. 35. Simulation of Swiss electricity supply in January 2050 based on January 2017 and the essential components of the Swiss electricity plan 2050 (Source: Mearns & Sornette 2022, based on BFE 2020).

Figure 35 shows that in January 2050, Switzerland would need a large amount of power imports, to the scope of 69% of demand for the month (6.1 TWh imported just for the month of January 2050). In the simulation, this was an outcome as a result of increased demand for the nations power (+37%) and closure of Switzerland's four remaining nuclear power stations. Solar PV production in January 2050 was only 4% of total demand. Multiplying solar PV capacity by a factor of 20 did not result in enough power to meet demand due to simulated solar radiance for the month of January (based on what was measured in 2017).

Figure 36 shows that in July 2050, Switzerland would easily be self-sufficient in power generation during the day using just solar PV power systems. The size of the peaks in surplus of power load demand shown in Figure 35 would need to be collected and stored. In this simulation, Pumped Hydro Storage (PHS) was used. This power surplus will have no export market since most surrounding countries will likely be producing a similar surplus of solar power during the day for most of the summertime.

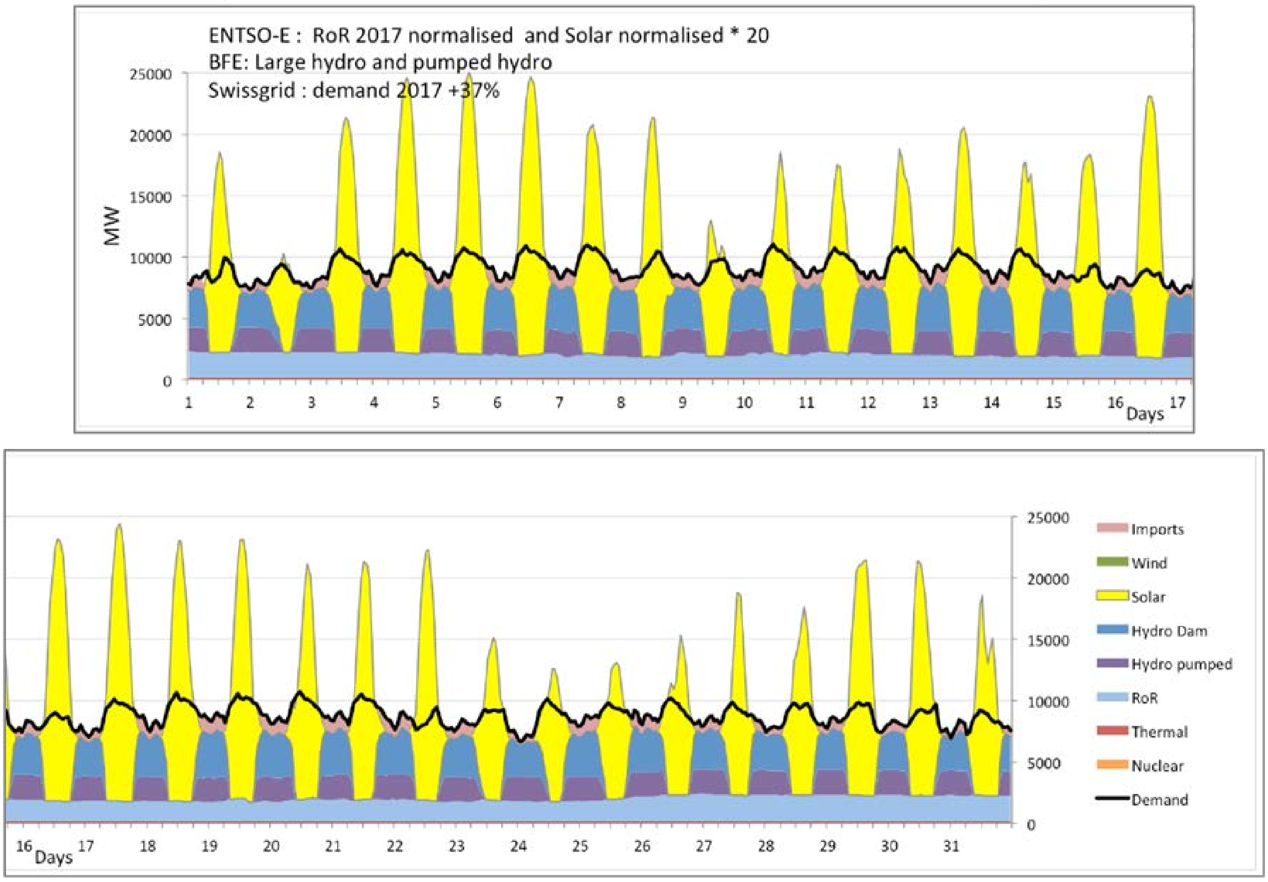

Fig. 36. Switzerland electricity supply and demand simulation for July 2050 (Source: Mearns & Sornette 2022 based on BFE 2020).

The Swiss simulation study (Mearns & Sornette 2022) also conducted an estimate of the energy surplus in July 2050 and energy deficit in January 2050. The energy surplus in July 2050 was 743 GWh, and the energy deficit in January was 6124 GWh. Even if the energy surplus in July was fully collected and stored, not even close to being enough to service the energy deficit in January. Consider now how this system would be stabilized and balanced if it was extended to represent 34.5% of the energy mix in Europe.

Figures 37 and 38 show the results of a study (Andrews & Mearns 2015) in Spain that examined the capabilities of concentrated Solar Power (CSP) systems in two months, June, and November 2015. In Table 38, Solar CSP represents 3.83% of the proposed energy mix.

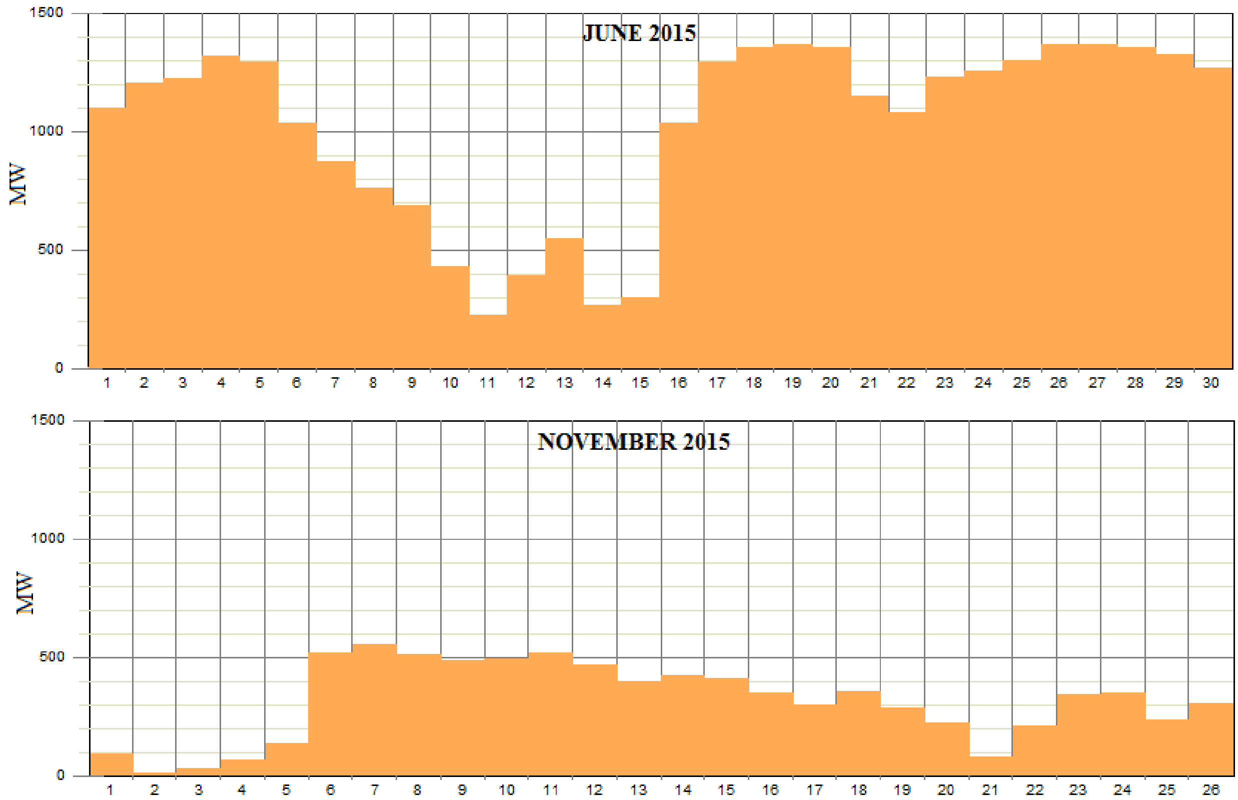

Fig. 37. Average daily CSP generation, June, and November 2015 (Source: Andrews & Mearns 2015 Dec 2nd).

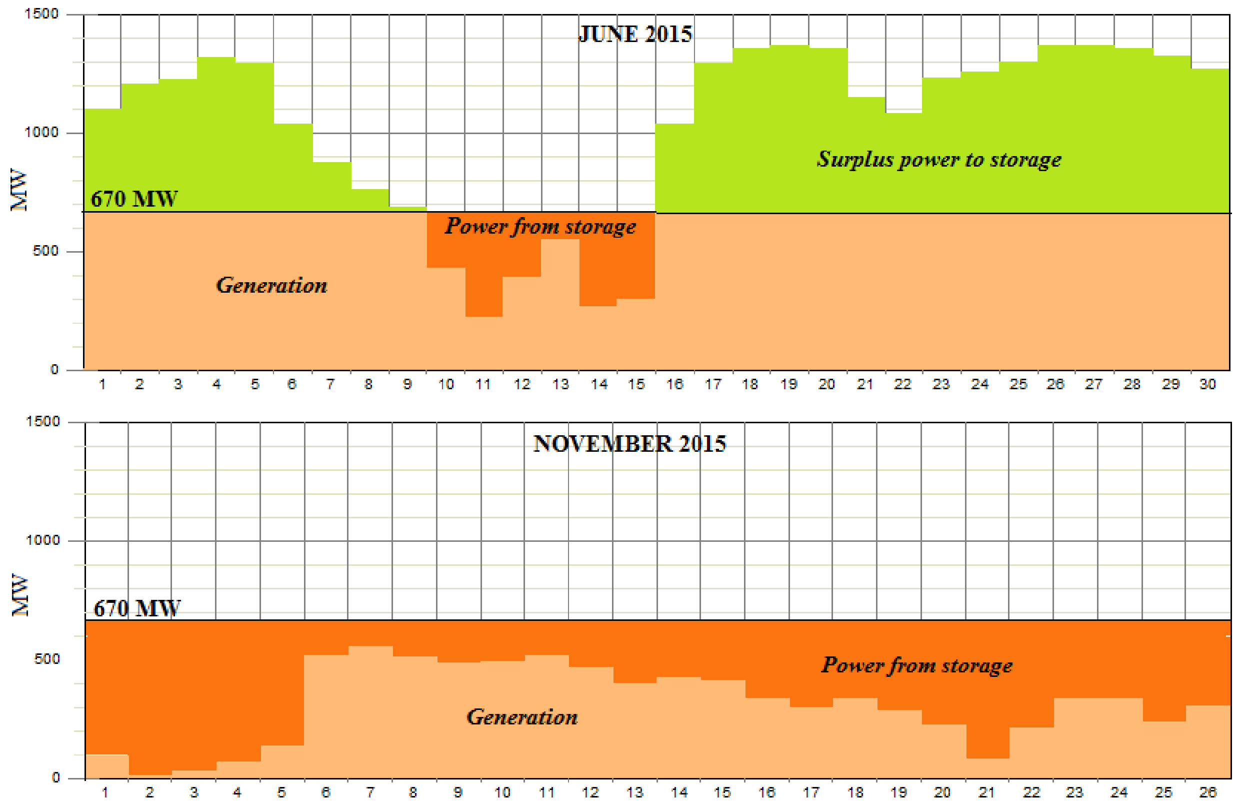

Fig. 38. Power to and from storage needed to maintain constant 670MW baseload generation, June, and November 2015 (Source: Andrews & Mearns 2015 Dec 2nd).

Figure 37 shows the electrical energy generated by Spanish CSP plants in two target months to represent summer and winter. Figure 38 summarizes the power storage and release requirements that would have been needed to maintain a constant 670 MW of baseload generation during June and November. Approximately 260 GWh of storage would have been required to cover the shortfalls in just the month of November alone (Andrews & Mearns 2015). This would be equivalent to 16.2 days of buffer capacity (for this system), to be stored for approximately 6 months, which would then be released gradually in the winter months. If 16.2 days were needed just for November, consider what would be required for the other 5 months to maintain steady power supply through winter (as per shown in Figs. 34 and 38).

Solar radiance and the capability to generate electricity from varies across the year in a seasonal context. If solar is to be a large part of the global energy mix, then a parallel technology would be required to stabilize it, in order to maintain a steady supply of electricity. At the time of writing this paper, this technology to deliver stationary power storage in future expansion was battery banks (EMA 2020). According to Table 35, solar power was operationally able to deliver electricity to the power grid for 1000 hours across the calendar year of 2018, or 11.4% of the time.

Currently most electrical energy generation grids are balanced through the sharing or trading of power (see Section 19). Trading power between solar grid systems will not be efficient. The seasonal changes of solar radiance will affect a wide geographical region. For example, the winter season will affect a whole hemisphere. So, when one solar power grid is underperforming due to a lack of solar radiance, most other solar power grids in a wide geographical area would have similar issues and would not be able to supply excess power in trade.

18 LONG TERM FLUCTUATIONS OF WIND POWER GENERATION

Wind power is much more intermittent in an unpredictable manner (EIA 2015, Huang et al. 2014, Ren et al. 2017, Ren et al. 2018, United Kingdom Parliament 2014). In a study into wind power generation, the reliable capacity for electricity delivery to the grid as a percentage of the maximum installed capacity was found to be 7–25% (United Kingdom Parliament 2014). Due to a number of large storms during the time of this enquiry, the prediction of the quantity and timing of wind power generation was very difficult to forecast due to the erratic nature of the weather.

Wind has an upper limit of power generation, called the Betz limit. This is where a maximum of 60% of kinetic energy in the air is captured by the turbine blade. Most modern turbines do not exceed 45% energy conversion efficiency (Schernikau & Smith 2023). When first installed, modern turbines have an energy conversion efficiency between 35 to 45%, which then degrades with use (Abu-Rub et al. 2014).

Figure 39 shows electrical energy generated in the United Kingdom in September, October, and November 2015 (Mearns 2015a). Note the many peaks and troughs of power generation. Consider what would be required to stabilize this power system to deliver constant and steady electricity. The thin red line in Figure 39 represents a 6 hour electrical power storage buffer. As can be observed, this will not be even close to being enough to providing enough buffer energy storage to smooth the power generated into a flat line.

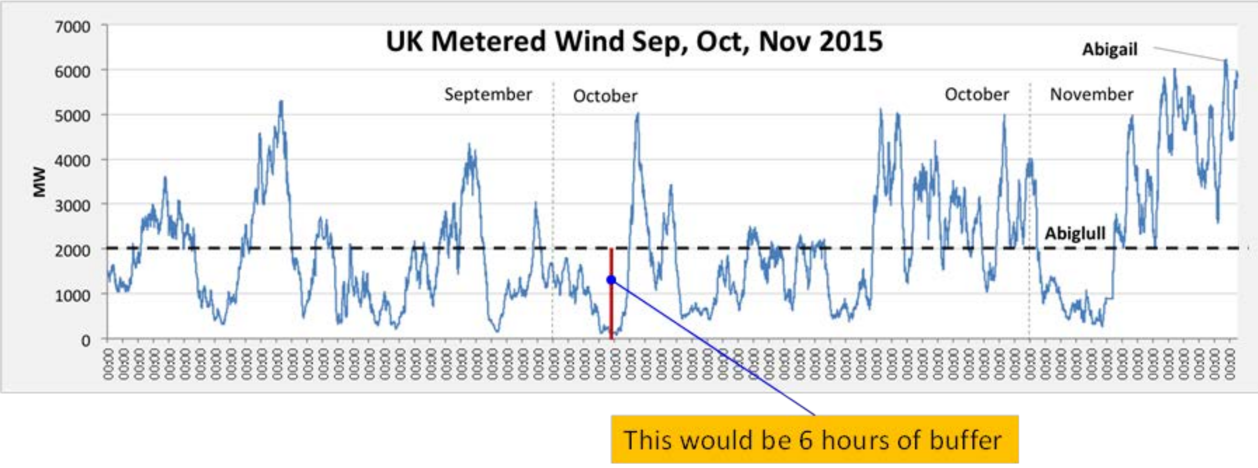

Fig. 39. United Kingdom Metered Wind UK metered wind output from 1st September to 13th November 2015 (Source: Mearns 2015a).

Figure 40 shows the power produced with wind generation in the Texas ERCOT grid in 2021 (Texas Comptroller 2022), where a 13 day lull in power production can be seen. Figure 39 shows data from before the serious winter storm that resulted in power outages (Penney 2021). Texas power generation from wind lost an average of -7.9 GW (-61%) beginning February 8 before the power crisis began on February 15 (Berman 2023). Annex J shows a more complete data set of this matter.

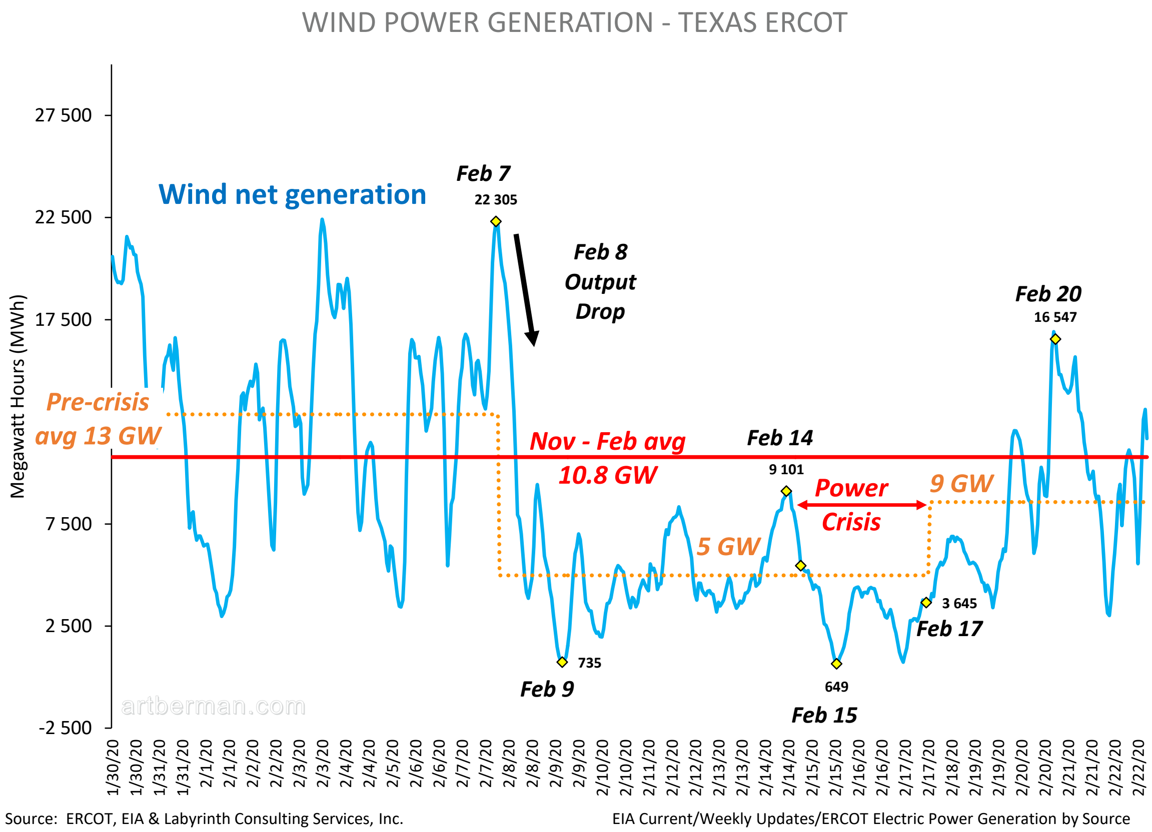

Fig. 40. Texas power generation from wind lost an average of -7.9 GW (-61%) beginning February 8 (Source: Berman 2023, Labyrinth Consulting) (Copyright granted: Art Berman).

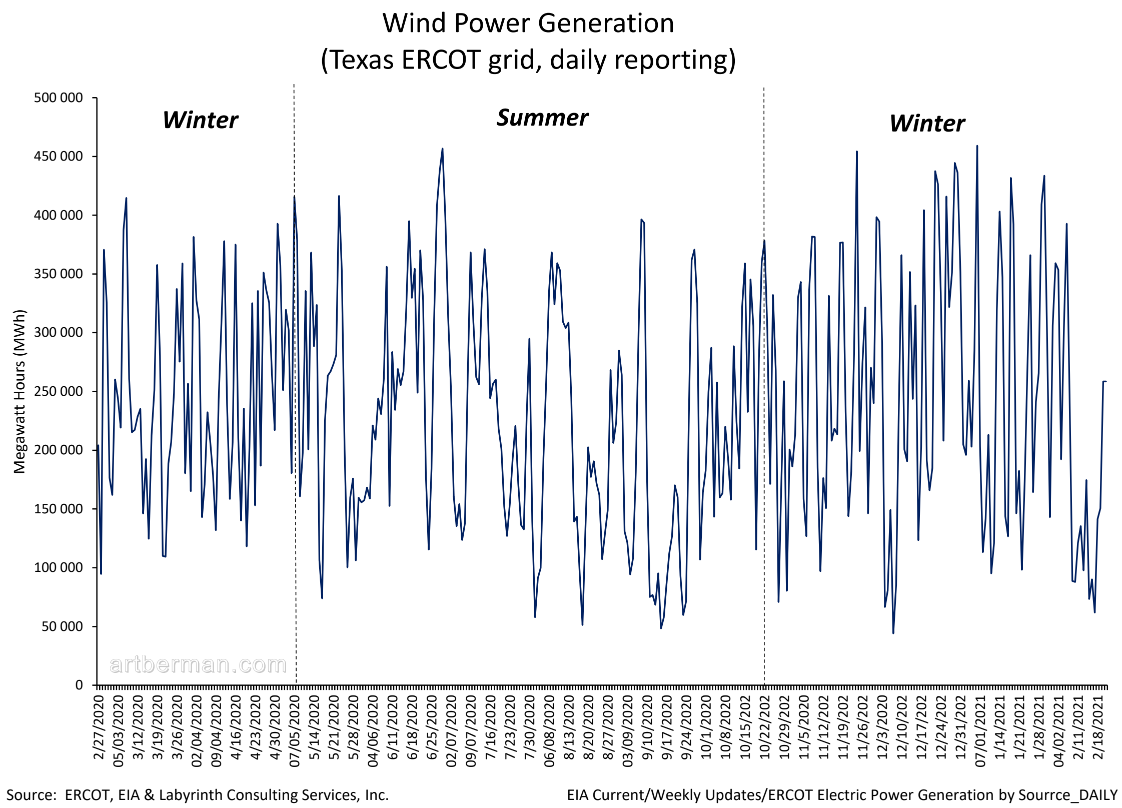

Fig. 41. Texas electric power generated from wind is cyclic Peak-to-peak cycles are approximately 5 days in winter and 7 days in summer (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting) (Source: Berman 2023, Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

Figure 41 shows the same data at a higher resolution, demonstrating the variable but cyclic nature of wind power. Annex J shows a more complete discussion of the power outage in Texas in February 2021. Figure 42 shows wind power generation across a 61 day time period in 2015 for five European nations. The power distribution shown in Figure 42 is quite heavily influenced by the size of the wind parks in the various countries, for example Denmark with 4.9 GW and Germany with 41.4 GW installed wind power capacity. Note the large peaks and troughs. The numbers 1 to 9 marked periods in Denmark, the UK and Germany when the combined wind output fell below 5000 MW, each lasting for serval days. The larger the amplitude of these peaks, the larger any power storage would be needed to collect and store this power to be later released slowly in a lull trough.

When one region had a lull in power production, where the wind dropped close to zero, the same weather conditions were observed across the whole of northern Europe (in Fig. 42, Sweden, Denmark, United Kingdom, France, and Germany all had peaks and troughs at the same time). No matter how many wind turbines might be installed or how many inter connectors might be constructed, Europe would always be dependent upon some kind of power storage buffer for its wind power energy generation station fleet. Currently, this buffer is supplied from external fossil fuel sourced power systems.

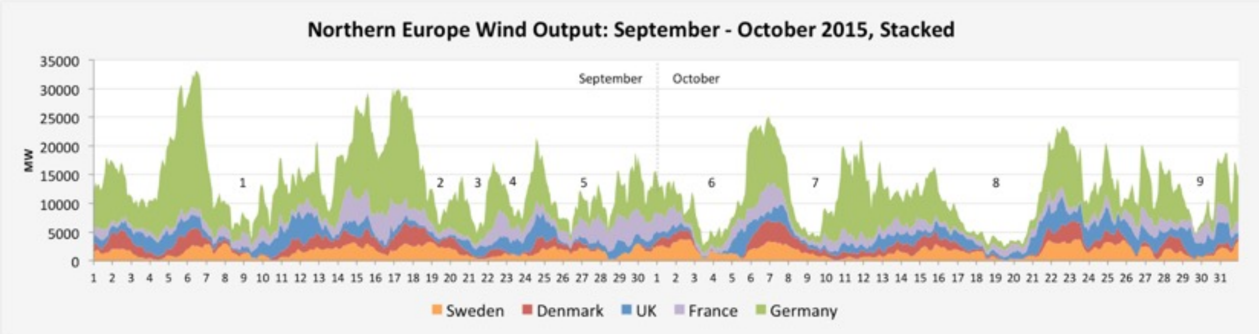

Fig. 42. Wind power generation in Sweden, Denmark, United Kingdom, France and Germany between 1st of September to 31st of October 2015 (Source: Mearns 2015b).

According to Table 35, wind power was operationally able to deliver electricity to the power grid for 2 184 hours across the calendar year of 2018, or 24.9% of the time.

19 SYSTEM RELIABILITY AND INTERMITTENT POWER SUPPLY CHALLENGES

The purpose of Section 19 is to examine how electrical energy networks are balanced now. Renewable power generation technologies are heavily influenced by weather and climate conditions (J.M.K.C. Hanania et al. 2017). There are nonlinear weather events that can greatly impact teach systems ability to function to specification. There have been several studies that examine the issue of intermittent power supply from systems like wind turbines, solar PV, and hydroelectricity (Wojick 2022, Ruhnau & Qvist 2021, Cannon et al. 2015, de Vries & Doorman 2021, Grams et al. 2017, Handschy et al. 2017, Leahy & McKeogh 2013, Kaspar et al. 2019, Raynaud et al. 2018).

(Ruhnau & Qvist 2021) conducted a study of a German 100% renewable case study, examining electrical power supply from renewable energy systems, using 35 years of hourly time series data (ENTSO-E 2024), based on the years 1982–2016. The dataset includes hourly load data and hourly generation profiles for wind and solar energy. Previous studies on renewable scarcity periods mostly focused on wind power (Cannon et al. 2015, Patlakas et al. 2017, Ohlendorf & Schill 2020). These studies identified the maximum duration of low-wind events identified in these studies is 4–10 days.

Low-wind events are more pronounced when focusing on single regional locations (Leahy & McKeogh 2013). This becomes less pronounced when the data set is expanded to a continental scale (Grams et al. 2017, Handschy et al. 2017, Kaspar et al. 2019).

(Raynaud et al. 2018) extended the scope of analysis of load demand against more renewable energy systems: solar, hydro, and wind. This was done to examine periods when renewables supply less than 20% of demand (termed an energy drought).

The analysis done by (Ruhnau & Qvist 2021) supported the outcomes of previous studies, where periods with persistently scarce supply last no longer than two weeks. However, (Ruhnau & Qvist 2021) also found that the maximum energy deficit occurs over a much longer period of nine weeks. This happened because it was found that there were multiple examples of more than one scarce power supply period closely follows another. The power storage buffer had not had time to replenish itself. For this reason, (Ruhnau & Qvist 2021) recommended a 12 week power storage capacity, to account for storage losses and charging limitations. It was also observed that a single-year optimization generally underestimates the required storage volume when compared to multi-year optimization (Ruhnau & Qvist 2021, Dowling et al. 2020).

For the last few decades, many of the large electrical energy grid systems have maintained supply and demand using electrical energy sharing between nation state grids. Figure 43 shows how electrical energy was shared in Europe in 2021. Each nation imported and/or exported power from their national grids. No nation generated just enough electrical energy for its own consumption. Each nation either imported power or exported power to other nations. Figure 43 shows how reliable capacity for electrical energy delivery has been achieved to date. In doing so, supply and demand could be balanced.

This system is also dependent on large power generators to maintain stability through small disturbances of supply throughput the grid (for example transformer breakdowns).

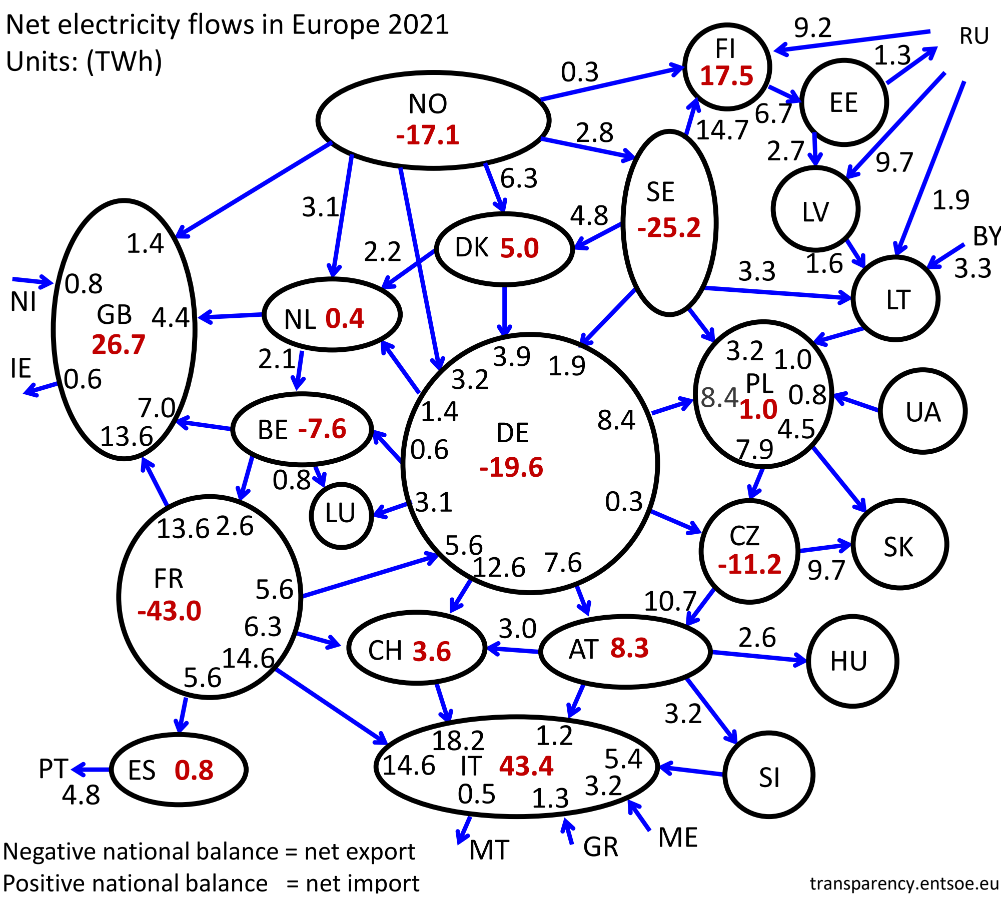

Fig. 43. Net electricity flows in Europe 2021 (Source: redrawn from ENTSOE, https://transparency.entsoe.eu/).

The large amount of kinetic energy stored in these large power plants as they operate acts as an intrinsic energy reserve with instantaneous response time to continue to deliver electricity with the same oscillations of 50 Hz. If this changes too much, the grid will fail. The technology used to do this now is based in coal, gas, oil, nuclear and the larger hydropower plants, which can supply electrical energy in any weather condition, at any time of year. To date, wind and solar have not been able to perform this function (or perhaps not been required to do so), as this task of kinetic energy storage in the grid cannot be replaced with many small generators.

How to build this new and expanded power grid is still not entirely understood. To date, power supply has been balanced through power sharing (Fig. 43). This means that most of the time, renewable power systems like wind and solar have been balanced with the support of external power systems, usually fossil fuel based. The proposed future energy mix has a large proportion of wind and solar power systems. This proportion is so large that these systems will have to be internally self-sufficient and will have to balance out supply to demand in a manner different to how it is done now.

All forms of electricity generation exhibit uncontrolled increases or decreases in output (intermittency). For example, conventional (fossil-fuelled and nuclear) power plants break down, causing larger instantaneous losses of capacity than renewables. However, the term intermittency is typically associated with the renewables: wind, solar, wave and tidal. Intermittency from these sources is characterised by very large variations in the amount of electricity they can provide at the national level. Although these variations are not normally controlled, they can be predicted with some accuracy. Wind power is dependent on the weather; thus, prediction of reliability is related to the accuracy of weather predictions (EIA 2015). Solar is also intermittent but can be predicted more reliably. Tidal power generation systems are reliant on the regional coastal tides, which are reliably predictable.

Sources of electricity that exhibit uncontrolled increases or decreases in output are often referred to as intermittent. All existing electrical energy generation systems have down time and intermittent supply profiles (United Kingdom Parliament 2014, May). Some systems are more reliable than others (Torriti 2016 and Table 41). While this study is now a few years old, the concepts discussed are related to the weather and its variability. Up to date wind generation of electrical power are subject to the same concepts.

Table 41. Contribution of technologies to electricity system reliability at times of annual peak demand (Source: United Kingdom Parliament 2014 May).

Technology	Reliable capacity as a% of maximum capacity	2013 UK max capacity, (GW)
Wind	7-25%	11,0
Solar †	0%	2,7
Hydro	79-92%	1,7
Tidal *	35%	<0.001
Wave *	35%	<0.001
Fossil Fuel	77-95%	
Nuclear	77-95%	78

* There was little data available on the contribution of tidal & wave
† Peak demand happens after sunset, solar not operational

20 STATIONARY POWER STORAGE

Some non-fossil fuel electrical energy generation systems are intermitted and not consistent in power delivery. To protect the grid and maintain reliable power delivery, a buffer of power storage of some kind is needed. This is termed stationary power storage. There are three scales of power storage that are used for balancing generation supply and demand load (Schernikau & Smith 2023).

- Short term, in the second/minute range.
- Intermediate term, in the daily peak and low loads.
- Long term storage surpassing 2 to 12 weeks (Ruhnau & Qvist 2021, Toke 2021)

A power buffer backup of some form is a critical sub-system for an electricity generation system that is intermittent, for example wind and solar. Existing electrical engineering technology depends on stable (no black outs), consistent and clean (sinusoidal, without power spikes), at a frequency of 50 Hz or 60 Hz in a very narrow specification bandwidth (Glover et al. 2022, Grigsby 2006, Gottlieb 1997). This must happen at a resolution of a microsecond. Any variation in power supply quantity and quality has the capacity to destroy sensitive electrical equipment. Without a power buffer the electrical energy grid would be subject to frequent black outs, brown outs and even system collapse could happen (Menton 2022, Grigsby 2006). While the volume of electrical energy from renewable sources is relatively small this is a manageable issue. Once renewable power becomes a larger share of power generation, then infrastructure will be needed in electrical energy storage (Friedemann 2021).

Energy storage is useful when energy is harvested at a different time from when it's used. For example, electricity must be used very quickly after it's been made (within milliseconds). Energy storage would be needed if the electrical grid starts relying on large amounts of intermittent electricity sources like wind power.

Table 42. Technology options for energy storage (Source: J.M.K.C. Donev 2018).

Storage Type	Form of energy stored	Technology
Mechanical	Potential	Compressed air energy storage (CAES)
		Pumped storage
	Kinetic	Flywheels
Electrical	Electrostatic	Capacitors
		Super capacitors
	Magnetic	Superconducting magnetic energy storage (SMES)
Chemical	Chemical	Batteries
	Electrochemical	Fuel cells
	Thermochemical	Fuels from solar power
Thermal	High temperature thermal	Sensible heat storage
		Latent heat storage

Energy economics dictates that storage will always reduce the Energy-Returned on Energy-Invested (ERoEI) ratio and the material efficiency of an energy system (Schernikau & Smith 2023). This happens because any storage system adds to the complexity and requires further energy transformation to work and is a manifestation of the 2nd law of thermodynamics (Moran et al. 2014).

The intermittent nature of renewable energy can be mitigated with measures like connecting lots of renewable power stations together and optimizing their power delivery through one system (Droste-Franke 2015). Power storage systems are mostly required to ensure consistent supply to the grid during the long periods of reduced sunlight hours and reduced wind where it is needed, for solar and wind systems (Mulder 2014).

A secure electrical energy system needs adequate levels of both system strength and inertia, which to date have been provided by synchronous power generation (Figs. 32 and 43) (U.S. Department of Energy 2020). System strength relates to the ability of a power system to manage fluctuations in supply or demand while maintaining stable voltage levels. Inertia relates to the ability of a power system to manage fluctuations in supply or demand while maintaining stable system frequency. The majority of stationary power storage in 2018 (and at the time of writing this paper) was through the use of pumped hydro, with a stored capacity of 164 761 MW in 2021 (IHA 2022).

Steinke et al. 2012 put forward the recommendation for a fully renewable powered Europe to have 2 days of power storage, plus 10%. This study was to examine all power requirements for Europe to be 100% renewable. Another study (Droste-Franke 2015) examined the possibility of a 'supergrid' across the European Union, North Africa, and the Mediterranean. This study found that there would still need to be 28 days (1 month) of energy storage to keep the grid up during seasonal variations (Droste-Franke 2015). Palmer & Floyd (2020) proposed that up to 7 weeks of storage would be required as well as large amounts of renewable capacity overbuild. (Ruhnau & Qvist 2021) proposed 12 weeks of power buffer. A study done in the United Kingdom (Fragaki et al. 2019) proposed a 30 day power buffer for a 100% renewable energy generation system, provided there was a 115% overbuild in renewable energy generation capacity.

In the literature, there are a number of opinions with regard to how much of a buffer is required. None of the studies examined worked to the assumption that the power grid would deliver the same current, voltage and frequency in clean sinusoidal power at the same quantity of energy, 365 days a year, 24 hours a day, to a resolution of a millionth of a second. This is what is required to protect delicate electronic equipment like computers from back outs, brown outs, and power spikes (Glover et al. 2022, Grigsby 2006, Gottlieb 1997). At this time power grids can achieve this by balance off against each other, usually using fossil fuel power generation. In a fully Green Transition scenario, a large solar or wind power generation system would not have the access of fossil fuel power generation systems and would have to be internally self-sufficient. In the projected energy split shown in Figure 31 (the IEA prediction for 2050), wind and solar represent about 70% of the generation of electricity. These renewable grids would be so large and so intermittent, that they could not be stabilized by an external power source.

Other studies have concluded that only a few hours power storage buffer capacity would be needed. Jacobson (et al. 2022) presented a roadmap that would allow a 100% transition of human society to a complete wind, water and solar energy system, where a 4 to 8 hour power buffer for load sharing was required. The Net Zero America project (Larson et al. 2021, Jenkins et al. 2021) concludes that 5 to 7 hours for a power storage buffer would be needed if the application of the following technologies were deployed in parallel with battery banks:

- Direct air capture of carbon
- Production of hydrogen with electrolysis
- Electric boilers run in parallel with gas -fired units in industry

The direct air capture and electric boiler technologies could be used to consume excess electrical energy in a useful fashion, but they would not store electrical energy for later use (which is the purpose of a power storage buffer). The reason for sending surplus electricity generated to another part of the grid to power electric boilers to generate steam, to in turn generate electricity (at an efficiency loss), is not clear. The use of electrolysis to produce hydrogen is only 28.6% efficient, as shown in Figure 14, where it takes 50 kWh to produce 1 kg of hydrogen (and 2.5 kWh to compress it into 700 bar tanks), and only 15 kWh is returned from a PEM fuel cell processing 1 kg of hydrogen. So, the use of excess power to produce hydrogen could be used to store power but would not be as effective as other storage methods like fly wheels, compressed air, or battery banks (EMA 2020). If hydrogen was used as an energy storage, the logistics of production, then later electricity generation, storage and transportation could require approximately 80% of the energy in that hydrogen (Schernikau & Smith 2023). A solution could be to use the intermittent power generated by wind and solar to directly produce hydrogen for the hydrogen economy, without any power storage buffer. This would mean that the whole wind and solar power station fleet would not be tasked to supply steady stable power to the electricity grid, but to generate hydrogen for the transport fleet. This change in paradigm could remove the need for a power buffer at all. What other power generation systems could be used instead, and how they may be balanced is a separate discussion.

Even if these technologies were able to function as a power storage buffer, the size of the buffer that Net Zero America (Larson et al. 2021) recommended (5 to 7 hours) is too small in capacity to be useful in managing seasonal variations. The size of the power storage buffer in America (Larson et al. 2021) mapped and modelled day to day fluctuations between power generation and demand load. The comparatively small amounts of excess power were captured, stored, and then used a few days later in the shown simulation. This study, as sophisticated as it was, did not map and model the long term seasonal fluctuations for wind and solar power generation. The season differences in solar radiance and what that results in regarding solar PV power generation (see Section 17) was not examined in Net Zero America (Larson et al. 2021). Also, the huge swings in wind power generation (see Section 18), which can be more than 65% of maximum capacity, followed by several days of almost no wind at all, was not examined in Net Zero America (Larson et al. 2021).

Rahnau and Qvist (2021) also conducted a study for the power storage requirements for a 100% renewable electrical system in Germany. Rahnau and Qvist (2021) used hourly data for electrical energy consumption and for production from the existing wind and solar facilities in Germany over 35 years. After analysis of the 35 year hourly time series, it was found that periods with persistently scarce supply last no longer than two weeks, and that the maximum energy deficit occurs over a much longer period of nine weeks. This was because multiple scarce periods were found to follow each other often closely. When considering storage losses and charging limitations, the period defining storage requirements extends over as much as 12 weeks. For this longer period, the cost-optimal storage capacity is about three times larger compared to the energy deficit of the scarcest two weeks (Rahnau & Qvist 2021). The construction of 56 000 GWh of power storage buffer was recommended, representing 1 120 hours of average use, or 47 days.

A similar methodology (to Andrews 2018) was used to examine the required storage capacity if the lower 48 states of the United States, using measured data (hourly electricity demand, and production patterns of wind and solar power stations) across the years 2019 and 2020 (Gregory 2022, Menton 2022). Several possible development vectors were examined. Scenario 1 required 233 TWh of annual power storage for the lower 48 states of the USA.

To develop this scenario 1, Gregory (2022) assumed the replacement of fossil fuel usage (which was 305 GW in 2020) and another 10 GW to account for battery losses. This is a required 740 hours of annual electrical energy storage, or 30.8 days.

Wind and solar in particular require some kind of external buffer to function. It doesn't matter if one builds wind and/or solar facilities with capacity of ten or one hundred or even one thousand times peak electricity usage (Menton 2022). These systems are highly influenced by changes in the weather, which is known to be volatile. For example, on a calm night, or during days or weeks of deep wind/sun drought, those facilities will produce nothing, or so little power quantities as not to be useful. This would happen regularly. When it does, only a full back up or buffer large enough to be sufficient to supply power needs to meet peak demand for as long as the weather remains volatile. If this does not happen, that electrical energy grid will fail and shut down.

How to develop and construct a large enough energy storage system to function as a power storage buffer to purpose of stabilizing wind and solar power generation grids is not known. All commercially available technologies examined work quite well at a small scale but are not viable when scaled up (Menton 2022). At this time, there is no proven and costed energy storage solution that can support a wind/solar electricity generation system fully to achieve Net Zero emissions (Menton 2022, Schernikau & Smith 2023, McKinsey 2021 shows the data to support this).

20.1 Size and capacity required for stationary power storage

For the purposes of this study, power buffer storage for the proposed global electricity grid was modelled at four capacities, each backed by a reference. It was also assumed that this power buffer was only for the purpose of managing intermittent energy supply for wind turbine and solar energy generation systems. Other applications were not considered. The capacities are as follows:

- 6 hours (Larson et al. 2021)
- 48 hours +10% (Steinke et al. 2012)
- 28 days (Droste-Franke 2015)
- 12 weeks (Ruhnau & Qvist 2021)

As shown in Sections 17 and 18, this size of 28 days capacity may well not be enough. An energy storage buffer of 6 hours will most certainly not be enough to stabilize the projected wind and solar power stations if they are to represent 70% of the global energy mix. Given number of months below the average solar radiance in Figure 34, 12 weeks may be more the scale of capacity required. More work needs to be done to determine the true value of the needed power buffer, which would involve a more complex and sophisticated study. One outcome of this required power buffer size is that wind and solar electrical power generation will certainly have its place in all future power grids, but it may not be viable as the primary energy generation system that underpins the next industrial era. Table 43 shows the estimated energy storage each of these capacities represent for the global energy production.

Table 43. Estimated stationary power storage buffer for a range of capacities.

Power Generation System 	**Expanded extra required annual global capacity to phase out fossil fuels** (TWh)	**Storage capacity for a 6 hour period to manage intermittent power supply from wind and solar** (Larson et al. 2021) (TWh)	**Storage capacity for a 48 hour +10% period to manage intermittent power supply from wind and solar** (Steinke et al. 2012) (TWh)	**Storage capacity for a 28 day period to manage intermittent power supply from wind and solar** (Droste-Franke 2015) (TWh)	**Storage capacity for a 12 week period to manage intermittent power supply from wind and solar** (Ruhnau & Qvist 2021) (TWh)
Wind	18 758,7	12,8	113,1	1 439,0	4 317,1
Solar PV	16 884,3	11,6	101,8	1 295,2	3 885,7
Solar Thermal	1 874,4	1,3	11,3	143,8	431,4
Total Power Storage Capacity		25,7	226,1	2 878,0	8 634,1

20.2 Pumped hydroelectricity systems used as power storage

Currently, pumped-storage hydropower (PSH) provides 98% of all the existing electrical energy stored in the world (Mongird et al. 2019, IEA 2021c, U.S. Department of Energy 2020) (Fig. 44).

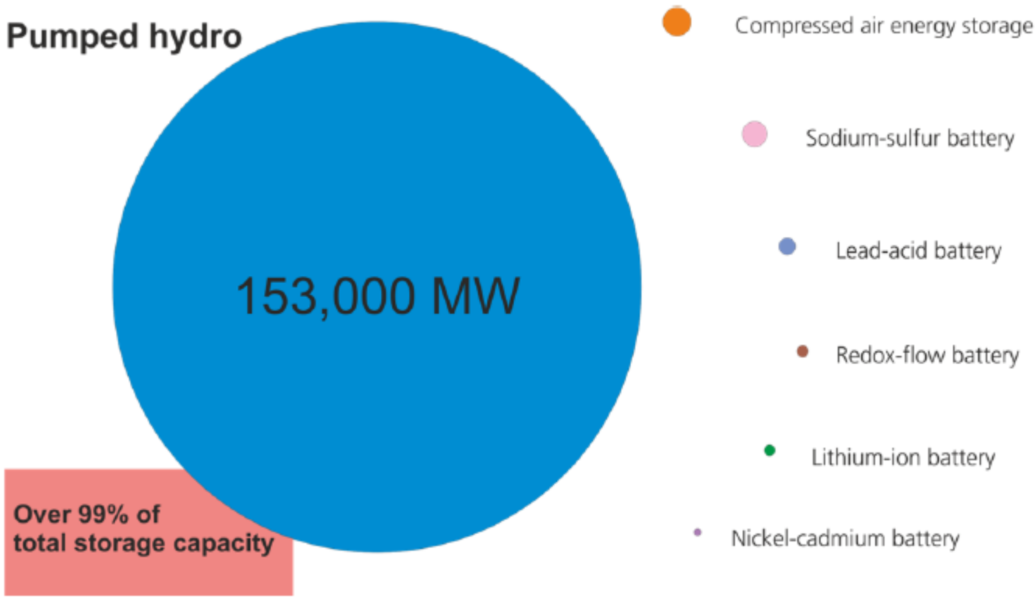

Fig. 44. Proportion of installed capacity of various electric storage systems in 2019 (Source: EMA 2020).

PHS is an energy storage method that is a parallel system to a hydropower plant, where water is pumped up to a reservoir at a higher elevation, and then at a later date, that reservoir is drained. As the water runs downhill back through the hydro power station, it is used to generate electricity (Fig. 45). As power systems are currently balanced by trading power between grids, PHS is often used to smooth out the demand to supply across the 24 hour cycle. For example, during off peak hours (2200 hours to 600 hours) when demand is in a trough, electricity is used to pump water to the upper reservoir. Then during peak demand, that water flows downhill to the lower reservoir, passing through the hydroelectric power generation system. The electricity generated is then supplied to the grid. In doing so, power was generated off-peak and stored for use at high demand a few hours later.

While the volume of electrical energy from renewable sources is relatively small this is a manageable issue. Once renewable power becomes a larger share of power generation, then infrastructure will be needed in electrical energy storage. The required power storage for the task of phasing out fossil fuels is much larger than what is currently in place.

The question is asked whether pumped storage could be used as the needed power buffer smooth out the intermittent power supply from wind and solar generation systems. A study was conducted a global audit for potential sites that could be developed for pumped hydro power storage applications (Lu et al. 2018). This study observed that prospective short-term off-river pumped-hydro energy storage sites combined, numbered 530 000 (Fig. 46), and had a global potential storage capacity of 22 million Gigawatt-hours (GWh), or 2.2 x 10^{10} TWh. As shown in Figure 46, there are very few suitable sites in Northern Europe. Most of these sites are far from the coast. This means that most of the water being used for power storage would have to be drawn from the global fresh water hydrological cycles.

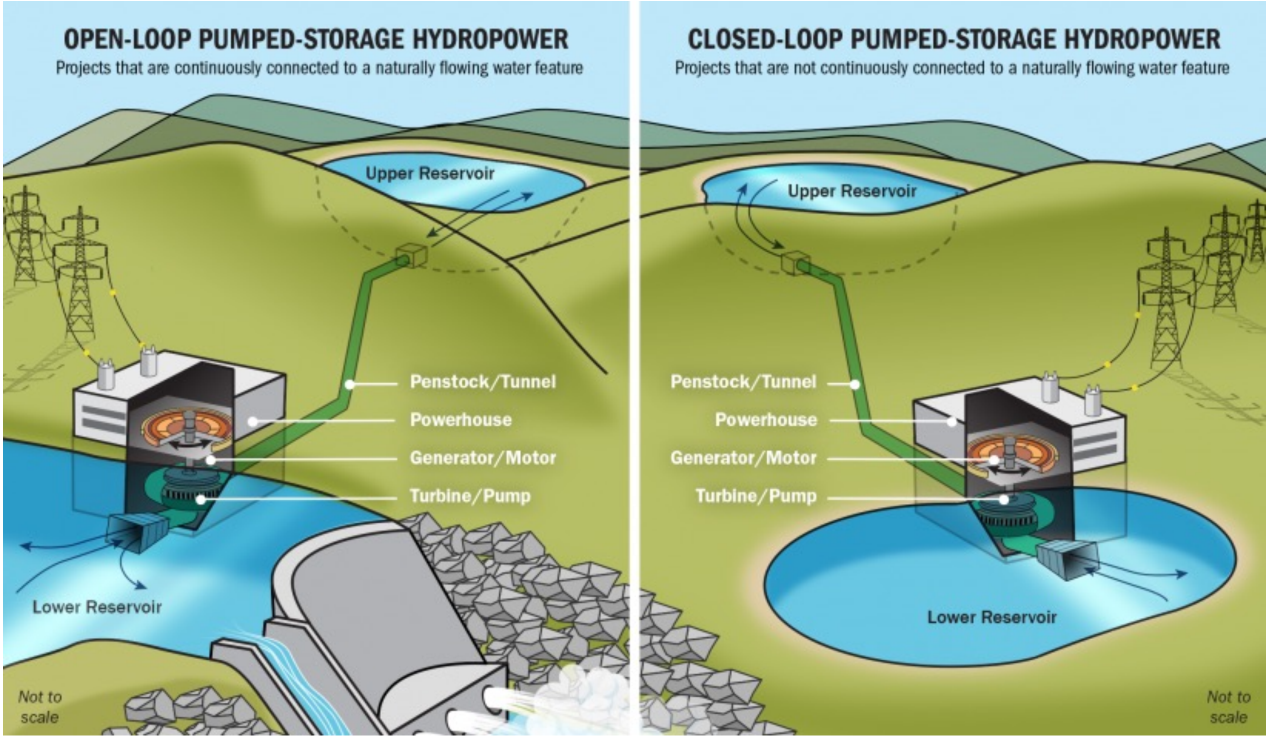

Fig. 45. Pumped-Storage Hydropower (Source: United States Department of Energy 2024) (Copyright License: https://www.energy.gov/about-us/web-policies).

Fig. 46. 530 000 potential pumped-hydro sites worldwide (Source: Matthew Stocks, ANU Research School of Electrical, Energy and Materials Engineering (RSEEME), Blakers et al. 2021).

Consider each of the modelled power storage capacities shown in Table 43 used as power storage capacities in a pumped hydro power station. The volume of water required to be stored then passed through the turbines was estimated of each capacity. As an average example of a pumped hydro power station, a flow of 100 m^3 of water per second through a turbine/generator operating at 90% efficiency in a system with a head of 570 m will yield electrical power of 500 MW (Blakers et al. 2021).

This results in a required 360 000 m^3 of water per 500 MWh (or 720 m^3/MWh) of energy produced. This production rate was applied to the capacities in Table 43, resulting in Table 44 and Figure 47. The calculations in Table 43 are for how much water would have to be collected. It could be assumed that once collected this water could just be recycled from upper and lower reservoirs. However, most of the sites shown in Figure 46 are not appropriate for this and have only one storage reservoir near a river. The water gets used just once and is then released back into the water shed.

Table 44. Estimated volume of water required for different capacities of power buffer storage in pumped hydro station reservoirs.

Application 	**2018 global annual fresh water withdrawal** (km^3)	**Required extra water to deliver 25.7 TWh of pumped hydro power storage** (km^3)	**Required extra water to deliver 226.1 TWh of pumped hydro power storage** (km^3)	**Required extra water to deliver 2 878.0 TWh of pumped hydro power storage** (km^3)	**Required extra water to deliver 8 634.1 TWh of pumped hydro power storage** (km^3)
Agriculture	2760				
Municipal	450				
Industry	300				
Power Generation	372				
Primary energy production	90				
Size of Power buffer storage capacity		6 hours	48 hours + 10%	28 days	12 weeks
Reference		(Larson et al. 2021)	(Steinke et al. 2012)	(Droste-Franke 2015)	(Ruhnau & Qvist 2021)
Estimated volume of water required	3 990	22,8	201,0	2 558,2	7 674,8
Proportion comparison to annual fresh water withdrawal of 3 990 km^3		0,6%	5,0%	64,1%	192,3%

The majority of these sites, even if they are viable to store water (this is probably speculative as it is not clear that any of these sites have been assessed with an engineering feasibility study to build dams), would store water next to an open source like a river. It was not clear from the study to show whether any of these sites are paired. As in two sites that could exchange water at all, let alone in the same volumes. Thus, would have water stored in them from a source like a river, then re used later. Water goes in, then goes back out to the open source. So most if not all these sites would need constant refilling of fresh water. The water would be fresh as these sites are far from the coast. While this water is being stored for energy generation, it is not being used for drinking water. The environmental impact of having such a large quantity of water being held static has not been done but clearly would be serious. The size of the water draw was the calculation.

As can be seen in Figure 47 and Table 44, the required additional fresh water for power storage if pumped hydro is used would impact the existing global freshwater withdrawals with significant extra demand. To put this in historical context the global annual water withdrawals from the planetary freshwater hydrological cycle over the last 113 years. As can be seen in Figure 48, freshwater consumption by the human species in the last few years has been at an unprecedented high.

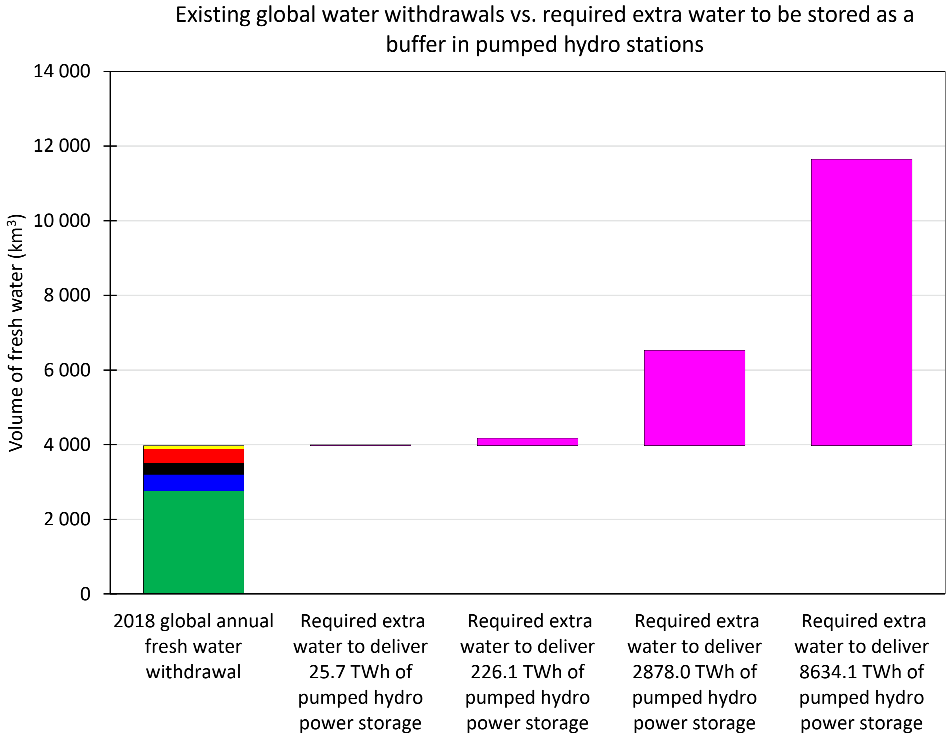

Fig. 47. Estimated volume of water required for different capacities of power buffer storage in pumped hydro station reservoirs (Source: WWAP 2019).

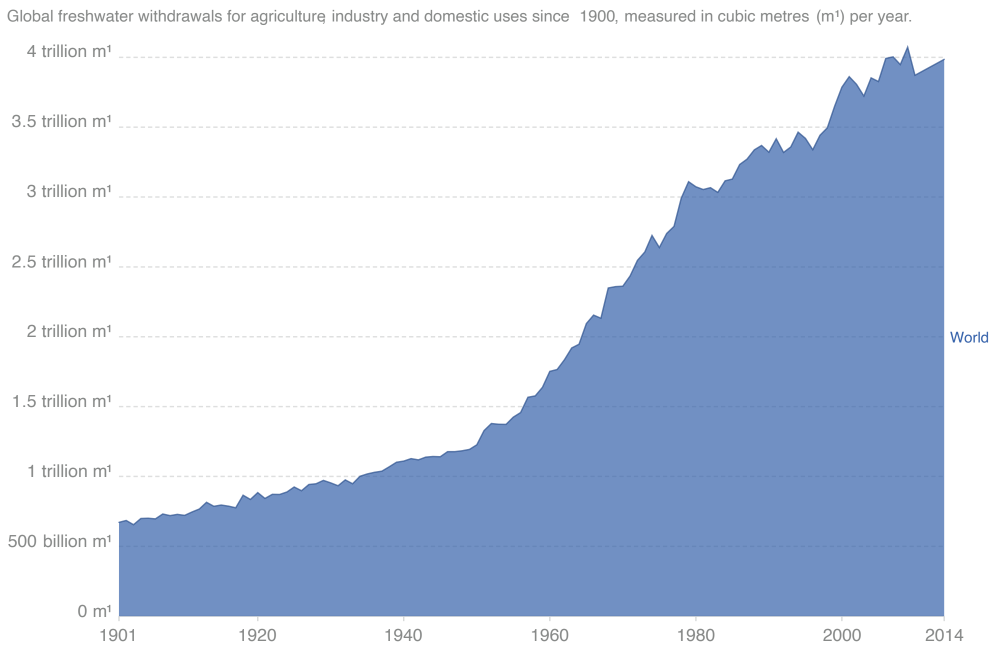

Fig. 48. Global freshwater use between 1900 and 2014 (Source: Our World in Data 2024, Hannah Ritchie and Max Roser (2017) – "Water Use and Stress". Published online at https://ourworldindata.org/ Retrieved from: 'https://ourworldindata.org/water-use-stress' [Online Resource]).

To put the required additional 4 trillion m³ (3 990 km³) freshwater to produce biofuels in context, consider how much of the existing human population that are already experiencing water supply stress. According to a United Nations study on global water demand (United Nations 2019, WWAP 2019), over 2 billion people live in countries experiencing high water stress in 2018.

This thought experiment did not account for the logistical difficulties associated with rezoning such a large area of land away from current land use to become water storage dams. Then there is the infrastructure needed to connect these ideal locations (in context of water storage) with the not so ideal sites where the majority of the proposed renewable power stations would be located. Power generated at these wind and solar power stations would have to be transferred to the pumped hydro station to store water, and have that energy returned as it is generated. These distances involved for this are unknown but would most certainly be very large. While pumped hydro power storage has its place, it is impractical to scale up to become the primary energy storage for such a large quantity of energy. This study also did not account for the environmental impact of disrupting the flow of such a large proportion of the hydrological cycle.

Pumped hydro power storage is the cheapest method of storing power at the time of writing this paper. It will be part of the future energy mix, and it has its place. However, such a large increase in potable water demand, as shown in Figure 47 and Table 44, is unlikely to be feasible for the task of managing intermittent power generation from wind and solar stations.

20.3 Hydrogen used as power storage

It has been proposed to use hydrogen as a power storage system (Kavadias et al. 2017, Zang et al. 2016, Rivard et al. 2019, Zuttel 2004). The proposed methods of power storage would be electrical power which is generated to produce hydrogen, which is then stored. Later, this hydrogen is used to generate electrical power when it is needed, to balance intermittent supply of electrical power from wind and solar stations. So, an understanding of how much hydrogen would be needed ahead of time. That hydrogen would have to be produced, stored, then consumed to make electricity to be delivered to the grid. That electricity is then transported to where it would be needed, at the solar or wind power station harvesting point in the grid. This does not account for losses during storage or maintenance issues of infrastructure becoming brittle due to hydrogens storage. It does not account for hydrogen transport if it would be required. The calculations resulting in Table 45 are shown in Annex I.

Assumptions in these calculations were as follows:

- Each 1 kg of H_2 can produce 15 kWh of electricity (IEA 2018, EIA 2024a, Thomas 2018)
- It requires 52.5 kWh to produce 1kg of hydrogen and compress it into 700 bar storage tanks (IEA 2018, EIA 2024a, Thomas 2018)

Hydrogen faces practical issues when considered by used as a power storage. The amount of electricity required to produce enough hydrogen to operate as a store of energy is 3.85 times the electrical power that could be delivered from the stored hydrogen once accessed (Table 45).

Table 45. Summary of mass of hydrogen needed and electrical power capacity to deliver power storage buffer.

Storage capacity to manage intermittent power supply from wind and solar	Electrical power to be stored and then delivered back to the grid (TWh)	Quantity of hydrogen required, where energy density of H2 is 15 kWh/kg (million tonnes)	Electicity production accounting for a 10% loss in transmission (@52.5 kWh/kg to produce hydrogen) (TWh)	Increase in power generation assuming 48 939.8 TWh is required annualy (%)	Wind and solar power that will require further buffer support (TWh)
6 hours	25,7	1,7	98,9	0,2%	19,7
48 hours +10%	226,1	15,1	870,6	1,6%	173,4
28 days	2 878,0	191,9	11 080,5	20,5%	2 206,3
12 weeks	8 634,1	575,6	33 241,4	61,4%	6 618,9

If it requires 52.5 kWh to produce 1 kg of hydrogen (then add 10% to account for transmission loss between powers station and application), and then getting 15 kWh of electrical energy in return, then using hydrogen as an energy storage has a round trip efficiency of 26%. Table 45 shows that the global electrical power generation system would have to expand as much as 61.4%, if hydrogen was used as a power storage buffer. Hydrogen as an energy storage system may well have its place, like so many other renewable energy technologies, but it is unlikely to be scalable to become the primary energy storage system needed to manage wind and solar power generation systems.

20.4 Size and capacity required for stationary power storage

As discussed previously, PHS and hydrogen power storage technologies work quite well in small systems but face logistical practical issues when those technologies are scaled up. It is postulated that PHS and hydrogen will not work at a large scale of electrical power supply over a period of several months. Battery banks thus far are still scalable. Senior members of the European Commission and civil servants from multiple governments around the world informed the author that it was a strategic policy that all new power storage requirements would come from the commissioning of battery banks in some form. This was a firm statement. What was open to debate was the chemistry of the batteries involved.

For the purposes of this study, power buffer storage for the proposed global electricity grid was modelled with four capacities, for just wind and solar power generation management. It was assumed that this power buffer would probably take the form of a battery bank, based in a range of battery chemistries. Table 46 shows the outcomes of a study done to examine the different types of stationary power storage (EMA 2020). This study examined a range of technology options in context of several performance metrics. It was concluded that a battery bank of some form would be the most favorable and preferred technology to use. Super capacitors were considered impractical due to the time required to store the power before using.

Table 46. Techno-economic parameters of ESS Technologies (Source: EMA 2020).

More favorable

Parameter	Flywheel[(a)]	Super Capacitor[(b)]	Lead Acid Battery[(c)]	Lithium-ion Battery[(c)]	ZEBRA (NaNiCl) [(c)]	Flow Battery[(c)]
Efficiency* (%) (DC+AC)	70-95	80-95	70-75	85-90	80-85	65-70
Response (seconds)	0.25	0.016	0.1-1	0.1-1	0.1-1	1-10
Lifetime (cycles to 80% DOD)	100K	100K	0.5K-0.9K	2K-4K	3.5K	10K
Lifetime (years)	20	40	3	10	10-15	15
CAPEX (DC+AC) (USD/kW)	1080-2880	835-930	1430-2522	1570-2322	2810-5094	2742-5226
CAPEX (DC+AC) (USD/kWh)	4320-11520	66K-74K	358-631	393-581	703-1274	686-1307
Energy Density (Wh/L)	20-80	10-20	50-90	200-800	170-190	20-70
Power Density (W/L)	5000	40K-120K	90-700	100-10K	250-260	0.5-2
Self-discharge per day (%)	1.3-100	20-40	0.1-0.3	0.2	1-14	0.2
Typical charging rate* [10], [11],[12]	N.A.	N.A.	0.1-0.3 C	0.2-0.8 C	0.1-0.15 C	0.1-0.15 C

(a) E/P = 0.25 h, (b) E/P = 0.0125h, (c) E/P = 4 h

Note: E/P refers to Energy to Power Ratio which represents the discharge duration of the ESS.

- 4 hours discharge period was chosen for lead acid, lithium-ion, ZEBRA and flow battery as 4 hours represents the transition point between short term discharge period (less than 4 hours) and medium term discharge (4 to 8 hours).
- Flywheel and supercapacitor are more suited to power intensive applications, and smaller discharge durations are chosen as indicated.
- *Actual charging rates vary with manufacturer specification to improve system lifetime. Special chemistries under each category can have different C rates (for example, lithium-titanate oxide (LTO) can charge at high rates 2 – 10 C).

Battery bank systems were seen as very practical, could be deployed in any geographical location, in any weather conditions, and in any scale or footprint. Other technologies like flywheels, compressed air, and super capacitors all had their place but faced engineering logistical challenges to scale them up in capacity. As already shown, pumped hydro and hydrogen face practical limitations in scaling up to the full capacity needed shown in Table 44.

An example of a large battery storage power station was the Australian Hornsdale Power Reserve, adjacent to the Hornsdale wind farm, built by Tesla (Parkinson 2017a,b). The plant is operated by Tesla and provides a total of 129 megawatt-hours (460 Gigajoules) of storage capable of discharge at 100 MW into the power grid. For this paper, it is now assumed that all new power storage stations will be one of these 129 MWh battery stations. Tables 47 to 50 show the number of stationary power storage stations that would be needed in context of each of the four capacities modelled in Table 43.

Table 47. Estimated stationary power storage buffer and number of 100 MW/129 MWh power storage stations, for a 6 hour capacity.

Power Generation System	**Expanded extra required annual global capacity to phase out fossil fuels** (TWh)	**Storage capacity for a 6 hour period to manage intermittent power supply from wind and solar** (Larson et al. 2021) (TWh)	**Number of 129 MWh capacity power storage stations to meet power generation in a 6 hour cycle** (number)
Wind	18 758,7	12,8	99 600
Solar PV	16 884,3	11,6	89 648
Solar Thermal	1 874,4	1,3	9 952
Total		25,7	199 200 storage stations

Table 48. Estimated stationary power storage buffer and number of 100 MW/129 MWh power storage stations, for a 48 hour + 10% capacity.

Power Generation System	**Expanded extra required annual global capacity to phase out fossil fuels** (TWh)	**Storage capacity for a 48 hour +10% period to manage intermittent power supply from wind and solar** (Steinke et al. 2012) (TWh)	**Number of 129 MWh capacity power storage stations to meet power generation in a 48 hour +10% cycle** (number)
Wind	18 758,7	113,1	876 480
Solar PV	16 884,3	101,8	788 900
Solar Thermal	1 874,4	11,3	87 579
Total		226,1	1 752 959 storage stations

As can be observed the infrastructure required is enormous. The size of the buffer needed is perhaps the most sensitive parameter in this study.

Table 49. Estimated stationary power storage buffer and number of 100 MW/129 MWh power storage stations, for a 28 day capacity.

Power Generation System	**Expanded extra required annual global capacity to phase out fossil fuels** (TWh)	**Storage capacity for a 28 day period to manage intermittent power supply from wind and solar** (Droste-Franke 2015) (TWh)	**Number of 129 MWh capacity power storage stations to meet power generation in a 28 day cycle** (number)
Wind	18 758,7	1 439,0	11 155 196
Solar PV	16 884,3	1 295,2	10 040 549
Solar Thermal	1 874,4	143,8	1 114 646
Total		2 878,0	22 310 391 storage stations

Table 50. Estimated stationary power storage buffer and number of 100 MW/129 MWh power storage stations, for a 12 week/84 day capacity.

Power Generation System 	Expanded extra required annual global capacity to phase out fossil fuels (TWh)	Storage capacity for a 12 week period to manage intermittent power supply from wind and solar (Ruhnau & Qvist 2021) (TWh)	Number of 129 MWh capacity power storage stations to meet power generation in a 12 week cycle (number)
Wind	18 758,7	4 317,1	33 465 587
Solar PV	16 884,3	3 885,7	30 121 648
Solar Thermal	1 874,4	431,4	3 343 939
Total		8 634,1	66 931 174 storage stations

21 SENSITIVITY ANALYSIS OF TOTAL POWER CAPACITY REQUIRED TO PHASE OUT FOSSIL FUELS

A sensitivity analysis was conducted on the entire data set to assess the influence of each parameter to the annual electrical power generation requirements. One parameter at a time was changed, then the full calculation was done again. This was done to assess the influence of each parameter. Some parameter changes were made to reflect a possible policy change. For example, if annual steel production increased 500% (Sensitivity Scenario R), to support the industrial reform of the fossil fuel technology system. The sum total of the additional annual electrical power generation requirement to be developed was compared to the baseline of 48939.8 TWh. All examined scenarios are described below and Annex I shows the data.

Scenario A: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were reduced by 50% to a fleet size of 693.8 million vehicles, which would annually travel 7.13 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles.

Scenario B: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were reduced by 90% to a fleet size of 167.7 million vehicles which would annually travel 1.43 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles.

Scenario C: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were increased by 200% to a fleet size of 2.78 billion vehicles annually travelling 28.50 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles. This Scenario was developed to examine what impact a larger EV fleet might have on material demands. The size of the transport fleet is projected to grow 2.4 times between 2018 and 2050 (IEA 2021a).

Scenario D: The 28.9 million HCV Class 8 trucks were assumed to be EV, instead of H_2-Cell vehicles. The entire EV fleet now includes HCV Class 8 trucks + passenger cars + commercial vans/light trucks + buses + motorcycles (1.416 billion vehicles annually travelling 16.26 trillion km).

Scenario E: The existing fleet of 19 million buses, which annually travelled 560.8 billion km, was assumed to be expanded by 300% and were all assumed to be EV (58 million buses annually travelled 1.68 trillion km).

Scenario F: The existing fleet of 28.9 million HCV Class 8 trucks were assumed to be H_2-Cell vehicles and reduced by 50% in size (14.4 million H_2-Cell Class 8 trucks annually travelled 829 billion km).

Scenario G: The existing fleet of 28.9 million HCV Class 8 trucks were assumed to be H_2-Cell vehicles and increased by 200% in size (57.8 million H_2-Cell Class 8 trucks annually travel 3.31 trillion km). This Scenario was developed to examine the growth of the consumption of materials goods. The just-in-time supply grid would have to become large and more complex. Trucking transport would be just one input into a possible future study.

Scenario H: The existing rail transport network is expanded 300%. It was assumed that all new trains were H_2-Cell fueled electrical systems. One of the solutions to the challenge of phasing out fossil fuels is to restructure our society, where communal transport became much more important. Rail, metro, and buses would all significantly increase, and the use of personal vehicles would significantly decrease.

Scenario I: The maritime shipping fleet was reduced to by 10% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 10% fewer vessels and 10% less total distance travelled by shipping.

Scenario J: The maritime shipping fleet was reduced to by 50% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 50% fewer vessels and 50% less total distance travelled by shipping.

Scenario K: The maritime shipping fleet was reduced to by 90% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 90% fewer vessels and 90% less total distance travelled by shipping.

Scenario L: If Ammonia production was reduced by 50%, where in this study, it was tasked to fertilizer production, and ammonia fuel production for 46% of the maritime shipping fleet.

Scenario M: If Ammonia production was reduced by 90%, where in this study, it was tasked to fertilizer production, and ammonia fuel production for 46% of the maritime shipping fleet.

Scenario N: If Ammonia production was increased by 200%. This scenario was to examine the impact of a larger human population, that is increasingly dependent on petrochemical supported industrial agriculture, to supply food production.

Scenario O: The quantity of steel produced annually is reduced by 50%. It was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology (which is reported to be more efficient than conventional coking coal systems).

Scenario P: The quantity of steel produced annually is reduced by 90%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology.

Scenario Q: The quantity of steel produced annually is increased by 200%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology. Scenarios Q and R were assembled to examine what would happen if construction was stepped up in annual capacity. To phase out fossil fuels, a new system will have to be built around the replacement technology, using a completely different set of metrics. This would require an unprecedented demand for raw materials of all kinds, steel, and concrete in particualr (which are often used as proxies for industrialization).

Scenario R: The quantity of steel produced annually is increased by 500%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology.

Scenario S: Global building heating, now delivered with heat pumps, was reduced by 50%.

Scenario T: Existing conventional electricity demand was reduced by 50%. This includes all electrical demands (domestic and industrial) in 2018, where fossil fuel systems were fueling the vast majority of the transport fleet.

Scenario U: Existing conventional electricity demand was reduced by 90%.

Scenario V: Existing conventional electricity demand was increased by 200%. This Scenario was developed to see the impact of a significant increase in electrical demand. This study was founded in the paradigm to map the industrial system as it is currently (in 2018), then substituting with non fossil fuel technology to maintain the existing society. A non fossil fuel world will be different. If it will be founded in electrical technology (where we are currently founded in fossil fuel technology), then how that society will function will be different in form and complexity. It could be possible that an electrical non fossil fuel technology system would need more electrical power to service its many networks. We may need proportionally more electricity per capita than we do now.

Scenario W: Existing conventional electricity demand was increased by 300%.

Scenario Mu: Scenario Mu (μ) is a hybrid of different other scenarios. This scenario was to assemble a profile of data that shows the implications of sharp degrowth of societal footprint, in conjunction of a fundamental restructure of society and the construction of the post fossil fuel industrial society. This was to map out what a sharp degrowth of the system would look like as per recommendations from The Limits to Growth study (Meadows et al. 1972), and to fully replace all fossil fuel technology systems. Electricity demand for conventional applications would contra§ct. The number of passenger cars and the distance they travelled would contract. Communal transport would become much more prominent and important (buses would expand greatly). Rail transport would become more important in the movement of physical goods, and the manufacture sector would relocate to be directly on a train line. So, rail would have to expand greatly. Manufacture would reduce its global dependency and become more regional. This resulted in a reduction in the maritime shipping transport of physical goods. In addition to this, society would reorganize itself around a different energy and transportation system. This means the retooling, and reconstruction of the industrial system across the full value chain, of the largest, most complex and sophisticated society the world has ever known. This will require the consumption of unprecedented quantity of raw materials and metal. Vast amounts of steel and concrete will be needed in quantities never seen before. To reflect this steel manufacture would greatly increase. The parameters selected for Scenario Mu may well be too small in size, and this Scenario really is a ranging shot to develop a more appropriate study. The parameters changed for Scenario Mu were as follows:

- Class 8 HCV trucks reduced by 50%. So, the existing fleet of 28.9 million H_2-Cell fueled HCV Class 8 semi-trailer trucks that traveled 1.66 trillion km (in 2018), would contract to 14.5 million H_2-Cell fueled HCV Class 8 semi-trailer trucks that would annually travel 828.7 billion km.
- Delivery trucks (Rigid) reduced by 50%. So, the existing fleet of 9.6 million delivery trucks, which annually travelled 250 billion km, reduces to 4.8 million buses which would annually travel 127 billion km, and were all assumed to be EV's.
- Rail transport increased by 300%.
- Buses increased by 300%. The existing fleet of 19 million buses, which annually travelled 560 billion km, expands to 58 million buses which would annually travel 1.68 trillion km, and were all assumed to be EV's.
- Commercial vans and light trucks reduced by 40%. The existing fleet of 601.3 million commercial vans and light trucks, which annually travelled 8.07 trillion km, contracted to 360.8 million vehicles that would instead annually travel 4.84 trillion km, and were all assumed to be EV's.
- Passenger cars reduced by 70%. The existing fleet of 695.2 million passenger cars, which annually travelled 5.6 trillion km, contracted to 208.6 million vehicles that would instead annually travel 1.67 trillion km, and were all assumed to be EV's.
- Motorcycles reduced by 70%. The existing fleet of 62.1 million motorcycles, which annually travelled 163.7 billion km, contracted to 18.6 million vehicles that would instead annually travel 49.1 billion km, and were all assumed to be EV's.
- Maritime shipping reduced by 60%. The existing base line study had a maritime fleet of 116 857 vessels where 17% were fueled by hydrogen (needing 844.9 TWh annually, reduced to 338 TWh), 46% fueled by ammonia (needing 3903.1 TWh annually, reduced to 1 561.3 TWh), and 37% biofuels (needing 477.5 million tonnes of soy biomass, reduced to 191 million tonnes of soy biomass).
- Steel production increased by 300%. Existing annual production of steel (1 808.6 million tonnes for the year 2018) in a hydrogen atmosphere would require an estimated 6 939.2 TWh, where each tonne of steel requires 3 488 kWh, giving a total of 20 817.6 TWh.
- Conventional electrical power reduced by 50%, from 17 086.1 TWh to 8543.1 TWh
- Nuclear power accounts for 20% of the energy power generation mix.

This gives a total annual electrical demand for Scenario Mu of 48 988.5 TWh, of which steel production accounts for 42.5% (20 817.6) TWh. Table 51 and Figure 49 summarizes the outcomes of Annex I. As can be observed the biggest change was the result in changes to electric demand for existing consumption activities. The second most influential parameter was the amount of steel to be produced. To replace the existing fossil fuel industrial system will require a fundamental transformation, which will consume resources like steel. The third influential parameter was the size and activity of the Class 8 HCV truck transport fleet.

Table 51. Summary of sensitivity analysis of applications for power consumption – Part I.

Application Task		Sensitivity Scenario	Average change from base line
Electirc Vehicle Fleet		A, B, C, D, E	-1,75%
Hydrogen fueled trucks		F, G	3,57%
Hydrogen fueled rail		H	3,24%
Maritime shipping		I, J, K	-6,64%
Steel production Hydrogen		L, M, N	-0,69%
Ammonia production Hydrogen		O, P, Q ,R	12,76%
Building heating		S	-2,88%
Conventional electricity demand		T, U, V, W	13,96%
Degrowth + Reconstruct Society		Mu	0,10%

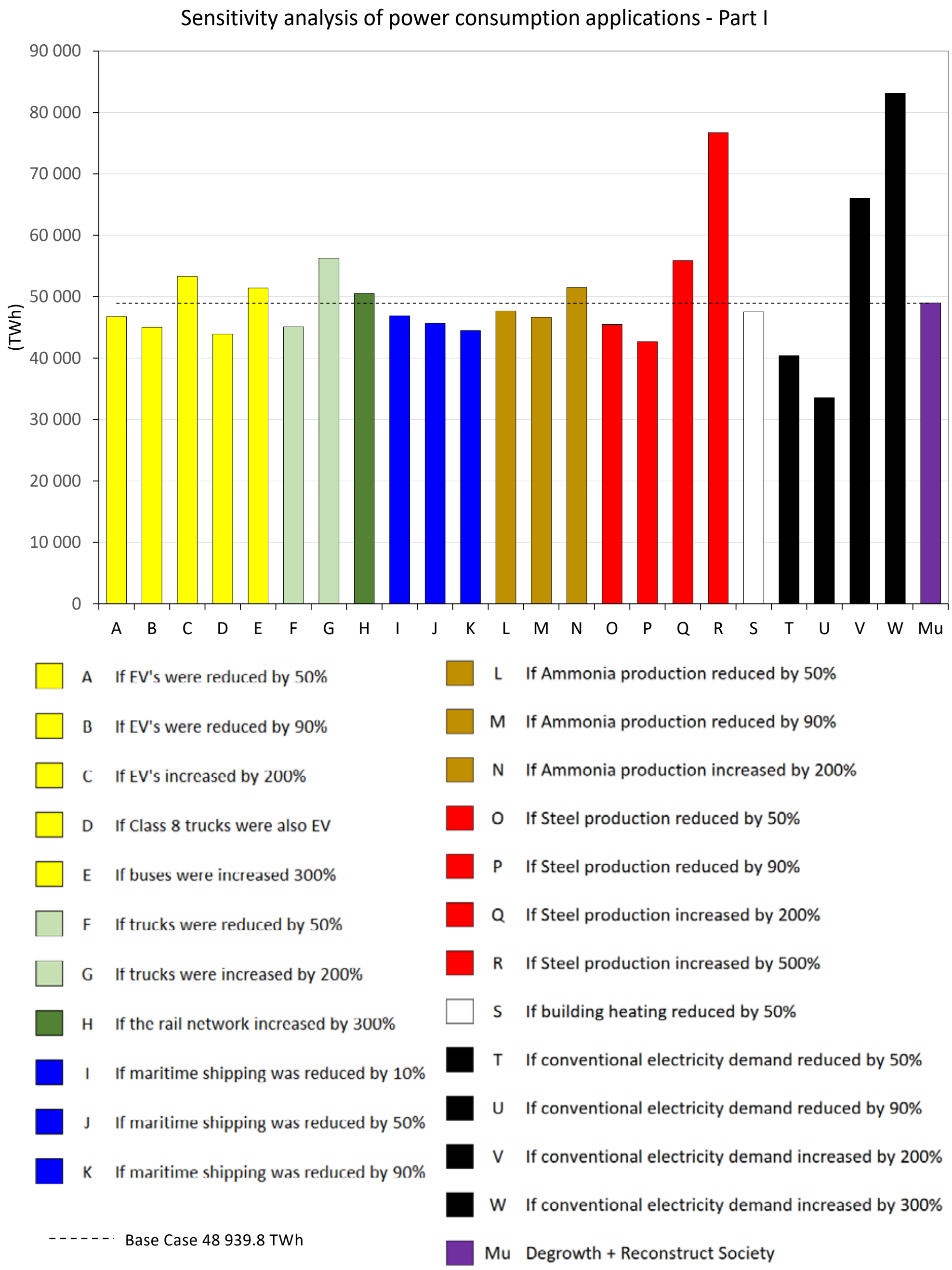

Fig. 49. Sensitivity analysis of power consumption applications – Part I (Part II is in another paper).

As discussed, the network of calculations in this paper was subject to a sensitivity analysis with a series of scenarios, each one reflecting a single large change in input parameters (Table 51 and Fig, 49). The outcomes were interesting. The following are the parameters that changed the total power needed to phase out fossil fuels, in order of influence.

1. The biggest change by far happened when conventional electrical power demand expanded or contracted (Scenarios T to W). Conventional demand was contracted as much as by 90% or increased by as much as 300%. Remember on one hand society must become more efficient and reduce its footprint. On the other hand, electrifying all industrial actions and activities will require more electricity. The outcome of scenarios T to W resulted in change between -17.46% to 70% in total electrical power needed.
2. The second largest change was expanding or contracting the annual production of steel (Scenarios O to R). Annual steel was contracted by 90% and then increased by 500%. The rationale for this was that to phase out fossil fuels, the whole of society would need to be to redesigned and reconstructed, needing an unprecedented quantity of raw materials, steel in particular. The outcome of Scenarios O to R resulted in change between -7.09% to 56.72% in total electrical power needed.
3. Scenarios F and G examined what would happen if the hydrogen fueled heavy truck fleet changed in size (-50% to +200%). This was pertinent as trucks form a vital part of our industrial system (Friedemann 2016). The outcome of Scenarios F and G resulted in change between -7.84% to 14.98% in total electrical power needed.
4. Scenarios I, J and K examined what would happen if the hydrogen fueled maritime shipping fleet was reduced by as much as 90% in size and distance travelled. The outcome of Scenarios I, J and K resulted in change between -4.19% to 9.09% in total electrical power needed.
5. Scenarios L, M and N examined fluctuations (-50+200%) in the production of ammonia. The outcome of Scenarios L, M and N resulted in change between --2.60% to 5.20% in total electrical power needed.
6. Scenario H examined a 300% increase in the size and activity of the rail transport network. The outcome was just a 3.24% change in total power needed.
7. Scenarios A to E examines what would happen if the size of the EV fleet changed (from -90% in size of the full fleet to a 200% increase). The outcome of Scenarios A to E resulted in change between -4.45% to 5.06% in total electrical power needed. This is a very small output change for a very large input change. The number of EV's was not very influential at all on the total electrical power needed.

Scenario Mu represented an opportunity to examine what a serious attempt at a system contraction, as has been recommended by many studies inspired by the Limits to Growth publication (Meadows et al. 1972, Taylor 2008) would look like. To achieve such a radical restructure of society, a massive redesign, retooling and construction of every part of society would have to be undertaken. This would take decades and require an unprecedented demand of energy and raw materials of all kinds. Transport would have to be reinvented. The annual consumption of steel and cement would be much more than it is now. Individual passenger car ownership would have to be phased out in place of communal transport like trains and buses. This combination of system contraction (resulting in less energy demand) and massive reconstruction (resulting in more energy demand) would to some extent cancel each other out. Figure 50 shows a direct comparison between the Base Case and Scenario Mu annual power demand. For Scenario Mu, the whole system (excluding steel production) contracted 32.9%. The passenger car fleet was contracted by 70%, commercial vans was contracted by 40%, and trucks was contracted by 50%. Conventional electricity demand was contracted by 50%. These cuts are enormous. However, they were counterbalanced by an expansion of communal transport expanding by 300% (buses and rail).

The expansion of steel production by 300% was a very conservative estimate of society reconstructing itself very quickly (steel production is an excellent proxy for industrialization).

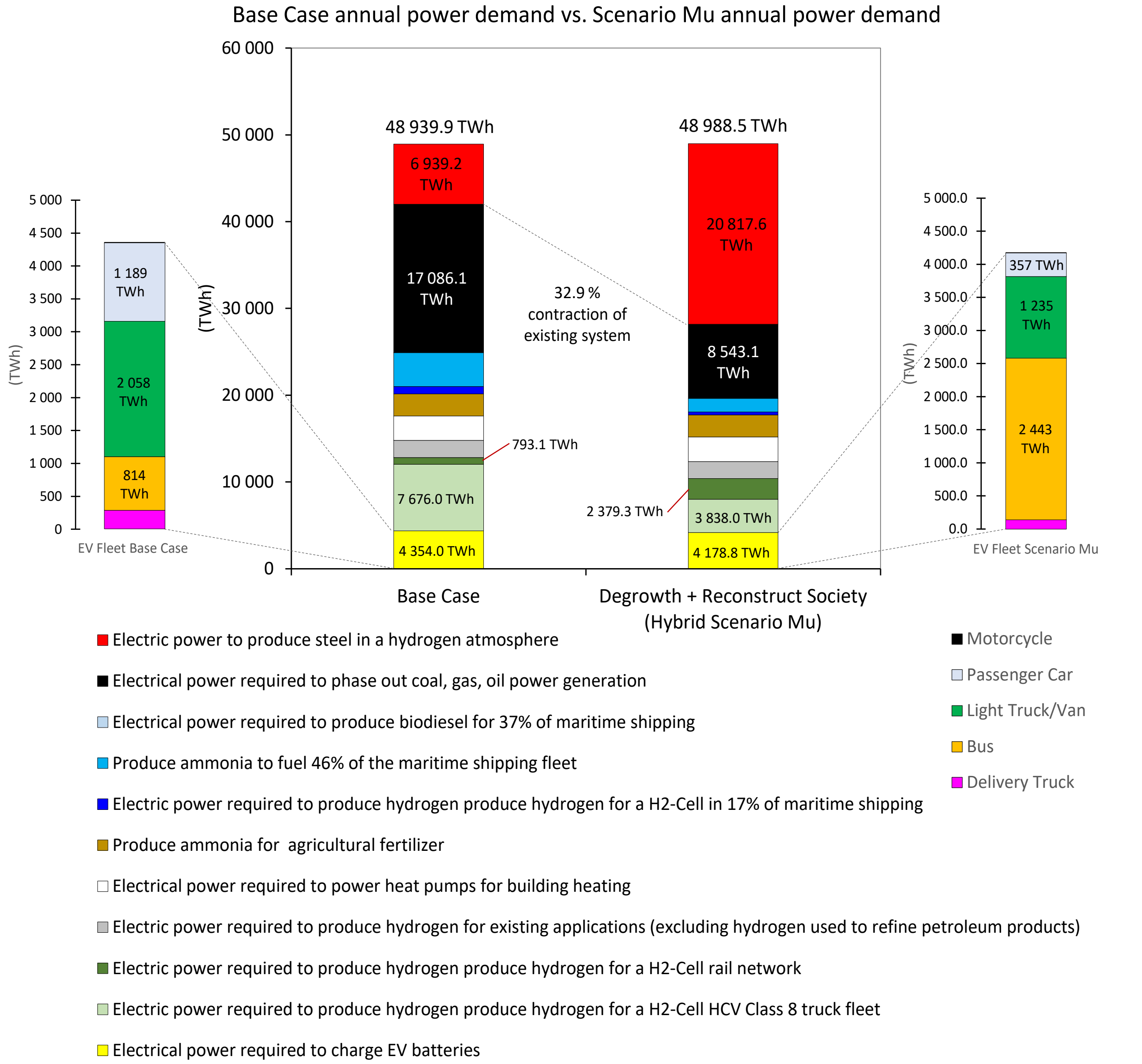

Fig. 50. Electricity demand comparison between the Base Case and Scenario Mu (Degrowth + Reconstruction).

This was a very crude thought experiment. It does show however that attempts to contract the system in degrowth will not operate like it is hoped.

22 DISCUSSION

This study examines what a complete phase out of fossil fuels would entail. The most sophisticated prediction for what the future energy mix might be and what technology units might make up the market available at the time of writing was published by the International Energy Agency (IEA). These predictions are what was used to calculate the numbers in this paper. Whether the outcomes are practical or even possible have not been discussed.

In this paper, the results and numbers quoted often have more decimal places, or more significant figures than is appropriate for such a broad calculation. The reason this is done is that so the reader can audit these numbers and recreate the numbers published here. If all of the calculations were quoted with fewer significant figures (for example needed additional global solar PV capacity of 17 000 TWh, where the actual calculation was 17 463.4 TWh), and those rounded figures were used to recreate the shown calculation path, then the final numbers would be different due to rounding errors and propagation of error. It is for this reason that so many tables have been included in the main paper body, each with numbers presented the way they are.

It was proposed that an extra 16 884 TWh of solar PV capacity would be added to the 2018 global solar capacity of 579 TWh (Tables 38 & 39), resulting in global solar PV capacity of 17 463.4 TWh. This addition is more than 29 times the existing Solar PV capacity. It was proposed that an extra 18 758.7 TWh of wind turbine capacity would be added to the 2018 global wind turbine capacity of 1 303.8 TWh (Tables 38 & 39) resulting in global wind turbine capacity of 20 062.5 TWh. This addition is more than 14 times the existing wind turbine capacity. This study uses a future energy mix based on an IEA prediction of what it might be in 2050. This proposes a proportion of 76.7% (wind, solar PV and solar CSP thermal) of the total mix, where the IEA proposed 68.2% (IRENA 2022 and Table 37). These wind and solar systems are so large, that they would be required to be self-sufficient in context of balancing supply and demand. This is a logistical and engineering challenge that society has not achieved yet and may not understand what is required.

To date, renewable power systems (like wind) have been balanced with power from external power grids through power sharing agreements as shown in Figure 43. Currently, the electrical grid balances power generation against demand load with the use of inter-grid sharing of power. Most of the time, this has happened with the flexible of use of fossil fuel power generation systems, natural gas in particular. In a future non-fossil fuel network this may not be practical. As wind and solar power generation are highly intermittent, they require a power storage buffer to be viable. The size of that power storage buffer at this time is still unknown, with little agreement in the literature. Proposed power buffer sizes of 4 to 8 hours (Larson et al. 2021 and Jacobson et al. 2022) are not large enough as they only account for day-to-day fluctuations in difference of supply and demand (Section 19), and do not account for long term power generation capacity for wind and solar systems (Sections 17 and 18). The seasonal differences in solar radiance (winter vs summer) mean that solar power would have to be collected over a several months (summer, variable to geographical location), stored for several months, then released slowly again over several months (winter). The closer to the geographical poles, the more extreme this would become. How large a storage capacity to achieve this is not clear. It is entirely possible that the 28 days selected for this study is inadequate, and something to the scale of 12 weeks might be needed. The difficulty here is that the technology to store such a large amount of power for so long may not be technological feasible, let alone economically viable at this time (Menton 2022). If this power buffer is not able to be constructed in practically useful manner, then wind and solar are not viable as a large scale power generation systems. A solution could be to develop an electrical engineering technology that could cope with variable power supply (current, voltage and frequency all variable) and also with regular shutdowns without damage. If this was achieved, the need for a power storage buffer may not be necessary.

It was proposed in this study that an extra 6 538.4 TWh of hydroelectricity capacity would be added to the 2018 global hydroelectricity capacity of 4 193 TWh (Table 39), to have a total global annual hydroelectric capacity of 10 731.5 TWh. This is more than double existing capacity. It would involve the construction of 4 932 average size hydro stations, where the average installed capacity was 225.4 MW (Table 38 & 39). Is this even possible? To site a hydroelectric power station, certain geographic conditions need to be met (river size, water speed, water depth, etc.). Are so many such sites available? Is this ecologically sustainable, or logistically sensible, let alone economically feasible?

Currently, the nuclear industry is struggling to replace nuclear power plants to replace older decommissioned units (World Nuclear Association 2019). The nuclear value chain requires development. The front end of the nuclear cycle (manufacture of nuclear fuel rod assemblies) is dominated by a very small number of countries. If the nuclear industry is to expand, then more production capability for the support functions is required in more places around the world. The back end of the nuclear fuel cycle is serious under resourced and not taken seriously enough at the current size of Nuclear Power Plant (NPP) fleet. Handling and storage facilities for the storage of Spent Nuclear Fuel (SNF) need to be constructed in a much greater capacity. Currently it takes approximately 25 years incubation time (with 7 years actual construction) to permit, construct and commission a single nuclear power plant. Given all that, is it feasibly to expand the current global NPP fleet an extra 287 average size stations? How long would this take? This suggests that the fleet of conventional uranium fueled Light Water Reactors will not be able to be expanded fast enough to be useful due to the complex nature of the current nuclear fuel cycle. An evolution of the nuclear power generation technology that does show promise is the liquid fuel fission systems that use a thorium fluoride salt as a fuel (ORNL 1972). This topic was too complex to include in this study and will be the subject of future work.

The business model behind the current industrial system and the economy it serves relies on continuous growth to function (Martenson 2011). Human population growth is predicted grow from 8 billion in 2022 to more than 11.2 billion in 2100 (World Bank 2018). The demand for electricity in 2050 is predicted to be more than 3 times what it was in 2018 (Fig. 2.3 from IRENA 2022 and Fig. 31 in this paper). Yet many strategic plans for the future (for example the Transforming Energy Scenario (TES) in IRENA 2020) predict a preferred decline in industrial energy intensity, and over all contraction in quantity of energy consumed over the next few decades and assumes this will continue to 15–20% lower than the shown current reference case (which was supposed to map a continuation of the current system).

Between 2015 and 2021, renewable energy production expanded by 24.6 Exajoules accounting for a 4.14% expansion of the global market share of primary energy in that time. In that same time period, total primary energy consumption for the global market increased by 8.12% (BP Statistical Review of World Energy 2011, 2016. 2020 and 2022). All three fossil fuels (oil, gas, and coal) increased in annual consumption. Coal did decline in annual consumption for a few years after a peak in 2014 but is now on track to recovering that peak production in 2023. So far, nothing has been phased out and the system has grown. Is society able to outpace energy demand growth with renewable energy production? How do decarbonize industry and maintain the existing performance is not clear (Menton 2022). For example, the United States has exported most of its industrial capability to other nations (China in particular). So, to achieve true net zero, the United States would also have to include its industrial actions that serve its population, regardless of whether this activity is done domestically or accessed from foreign markets.

How do we manage the concepts stated in the previous few paragraphs? The two paradigms of continuous industrial growth and a contraction of energy footprint with complete decarbonization do not coexist peacefully. We seem to live in a society where what is proposed for future planning, what is practical, and what is actually done are all in sharp contradiction.

Current expectations are that global industrial businesses will replace a complex industrial energy ecosystem that took more than a century to build. The current system was built with the support of the highest calorifically dense source of energy the world has ever known (oil), in cheap abundant quantities, with easily available credit, and seemingly unlimited mineral resources. The replacement needs to be done at a time when there is comparatively very expensive energy, a fragile finance system saturated in debt, not enough minerals, and an unprecedented world population, embedded in a deteriorating natural environment. Most challenging of all, the task to phase out fossil fuels has to be done by 2050 (IEA 2021a and Table 3), or within 27 years. It is also worth noting that most nations around the world have a very short buffer stockpile of needed commodities and goods. For example, Australia has only a few days supply of petroleum products (Australian Dept. of Environment and Energy 2019). This means that most industrially supported economies are not very resilient to shocks or unforeseen changes. If the size of the global EV transport fleet is 1.39 vehicles (Table 13), then this would require a global annual EV production of 51.4 million units (51 392 565). This would have to happen each year for the next 26 years. It is the author's opinion, that this will likely not go as fully planned.

This paper has documented many interlocking issues and attempted to assemble numbers in a form where they can be used. The approach taken is quite different compared to other studies done in this complex topic. The general approach of most other studies has taken the approach of a top down market price economic analysis (Wang et al. 2023b, Jacobsen et al. 2022, ReThinkX 2021, ReThinkX 2024). These studies work with the paradigm that this set of challenges would be resolved with just the application of economic market forces. Most of the published studies don't consider the physical number of units needed, or what physical activity they would have to do, and what would be physically required to support the renewable technologies. They certainly don't consider the practicalities of a fully scaled up renewable technology industrial system. The industrial capability to deliver the production of EV's, batteries, wind turbines and solar panels took many years to develop. Expanding their production capacity will not be easy or simple.

Jacobsen (et al. 2022) modelled how fast the transition away from fossil fuels could happen, shows two possible timelines for transition to 100% Wind-Water-Solar (WWS) in a global scope. In both cases, an 80% transition occurs by 2030. In one case, 100% occurs by 2035; in the other, 100% occurs by 2050. The mechanism to facilitate this was the assumption that the cost of renewable power has declined with engineering performance capability and efficiency.

The papers examined in this topic made many assumptions that were incomplete. For example, one paper (Wang et al. 2023b) did not examine batteries of any kind (see comments in the first paragraph), moreover did not examine energy storage at all, just power generation. These differences alone would explain the very different outcomes between my work and this paper.

The issue of how large the power buffer should be was something that has not been handled appropriately. None of the studies examined considered long term seasonal variation in power production. Jacobsen (et al. 2022) assumed that only 4 hours needs to be used for power storage. Princeton University published a study called Net Zero America (Larson et al. 2021), which is an excellent analysis that considered this issue of phasing out fossil fuels of the United States and examined many of the relevant practical issues involved. However, this remarkable study assumed that a 5 to 7 hour power buffer was all that was needed. The whole Net Zero America study, as sophisticated as it was, only considered short term variations between supply and demand. The day/night cycle of power demand was matched over a period of years. It did not consider the long term variations for either wind or solar power generation, for example between summer and winter.

The focus of Part II of this work was to calculate the quantities of metals needed to produce so many renewable technologies so quickly. The conventional assumption seems to consider the entire commodities sector behaves the same way as technology development, where only market forces dictated reality. Raw materials were always just a cost and were not worth considering. If there is a need, demand will force up the market price, and that need would be met through innovation in a free market. Technology development has a development cycle of 2 to 10 years, and assumes that cheap abundant energy, and raw materials like minerals will always be there. Technology development has evolved in context of the limits to available capital. Yet the commodities industry (minerals, oil, gas, coal, etc.), has an approximate 20 year development cycle.

23 CONCLUSIONS

The following conclusions can be drawn from this study.

The estimated number of EV's needed to phase out fossil fuels and maintain the existing industrial ecosystem was 1.39 billion vehicles of various classes (all vehicle classes except HCV Class 8 trucks), which would need 65.05 TWh of batteries and 4 354.0 TWh of electricity annually supplied to charge them. In parallel to the EV vehicle fleet, a fleet of hydrogen fuel cell powered transport network was recommended. This includes 29 million Class 8 HCV heavy trucks, a hydrogen powered intercity rail network to transport people and freight, and a hydrogen powered international maritime shipping fleet. This H_2 Cell powered system fleet (in conjunction with the existing hydrogen market, with demand for refining petroleum products removed) would require approximately 355 million tonnes of hydrogen fuel a year at the point of application, and 20 001 TWh to manufacture that hydrogen with electrolysis. Hydrogen is an interesting energy carrier, but it faces many practical limitations in storage and transport in large quantities. The practical engineering challenges in this are still being resolved.

The electricity needed to produce hydrogen is 2.5 times the electricity needed to charge an equivalent EV system. This poses a logistical challenge in the implementation of hydrogen as a fuel source. Conversely, the weight of an EV battery is 3.2 times the weight of the equivalent hydrogen fuel tank. This presents an opportunity for hydrogen systems to be developed. It is recommended that all short-range vehicles should be Electric Vehicles (PHEV or BEV) and all long-range (or heavy) vehicles should be hydrogen fuel cell vehicles (FCEV). This takes into account the required electrical energy to charge the EV batteries compared to production of the hydrogen, and the physical size of energy storage in each comparable transport vehicle.

Ammonia is an interesting fuel and has potential for future developments. There are a number of practical issues that need to be overcome. Ammonia is a safety hazard to living things and is a gas at room temperature and normal atmospheric pressure. Also, burning ammonia has a toxic exhaust product. These issues may well be overcome but have yet to be resolved in large scale up operations.

The estimated mass of biomass feedstock for biofuels, where only a 37% of the total 2018 maritime shipping and 62% of 2018 aviation aircraft are examined, is projected to be 2.34 times the size of the global 2018 annual wheat crop. That same biomass for biofuels would need 2.66 million km^2 of arable land, which would be 24.1% of 11 million km^2 available arable land on the planet surface. Both biofuels (corn and soy) together would need 1 935.2 km^3 of fresh water in irrigation. This would be 48.5% of the 2018 global water withdrawal for the global human society, from the planetary hydrological freshwater cycle was 3 990 km^3.

To phase out existing fossil fuel annual global electrical energy generation, an annual 17 086.1 TWh of non-fossil fuel power generation would need to be commissioned. Other industrial tasks like the gas heating of buildings and the manufacture of steel using coal would have to be substituted with non-fossil fuel alternatives.

Calculations reported here suggest that the total additional non-fossil fuel electrical energy annual capacity to be added to the global grid will need to be around 48 939.8 TWh. Given that electrical power consumption in 2018 was 26 652.7 TWh, this implies that future electrical power consumption will be substantially larger than it is now. Hopes for a massive reduction in power consumption will probably not happen.

If the same non-fossil fuel energy mix as that reported in in IEA (2021) is assumed, then this translates into an extra 796 709 new power plants will be needed to be constructed and commissioned. The combined installed power capacity of the additional systems would be 29 914 GW.

To put this in context, the total power plant fleet in 2018 (all types including fossil fuel plants) was only 46 423 stations. On one hand, this large number of non-fossil fuel stations reflects the lower Energy Returned on Energy Invested (ERoEI) ratio of renewable power compared to current fossil fuels. On the other hand, this same number also reflects the fact that some of these non-fossil fuel systems (wind, solar and biomass CHP) are smaller and/or less capital intensive and/or can be more easily built. So, increasing both the total power draw needed and the higher percentage of them in the mix necessarily needs exponentially larger numbers in comparison to gas and coal stations. Nuclear, geothermal and hydropower stations are of similar size to coal and gas stations. Future work is required, where the energy production is quantified, and the required Capital Expenditure (CAPEX) for each energy system is quantified. This would be an evolution of the ERoEI calculation for each energy sourced electrical energy generation system.

To mitigate intermittency of supply issues (from wind and solar), global stationary power storage would be required. This paper presents calculations around four power buffer sizes: 6 hours, 48 hours + 10%, 28 days and 12 weeks, each one associated with a reference. Conventional thinking believes that only 5 to 7 hours (6 hours) of buffer is needed (which would require 199 200 battery bank stations of 100 MW/129 MWh capacity to annually deliver 25.7 TWh). This paper makes the case this will not be even close to being enough to balance the long-term seasonal variations, where the difference between summer and winter solar radiance could need several months. How large this buffer should be is still largely unknown. A case can be made though that it would be at best several months. The 12 week buffer would require 66.9 million battery bank stations of 100 MW/129 MWh capacity to annually deliver 8 634 TWh.

This paper has shown that large wind and solar power systems would need to be internally self sufficient and need a buffer for stable operation. This is a pertinent point as conventional thinking for future power generation is to have an energy mix dominated by wind and solar power systems. It is well understood that these systems are highly variable and intermittent in supply. The assumption for future developments was a power buffer would be available in some form. If there are technical issues in storing the needed quantity of power for the needed time period, then it is concluded that wind and solar power generation systems are not practical as the primary energy source for the next industrial era after fossil fuel based technology.

The size of the buffer, even at just 6 hours capacity is far larger than conventional thinking allows for. Development work done for the practical scale up of renewable energy, wind and solar systems in particular, have not considered long term seasonal variation at all. All work done seems to have considered short term variations between supply and demand only. A case can be made that this whole issue has been misunderstood. The technology to store such a large quantity of power for so long does not yet exist in a viable form. This paper concludes that the actual size of the power buffer needed to make wind and solar power generation stable would be much larger than just 6 hours and could be closer to 12 weeks in capacity, yet the work to establish a true number for this has yet to be done. This work would have to be of similar sophistication in methodology of (Larson et al. 2021), but for the whole global system and would have to include long term seasonal variations over a 12 month time frame.

Pumped Hydro storage (PHS) is the cheapest and most effective way to store power at the time of writing this paper. Like all other systems examined, PHS works quite well on a small scale but faces practical logistical scale up issues. The establishment of hundreds of thousands of new PHS sites (especially paired sites that can exchange water) faces many challenges. At least some of these challenges could be met with engineering feasibility studies. The real issue with PHS is the volume of fresh water that would be required to taken from the planetary hydrological cycle. These quantities of water are so large that it is not practical to consider due to the perceived environmental impact.

Hydrogen also faces practical issues when considered by used as a power storage. The amount of electricity required to produce enough hydrogen to operate as a store of energy is 3.85 times the electrical power that could be delivered from the stored hydrogen once accessed. Battery banks are still considered scalable, although part II of this study will examine the quantity of metals needed to supply those batteries. Many strategic policy makers around the world consider battery banks as the primary form stationary energy storage.

The network of calculations in this paper was subject to a sensitivity analysis (Section 21). The pertinent learnings from the sensitivity analysis (Section 21) were as follows. Restructuring society will require a massive increase of resource and energy consumption for the next several decades (steel production for example, Sensitivity Scenarios O to R). Once done though the resulting society could be designed to be more efficient, resulting in a greatly reduced energy consumption (reducing the current demand of electrical energy, (Sensitivity Scenarios T to W). Reducing the quantity of freight goods being transported (heavy trucks and maritime shipping) also has a significant result in contracting the total electrical power needed (Sensitivity Scenarios F and G, I, J and K). Society would need to be restructured not to need such a lot of freight transported over such long distances though. An increase of the train transport network by 300% (Scenario H) had a very small impact and should be considered when strategic planners are reinventing freight transport and passenger transport over long distances. In terms of the total annual electrical power required to phase out fossil fuels, the size of the EV fleet had very little impact at all (Sensitivity Scenarios A to E).

The reconstruction of society will require an unprecedented quantity of energy and raw materials of all kinds. While it could be argued that degrowth is a good long term target, Figure 50 shows that the practicalities of reimagining society into a post fossil fuel world will have to be thought through more effectively.

In conclusion, the data presented suggests that replacing the existing fossil fuel powered system (oil, gas, and coal), using the planned renewable technologies, such as solar panels or wind turbines, will be extremely difficult for the entire global human population, if the proposed Green Transition plan is undertaken on a large scale.

LIST OF ANNEXES

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ANNEX A.
TRANSPORT FLEET ICE SIZE AND DISTANCE TRAVELLED IN 2018

Table A1. (Part 1 of 3). Number of ICE vehicles in the global fleet. (This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Refence/Source	Date of Estimate
Global	205	1 416 528 615		
United States	811	268 913 221	U.S. Dept of Transportation (2017)	2017
European Union	543	261 019 964	ACEA (2018)	2015/2016
China	179	232 312 300	National Bureau of Statistic of China 2019	2018
Japan	615	77 938 515	Japan Dept Transport (2017)	2018
Brazil	350	74 454 951	Balconista (2019)	2019
Russia	373	54 779 626	Е М И С С (2019)	2018
United Kingdom	579	39 240 439	ACEA (2018)	2016
Mexico	297	37 353 597	The World Bank (2014)	2015
India	22	28 860 000	CEIC (2015)	2015
Canada	650	23 846 147	Statistics Canada (2019)	2017
Indonesia	87	22 512 918	UK Dept of Transport (2015)	2015
South Korea	411	20 989 885	UK Dept of Transport (2015)	2015
Australia	730	19 200 000	Australian Bureau of Statistics (2018)	2018
Thailand	226	15 490 503	UK Dept of Transport (2015)	2015
Turkey	199	16 320 927	ACEA (2018)	2015
Iran	178	14 130 000	UK Dept of Transport (2015)	2015
Argentina	316	13 726 226	UK Dept of Transport (2015)	2015
Malaysia	433	13 308 716	UK Dept of Transport (2015)	2015
Nigeria	64	11 458 370	Nigeria National Bureau of Statistics (2017)	2017
Pakistan	17	10 000 000	UK Dept of Transport (2015)	2015
South Africa	174	9 600 412	UK Dept of Transport (2015)	2015
Ukraine	219	9 290 000	MIUS (2019)	2018
Taiwan	333	7 842 423	Taiwan MTOC (2016)	2016
Syria	368	6 900 000	UK Dept of Transport (2015)	2012
Saudi Arabia	209	6 600 000	UK Dept of Transport (2015)	2015
Colombia	116	5 800 000	ANDEMOS (2018) & Columbian National Census (2018)	2018
Egypt	62	5 733 810	UK Dept of Transport (2015)	2015
Algeria	140	5 570 000	UK Dept of Transport (2015)	2015
Switzerland	539	5 003 551	Switzerland Federal Statistical Office FSO (2018)	2018
Venezuela	145	4 510 000	UK Dept of Transport (2015)	2015
Chile	230	4 444 941	UK Dept of Transport (2015)	2015
Kazakhstan	251	4 397 354	UK Dept of Transport (2015)	2015
New Zealand	860	4 240 000	New Zealand MIA (2018)	2018
Iraq	105	3 900 000	CEIC (2015)	2015
Philippines	38	3 822 544	UK Dept of Transport (2015)	2015
Morocco	103	3 570 000	CEIC (2015)	2015
Belarus	369	3 501 981	UK Dept of Transport (2015)	2015
Israel	384	3 373 139	Israel Central Bureau of Statistics. (2018)	2017
Norway	616	3 236 944	ACEA (2018)	2015
Libya	439	2 740 000	UK Dept of Transport (2011)	2015
Peru	78	2 444 478	UK Dept of Transport (2015)	2015
Ecuador	141	2 267 344	UK Dept of Transport (2015)	2015
Vietnam	23	2 170 000	UK Dept of Transport (2015)	2015
United Arab Emirates	234	2 140 000	UK Dept of Transport (2015)	2015
Serbia	288	2 052 067	Serbian Statistical Office (2016)	2015
Congo, Democratic Republic of the	25	1 900 000	UK Dept of Transport (2015)	2015

Table A1. (Part 2 of 3). Number of ICE vehicles in the global fleet. (This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Refence/Source	Date of Estimate
Kuwait	477	1 876 188	UK Dept of Transport (2015)	2015
Guatemala	115	1 862 535	UK Dept of Transport (2015)	2015
Dominican Republic	153	1 610 551	UK Dept of Transport (2015)	2015
Afghanistan	47	1 572 663	UK Dept of Transport (2015)	2015
Sri Lanka	70	1 469 821	UK Dept of Transport (2015)	2015
Tunisia	129	1 450 000	UK Dept of Transport (2015)	2015
Kenya	29	1 381 473	UK Dept of Transport (2015)	2015
Kyrgyzstan	223	1 330 000	UK Dept of Transport (2015)	2015
Azerbaijan	135	1 301 926	UK Dept of Transport (2015)	2015
Jordan	123	1 130 000	UK Dept of Transport (2015)	2015
Costa Rica	224	1 076 041	UK Dept of Transport (2015)	2015
Myanmar	20	1 065 897	CEIC (2015)	2017
Georgia	281	1 043 900	UK Dept of Transport (2015)	2015
Qatar	411	1 020 000	UK Dept of Transport (2015)	2015
Yemen	37	1 000 000	UK Dept of Transport (2015)	2015
Oman	233	980 000	UK Dept of Transport (2015)	2015
Uruguay	280	960 000	UK Dept of Transport (2015)	2015
Singapore	170	957 006	Singapore Land Transport Authority (2018)	2018
Zimbabwe	60	940 000	UK Dept of Transport (2015)	2015
Cote d'Ivoire	41	940 000	UK Dept of Transport (2015)	2015
Bosnia and Herzegovina	258	910 969	UK Dept of Transport (2015)	2015
Ghana	32	890 000	UK Dept of Transport (2015)	2015
Angola	32	880 000	UK Dept of Transport (2015)	2015
Ethiopia	9	831 000	2Merkato Business Portal (2017)	2017
Bolivia	72	770 000	UK Dept of Transport (2015)	2015
Moldova	201	715 480	UK Dept of Transport (2015)	2015
Lebanon	117	683 000	Al-akhbar (2019)	2018
Panama	171	677 356	UK Dept of Transport (2015)	2015
Hong Kong	92	674 253	UK Dept of Transport (2015)	2015
Senegal	44	660 000	UK Dept of Transport (2015)	2015
Madagascar	27	660 000	UK Dept of Transport (2015)	2015
Paraguay	98	652 886	CEIC (2015)	2015
Bangladesh	4	620 000	UK Dept of Transport (2015)	2015
Bahrain	422	578 471	UK Dept of Transport (2015)	2015
Uganda	12	490 000	UK Dept of Transport (2015)	2015
Armenia	167	489 346	Armenia vehicle statistics (2018)	2018
Albania	167	481 114	UK Dept of Transport (2015)	2015
Nicaragua	79	480 000	UK Dept of Transport (2015)	2015
Cuba	42	480 000	UK Dept of Transport (2015)	2015
North Macedonia	206	425 764	UK Dept of Transport (2015)	2015
Mozambique	14	400 000	UK Dept of Transport (2015)	2015
Trinidad and Tobago	292	397 000	UK Dept of Transport (2015)	2015
Botswana	177	391 686	UK Dept of Transport (2015)	2015
Tanzania	7	380 000	UK Dept of Transport (2015)	2015
Zambia	23	370 000	UK Dept of Transport (2015)	2015
Cameroon	15	347 000	UK Dept of Transport (2015)	2015
Brunei	721	300 897	UK Dept of Transport (2015)	2015

Table A1. (Part 3 of 3). Number of ICE vehicles in the global fleet. (This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Refence/Source	Date of Estimate
Burkina Faso	16	297 000	UK Dept of Transport (2015)	2015
Iceland	824	278 924	UK Dept of Transport (2015)	2016
El Salvador	41	260 000	UK Dept of Transport (2015)	2015
Benin	24	252 000	UK Dept of Transport (2015)	2015
Mauritius	192	236 853	UK Dept of Transport (2015)	2015
Mali	12	203 000	UK Dept of Transport (2015)	2015
Montenegro	326	202 322	Montenegrin Statistical Office (2017)	2016
Togo	27	198 000	UK Dept of Transport (2015)	2015
Suriname	349	193 000	UK Dept of Transport (2015)	2015
Jamaica	66	190 000	UK Dept of Transport (2015)	2015
Honduras	18	160 000	CEIC (2015)	2017
Malawi	8	139 000	UK Dept of Transport (2015)	2015
Barbados	387	110 000	UK Dept of Transport (2015)	2015
Haiti	7	80 000	UK Dept of Transport (2015)	2015
Liberia	14	63 000	UK Dept of Transport (2015)	2015
Burundi	6	63 000	UK Dept of Transport (2015)	2015
Belize	139	50 000	UK Dept of Transport (2015)	2015
Mauritania	10	41 000	UK Dept of Transport (2015)	2015

Table A2. Total number of km driven in the United States in 2018 (Source: U.S. Department of Transportation 2017, Bureau of Transportation Statistics: National Transportation Statistics).

Vehicle Class	Number of Self Propelled Vehicles	Proportion of U.S. Fleet in 2018 (%)	Average annual miles driven by class in 2018 (miles)	Average annual km driven by class in 2018 (km)	Total miles driven in 2018 (miles)	Total km driven in 2018 (km)
Class 8 Truck	4 694 851	1,75%	63 428	102 077	297 785 023 606	479 238 392 763
Transit Bus	2 517 520	0,94%	34 012	54 737	85 625 901 695	137 801 488 504
Refuse Truck	1 850 465	0,69%	25 000	40 234	46 261 619 737	74 450 837 120
Paratransit Shuttle	1 678 668	0,62%	22 679	36 498	38 070 503 372	61 268 517 223
Delivery Truck	959 133	0,36%	12 958	20 854	12 428 444 244	20 001 635 985
School Bus	888 223	0,33%	12 000	19 312	10 658 677 187	17 153 472 873
Light Truck/ Van	82 569 993	30,71%	11 991	19 298	990 096 783 911	1 593 405 825 638
Light-Duty Vehicle	79 237 170	29,47%	11 507	18 519	911 782 117 028	1 467 370 625 372
Passenger Car	78 293 789	29,11%	11 370	18 298	890 200 375 687	1 432 638 190 179
Motorcycle	16 223 409	6,03%	2 356	3 792	38 222 352 737	61 512 895 012
Total	268 913 221	100,0%			3 321 131 799 203	5,34,E+12
	269 million vehicles					5.3 trillion km travelled in 2018

Table A3. Estimated total number of km driven by vehicles in the European Union in 2018 (Source: ACEA 2018).

Vehicle Class	**Number of Self Propelled Vehicles in 2018 European Union Fleet** (Data Source: ACEA 2018)	**Proportion of EU-28 Fleet** (%)	**Average annual km driven by vehicle in class for EU-28 in 2018** (km)	**Total km driven by class in 2018 EU-28 Fleet** (km)
Class 8 Truck	5 716 322	2,19%	2,41E+04	1,4E+11
Bus	657 714	0,25%	8,70E+03	5,7E+09
Light Truck/Van	27 413 946	10,50%	4,46E+03	1,2E+11
Passenger Car	222 683 327	85,31%	4,32E+03	9,6E+11
Motorcycle	4 548 655	1,74%	8,95E+02	4,1E+09
Total	261 019 964	100,0%		1,23E+12
	261 million vehicles			Travelled 1.23 trillion km in 2018

Table A4. Number of vehicles in the Chinese fleet 2018, by class, and estimated km driven (Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm).

Vehicle Class in China	**Vehicle Mass According to Chinese Classification**	**Number of Vehicles in China in 2018** (number)	**Proportion of Vehicle Class in 2018** (%)	**Vehicle Class in U.S. Dept of Transport Classification System**	**Proportion of vehicles in Chinese fleet, reclassified with U.S. dept transport Classification System**	**Average km traveled in 2018 by vehicle in class for Chinese Transport system** (km)	**Estimated total km driven by class in 2018 Chinese Fleet (projected from US dept of Transport)** (km)
Passenger Vehicle		**205 554 100**	88,5%	Passenger Car	203 689 500	4 529	9,22456E+11
Large		1 583 300					
Medium Size		754 000					
Small		201 352 200					
Mini		1 864 600		Motorcycle	1 864 600	938	1,75E+09
Goods Vehicle		**25 678 200**	11,1%				
Heavy Duty	>= 12000 kg	7 095 300		Class 8 Truck	7 095 300	25 264	2,89E+11
Medium	4500 >= Medium < 12000	1 243 900		Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1 243 900	8 496	1,06E+10
Light	< 4500 kg	17 285 300		Light Truck/ Van + Light-Duty Vehicle + Other Vehicle Type	18 419 000	4 680	8,62E+10
Mini	=< 1800 kg	53 700					
Other Vehicle Type		**1 080 000**	0,5%				
	Total	232 312 300			232 312 300		1,31E+12
		232.3 Trillion Vehicles			232.3 Trillion Vehicles		1.31 Trillion km

Table A5. Rest of World (RoW) total number of km driven in 2018.

Vehicle Class	Number of Self Propelled Vehicles in U.S. in 2018 (number)	Proportion of U.S. Fleet in 2018 (%)	Estimated number of Self Propelled Vehicles in 2018 RoW Fleet (number)	Average km traveled in 2018 by a vehicle in class in Rest of World Transport system (km)	Estimated total km driven by class in RoW Global Fleet (km)
Class 8 Truck	4 694 851	1,75%	11 422 874	65 757	7,5E+11
Transit Bus	2 517 520	0,94%	6 125 289	35 261	2,2E+11
Refuse Truck	1 850 465	0,69%	4 502 300	25 918	1,2E+11
Paratransit Shuttle	1 678 668	0,62%	4 084 306	23 512	9,6E+10
Delivery Truck	959 133	0,36%	2 333 632	13 434	3,1E+10
School Bus	888 223	0,33%	2 161 104	12 441	2,7E+10
Light Truck/Van	82 569 993	30,71%	200 898 093	12 431	2,5E+12
Light-Duty Vehicle	79 237 170	29,47%	192 789 122	11 930	2,3E+12
Passenger Car	78 293 789	29,11%	190 493 814	11 787	2,2E+12
Motorcycle	16 223 409	6,03%	39 472 597	2 443	9,6E+10
Total	268 913 221	100,0%	654 283 130		8,377,E+12
* assembled from Table A1			654 million vehicles *		Travelled 8.38 trillion km in 2018

ANNEX B.
EV SPECIFICATIONS

Table B1. Electric Vehicle Passenger car range and distance per kWh capacity (Source: data taken from United States Environmental Protection Agency, Electric Vehicle Database https://ev-database.org/car/1125/Kia-e-Niro-64-kWh, and Cleantechnica 2020 https://cleantechnica.com updated October 17th, 2018).

Manufacturer	Model	Battery Capacity (kWh)	Distance per kWh (kWh/km)	Range Average (km)	Range in City (km)		Range in Freeway (km)	
					Min Distance (km)	Max Distance (km)	Min Distance (km)	Max Distance (km)
Smart	EQ for-four	16,7	0,13	88,5	96,5	144,8	64,4	80,5
Mitsubishi	i-MiEV	15	0,12	88,5	88,5	136,8	56,3	88,5
Volkswagen	e-up!	18,7	0,13	104,6	104,6	160,9	72,4	88,5
BMW	i3	27,2	0,17	168,9	168,9	257,4	120,7	152,9
KIA	Soul EV	30	0,13	177,0	177,0	265,5	120,7	152,9
Hyundai	Ioniq	28	0,10	201,1	185,0	289,6	136,8	177,0
Volkswagen	e-Golf	32	0,14	201,1	193,1	297,7	136,8	185,0
Renault	Zoe	37	0,16	233,3	225,3	345,9	160,9	209,2
KIA	Niro EV Mid-Range	39,2	0,17	233,3	241,4	362,0	168,9	217,2
Nissan	Leaf 2018	38	0,17	241,4	233,3	362,0	168,9	217,2
Hyundai	Kona Electric	40	0,17	249,4	241,4	378,1	168,9	225,3
Tesla	Model 3 (Standard)	52	0,15	329,8	345,9	571,2	257,4	345,9
Tesla	Model X 75D	72,5	0,18	329,8	337,9	490,7	241,4	289,6
Mercedes	EQC (2019)	70	0,21	345,9	370,1	539,0	265,5	337,9
Chevrolet	Bolt *	60	0,47	378,1	-	410,3	-	345,9
Opel	Ampera*	60	0,47	378,1	-	410,3	-	345,9
Hyundai	Kona Electric (64 kWh)	64	0,19	386,2	386,2	595,3	281,6	362,0
Tesla	Model S 75D	72,5	0,22	386,2	378,1	555,1	281,6	362,0
Jaguar	i-Pace	85	0,25	402,3	402,3	579,2	281,6	362,0
Tesla	Model 3 (Long Range)	78	0,17	490,7	466,6	708,0	345,9	458,6
Average		46,79	0,19	270,71				

"* Opel Ampera is the EU version of the Chevy Bolt, and figures are taken from the EPA site, where a range of ranges is not available, just city and highway ranges.
The Mitsubishi i-MiEV is not currently available, but is sold as Citroen C-Zero and Peugeot Ion.
All figures for range are rounded to 0 or 5."

Table B2. Electric Vehicle commercial van (Light Truck/Van) range and distance per kWh capacity (Source: https://evcompare.io/search/).

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (kWh/km)	Engine Torque (Nm)	Engine Horsepower (hp)
Citroen	Berlingo Electric	170	22,5			
Iveco	Daily Electric	280	91	0,33	300	107
Nissan	e-NV200	200	40	0,2	254	107
Peugeot	Partner electric	170	22,5			
Renault	Kangoo Z.E.	270	33	0,28	225	59
Renault	Master Z.E.	120	33	0,12	225	76
SAIC Maxus	EV-80	230	53	0,23	320	136
Average (Light Truck/Van)		205,76	42,14	0,23		

Table B3. Electric Vehicle Light-Duty Vehicle (Pick-up truck) range and distance per kWh capacity.

Manufacturer	Model	Date of Release	Possible Battery Capacity (kWh)	Estimated Range (miles)	Estimated Range (km)	Power Horsepower (hp)	Estimated Distance per kWh (kWh/km)	Source (Manufacturer website)
Chevrolet Silverado / GMC Hummer Electrics	Hummer EV SUT	2021	200	400	643,6	1000	0,31	https://www.gmc.com/electric/hummer-ev/suv
Ford	Electric Ford F-150	2022		300	482,7			https://insideevs.com/reviews/377328/ford-f150-electric-truck-details/
Tesla	Cybertruck			500	804,5			https://www.tesla.com/en_gb/cybertruck
Rivian	R1T	2021	105 135 180	230 300 400	370,07 482,7 643,6		0,28 0,28 0,28	https://rivian.com/r1t
Lordstown	Endurance	2021				600	0,25	https://www.nurideinc.com/news-releases/news-release-details/lordstown-endurancetm-pickup-truck-achieves-full-homologation/
Bollinger	B2	2020	142	200	321,8	614	0,44	https://bollingermotors.com/bollinger-b2/
Nikola	Badger	2022	160	300	482,7	455	0,33	https://www.nikolamotor.com/
Average (Light-Duty Vehicle – Pick up truck)			153,67	328,75			0,31	

Table B4. Electric Vehicle Bus (Transit Bus, Paratransit Shuttle, School Bus) range and distance per kWh capacity (Source: Volvo 2020, Volvo 7900 Electric specifications, http://www.volvobuses.co.uk/ and BYD 2020, https://www.byd.com/us).

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (kWh/km)	Engine Torque (Nm)	Engine Horsepower (hp)
Volvo	7900 Electric	200	150 200 250	1,25	400	160
BYD Auto	BYD K9	250	310	0.9-1.8	700 1100 3000	245 410 490
Average (Transit Bus, Paratransit Shuttle, School Bus)			227,5	1,32		

Table B5. Electric Vehicle HCV Trucks (Refuse Truck, Medium Duty Delivery Truck, Large Duty Rigid Delivery Truck, Long Haul Semi-Trailer Class 8) range and distance per kWh capacity (Source: Liimatainen et al. 2019).

Manufacturer	Commercial Name	Type	Maximum Weight (tonnes)	Battery Capacity (kWh)	Range (km)	Energy Consumption (kWh/km)
Mitsubishi	eCanter	medium duty	7,5	82,8	120	0,69
BYD	T7	medium duty	11	175	200	0,88
Freightliner	eM2 106	medium duty	12	325	370	0,88
Volvo	FL Electric	rigid	16	100-300	100-300	1,00
Renault	D Z.E.	rigid	16	200-300	300	1,00
eMoss	EMS18	rigid	18	100-250	100-250	1,00
Mercedes-Benz		rigid	26	212	200	1,06
Renault	D WIDE Z.E.	rigid	26	200	200	1,00
Tesla	Semi	semitrailer	36		480 - 800	1,25
BYD	T9	semitrailer	36	350	200	1,75
Freightliner	eCascadia	semitrailer	40	550	400	1,38
Average Medium Duty (Delivery Truck)				194,3	230,0	0,82
Average Rigid (Refuse Truck, Large Rigid Delivery Truck)				206,0	233,3	1,01
Average Semi Trailer (Class 8 Truck)				450,0	300,0	1,46

Table B6. Electric motorcycles (Source: The Best Electric Motorcycles Of 2023, https://luxe.digital/lifestyle/cars/best-electric-motorcycles/#Zero-FX).

Manufacturer	Model Electric Motorcycle	Range		Battery Size	Energy Consumption distance per kWh	Engine Torque	Engine Horsepower
		(km)	(miles)	(kWh)	(kWh/km)	(Nm)	(hp)
Energica	Experia	420	261	22,5	0,054	115	80
BMW	CE 04	128,7	80	8,5	0,066	62,0	20
Zero FX	ZF7.2	146,4	91	7,2	0,049	106	21
Average		231,7		12,7	0,056		

ANNEX C.
CALCULATION ELECTRICITY ANNUALLY REQUIRED FOR A HYDROGEN FUEL CELL MARITIME SHIPPING FLEET (17% OF GLOBAL FLEET)

The purpose of Annex C is to examine what is involved with phasing out diesel fueled ICE powered vessels in the global maritime shipping fleet, and substituting with a completely electric alternative, where each vessel has an electric propulsion system, powered with a hydrogen fuel cell. This propulsion method and fuel is assumed to account for 17% of the global maritime fleet as per the year 2050 prediction in Table 3 and (IEA 2021a). This Annex C is to examine the viability of a hydrogen fueled power cell system in each maritime shipping vessel.

The global industrial ecosystem is completely dependent on maritime shipping of commodities and cargo. Maritime/Ocean transport, fluvial transport, or more generally waterborne transport is the transport of people (passengers) or goods (cargo) via waterways. Global goods movement is a critical element in the global freight transportation system. This includes ocean and coastal routes, inland waterways, railways, roads, and air freight. In some cases, the freight transportation network connects locations by multiple modal routes, functioning as modal substitutes (Corbett & Winebrake 2008).

The purpose of this Annex C is to address the following questions:

- If 17% of the global ICE powered shipping vessel was converted to hydrogen fuel cell system, how much hydrogen is required for the global maritime fleet?
- How much extra capacity in the electric power grid is needed to produce this quantity of hydrogen, if 17% of the global volume of commodities (in tonne-km) in 2018 was transported by fully EV vessels?

These questions were addressed in a series of calculations in Steps 1 through to Step 22, with supporting data in (Michaux 2021, Annex N. MARITIME SHIPPING STATISTICS & DATA).

SIZE AND SCOPE OF THE EXISTING GLOBAL MARITIME FLEET

Maritime shipping of cargo is a vital part of the global industrial ecosystem. As raw materials are extracted on one continent (for example Africa, Middle East, South America, South Africa, etc.), then are used for manufacture on another continent (for example China in Asia), then used and consumed on yet other continents (for example Europe, North America, etc.). These material flows are so large, that they can only be transported in bulk volumes by large maritime shipping. Table C1 and Figure C2 shows the size and vessel type of the maritime shipping fleet as reported in 2018.

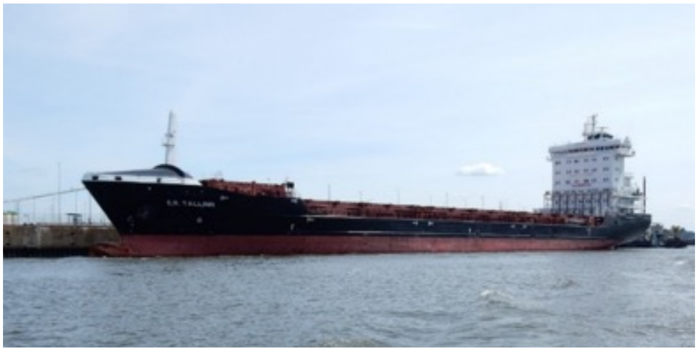
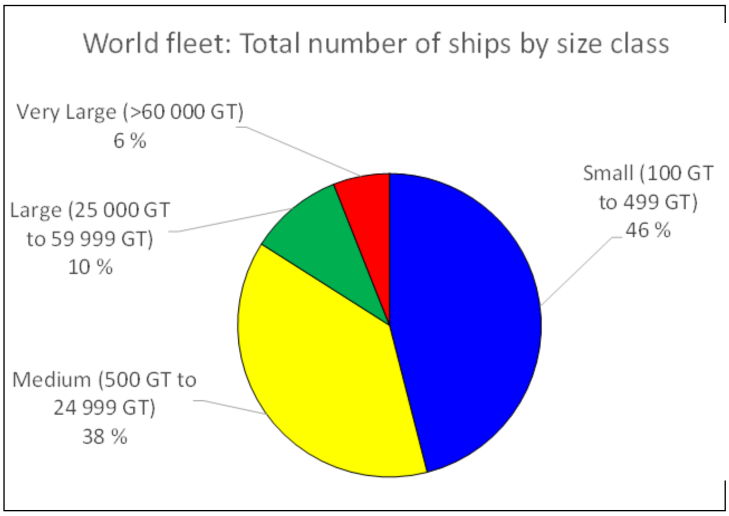


Fig. C1. LHS A large container ship vessel (Image by minka2507 from Pixabay), and RHS Commodity freight shipping vessel (Image by LisaMus from Pixabay).

Table C1. World Fleet: total number of ships by type and size (Source: The World Merchant Fleet in 2018 Statistics from Equasis 2024).

	Small		Medium		Large		Very Large		Total	
	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)
General Cargo Ships	4 346	8,1%	11 659	26,1%	245	2,0%			16 250	13,9%
Specialized Cargo Ships	8	0,0%	227	0,5%	61	0,5%	5	0,1%	301	0,3%
Container Ships	19	0,0%	2 213	5,0%	1 538	12,8%	1 441	22,8%	5 211	4,5%
Ro-Ro Cargo Ships	30	0,1%	629	1,4%	565	4,7%	247	3,9%	1 471	1,3%
Bulk Carriers	316	0,6%	3 788	8,5%	6 119	51,1%	1 706	27,0%	11 929	10,2%
Oil and Chemcial Tankers	1 931	3,6%	7 241	16,2%	2 642	22,0%	1 943	30,8%	13 757	11,8%
Gas Tankers	36	0,1%	1 116	2,5%	362	3,0%	481	7,6%	1 995	1,7%
Other Tankers	396	0,7%	698	1,6%	12	0,1%			1 106	0,9%
Passenger Ships	4 094	7,6%	2 793	6,2%	277	2,4%	184	2,9%	7 348	6,3%
Offshore Vessels	2 727	5,1%	5 297	11,9%	149	1,2%	294	4,8%	8 467	7,2%
Service Ships	2 744	5,1%	2 750	6,1%	27	0,2%	6	0,1%	5 527	4,7%
Tugs	17 848	33,1%	1 041	2,3%					18 889	16,2%
Fishing Vessels	19 359	35,9%	5 244	11,7%	3	0,0%			24 606	21,1%
Total	53 854	100,0%	44 696	100,0%	12 000	100,0%	6 307	100,0%	116 857	100,0%



Ships are grouped by size into four categories: (Source: The World Merchant Fleet in 2018 Statistics from Equasis 2024)

- Small Ships 100 GT to 499 GT
- Medium ships 500 GT to 24 999 GT
- Large ships 25 000 GT to 59 999 GT
- Very large ships greater than 60 000 GT

Fig. C2. World Fleet: total number of ships by type and size (Source: The World Merchant Fleet in 2018 Statistics from Equasis 2024).

Table C2. Global deadweight tonnes by commodity in 2018 (Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development).

Ship Type 	**Dead-Weight Tons** (1000's tonnes)	**Dead-Weight Tons** (%)
General Cargo Ships	73 951	3,84%
Container Ships	253 275	13,15%
Bulk Carriers	818 921	42,52%
Oil and Chemcial Tankers	606 492	31,49%
Gas Tankers	64 407	3,34%
Passenger Ships	6 922	0,36%
Offshore Vessels	78 269	4,06%
Other	23 946	1,24%
Total	1 926 183	100,0%

The scope of maritime freight shipping transport in 2018 was 60 414 billion tonne miles, or 97 206 billion tonne kilometers (97.2 Trillion tonne kilometers). This is a value calculated by the tonnes of freight moved multiplied by the distance travelled (UNCTAD 2018). Shown in Figure B3 and Tables B3 and B4.

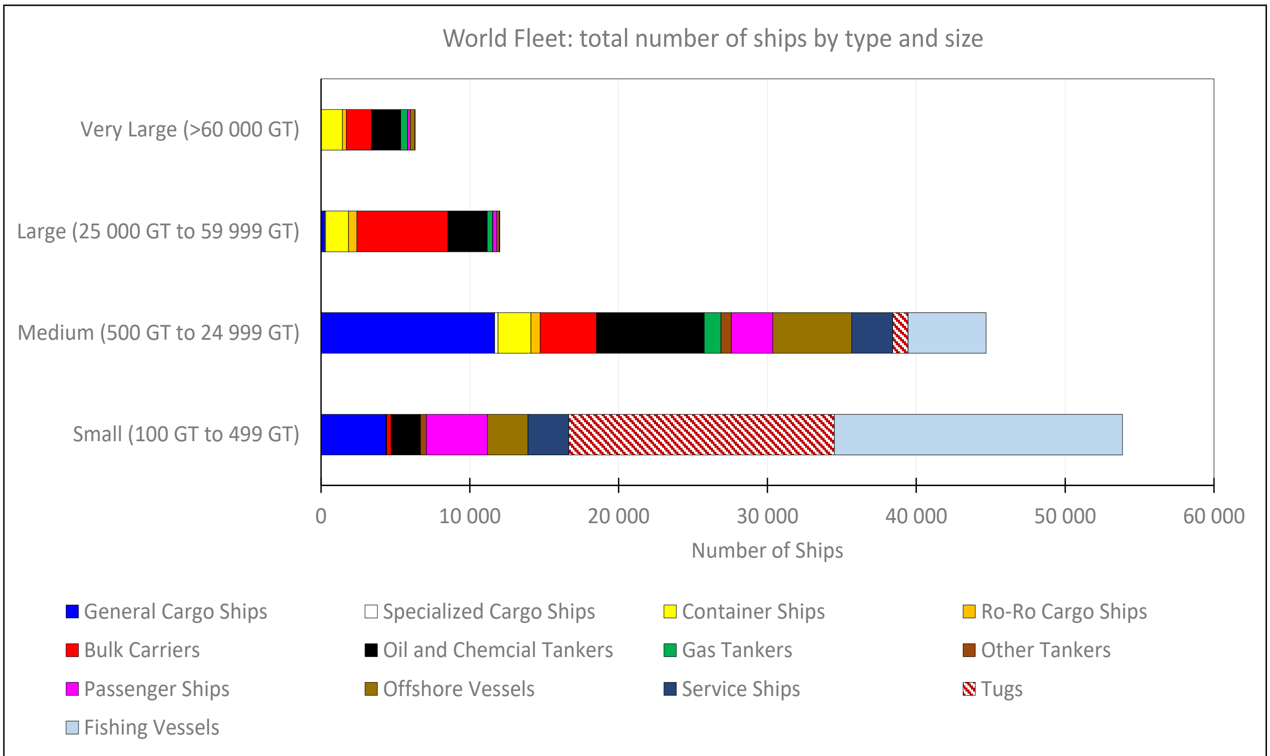


Fig. C3. World seaborne trade in cargo tonne-miles, 2000–2018 (billions of tonne-miles) (Source: UNCTAD 2018) (World Map Image by Clker-Free-Vector-Images from Pixabay) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/).

Table C3. World seaborne trade in cargo tonne-miles -2018 (billions of tonne-miles) (Source: UNCTAD 2018).

Commodity	**World seaborne trade in cargo tonne-miles in 2018** (billions of tonne-miles)	**World seaborne trade in cargo tonne-miles in 2018** (billions of tonne-km)	**Proportion in 2018** (%)
Chemicals	1 111	1788	1,8%
Gas	1 766	2 841	2,9%
Oil	13 809	22 219	22,9%
Other dry cargo	4 497	7 236	7,4%
Containers	9 535	15 342	15,8%
Minor dry bulk	11 967	19 255	19,8%
Main bulks	17 729	28 526	29,3%
Total	60 414	97 206	100,0%

Estimate the distance travelled by the maritime shipping fleet from the reported tonne-km.

Table C4. World seaborne trade in cargo tonne-miles -2018 (billions of tonne-miles) (Source: UNCTAD 2018, 2019).

Commodity	**Martime Cargo** (Million Tonnes Loaded)	**World seaborne trade of each commodity in cargo tonne-km** (billions of tonne-km)
Chemicals	220,9	1 787,6
Gas	351,1	2 841,5
Oil	2 745,6	22 218,7
Other dry cargo	2 752,9	7 235,7
Containers	2 000,0	15 341,8
Main & minor bulks	3 210,0	47 780,9
Total	11 280,6	97 206,1

OPTIONS TO PHASE OUT ICE POWERED MARITIME SHIPPING

There has been a lot of good work done to improve the efficiency and effectiveness of the maritime industry and the vessels it manufactures (Sources: UNCTAD 2019, OECD International Transport Forum 2018, Decarbonizing Maritime Transport: Pathways to Zero Carbon Shipping by 2035, European Federation for Transport and Environment 2018, Road Map to Decarbonizing European Shipping, University Maritime Advisory Services 2019). Work done seems to fall into two broad groups:

1. Technological measures to improve ship design efficiency

- Lighter construction materials
- Slender design
- Propulsion improvement devices
- Bulbous bows
- Air lubrication systems
- Advanced hull coating
- Ballast water system design
- Energy efficiency measures

Engine and auxiliary systems improvements

2. Use of alternative zero-carbon fuels or energy sources

- Batteries to power ships
- Hydrogen fuel cells
- Hydrogen as fuel for internal combustion engines
- Ammonia fuel cells
- Ammonia as fuel for internal combustion engines
- Synthetic diesel
- Synthetic methane
- Advanced biofuels
- Electricity to power ships
- Wind assistance

It will be a challenge to phase out fossil fuels in the maritime industry. The volumes of cargo and commodities moved are truly vast and the distances travelled are longer than any other transport system currently in use.

Multiple options to phase out fossil fuels have been proposed (EFTE 2018), ranging from fully EV, to sail assisted and nuclear propulsion (currently used in large military vessels like aircraft carriers). Several hybrid systems have also been proposed. Thinking outside the box, a solution could be engineered where large ships are propelled by sail, assisted by EV in port, where each sail could function like a solar panel, could be engineered. This conceptual idea is not available at this time, however. For the purpose of this report, the fully electric propulsion system is modelled.

The Internal Combustion Engine (ICE) diesel propulsion system is the most commonly used marine propulsion system converting mechanical energy from thermal forces. Diesel propulsion systems are mainly used in almost all types of vessels along with small boats and recreational vessels. In conventional power system arrangements, the ship's propellers are driven by a diesel propulsion engine while the supply of electricity for the other shipboard loads is transmitted via the shipboard generators (Fig. C4). As shown in Figure C4, 3 oil fueled generator-drive engines are referred to as the "ship's electric power station" supplying power for both propulsion and electrical requirements on board.

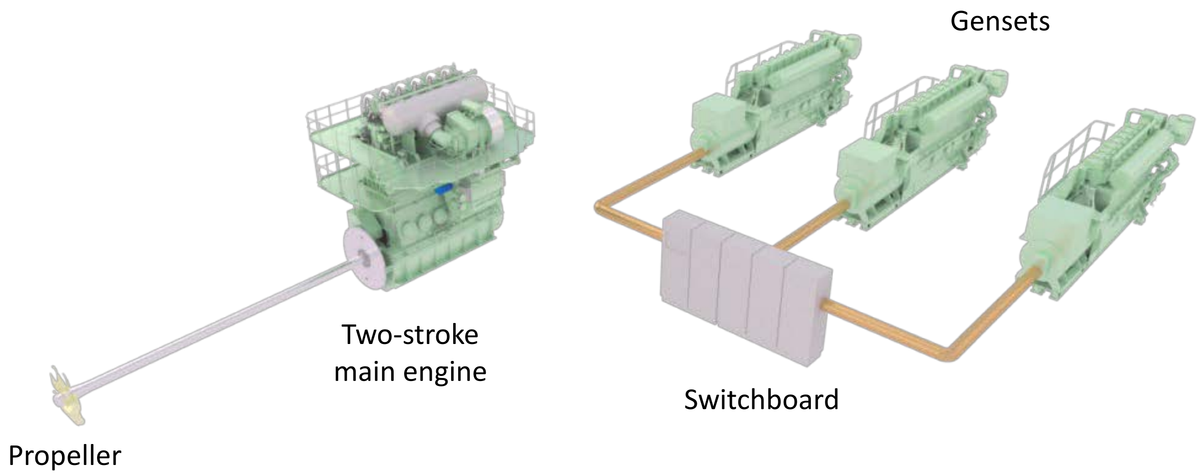


Fig. C4. Traditional diesel-mechanic propulsion of a large merchant vessel (Source: MAN Energy Solutions 2019).

In electric propulsion systems, the power used to drive the propellers becomes an electrical load meaning that the generators can take care of all shipboard loads. Electric propulsion systems utilize electrical power to drive propeller blades for propulsion. From commercial and research ships through to fishing vessels, over the last five years, electric propulsion has gained momentum in a wide range of marine applications across Europe and in Japan. The basic configuration of the electric propulsion system is shown in Figure C5. Figure C6 shows an electric propulsion system similar to the EV system, but instead of a battery bank, it is powered by a hydrogen PEM fuel cell, backed by tanks of hydrogen.

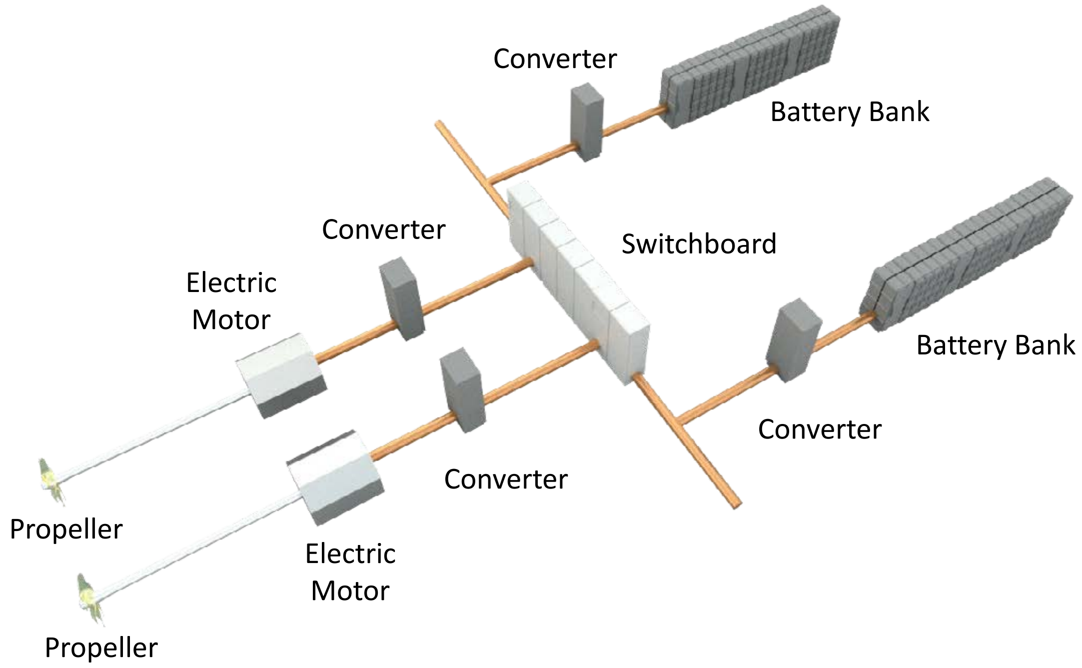


Fig. C5. Pure battery electric propulsion system for a maritime shipping vessel (Source: MAN Energy Solutions 2019).

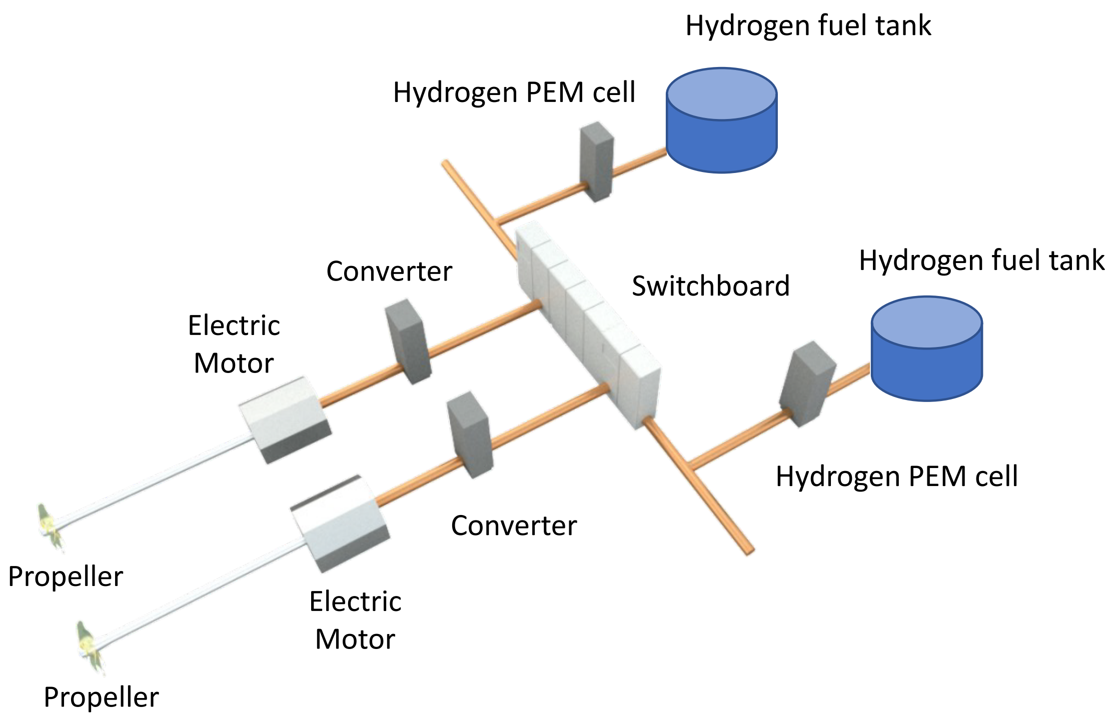


Fig. C6. Hydrogen fuel cell powered electric propulsion system for a maritime shipping vessel (Source: image developed from image in MAN Energy Solutions 2019).

MARITIME TERMS DEFINITIONS

- **Gross tonnage** (GT, G.T. or gt) is a nonlinear measure of a ship's overall internal volume. Gross tonnage is different from gross register tonnage. Neither gross tonnage nor gross register tonnage should be confused with measures of mass or weight such as deadweight tonnage or displacement. Gross tonnage (GT) is a function of the volume of all of a ship's enclosed spaces (from keel to funnel) measured to the outside of the hull framing. The numerical value for a ship's GT is always smaller than the numerical values of gross register tonnage (GRT).
- A **nautical mile** is a unit of measurement used in air, marine, and space navigation, and for the definition of territorial waters. Historically, it was defined as one minute (160 of a degree) of latitude along any line of longitude.
- In maritime tonnage, referred to as **deadweight tonnage,** is a measurement of total contents of a ship including cargo, fuel, crew, passengers, food, and water aside from boiler water. It is expressed in long tons of 2,240 lbs (1016.04 kg).
- Shipping containers come in different sizes, but most are the standard **twenty-foot equivalent units** (**TEU**)-rectangular prisms 6.1 meters (20 feet) long and 2.4 meters wide. The first small container ships of the 1960s carried mere hundreds of TEUs; now Maersk's Triple-E class ships load 18,000 TEUs, and OOCL Hong Kong holds the record, at 21,413 TEU's.
- **Tonne-mile** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 miles equals 500,000 tonne miles. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.
- **Tonne-km** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 kilometers equals 500,000 tonne km. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

ESTIMATION OF THE REQUIRED POWER DRAW TO CHARGE A TOTAL EV MARITIME SHIPPING FLEET

To estimate the required power draw that will have to come from the electric power grid, if the maritime shipping fleet phased out fossil fuel based Internal Combustion Engines (ICE) and 17% of them become hydrogen fuel cell powered (H_2-cell), the following calculations were conducted.

Step 1 – Determine the number of ships in the global fleet in 2018

The number of ships, (and proportions of different shipping class by vessel size) in the global fleet in 2018 was taken from Table B1.

Step 2 – Determine the different types of shipping class by size in 2018 (Gross Tonnes GT)

A large proportion of cargo in maritime shipping is transported in the Very Large shipping class (Table B5). One of the most common examples is the Maersk Triple E-class container ship, which is used for the example in the calculation of energy consumption of an H_2-cell very large ship (Source: https://www.ship-technology.com/projects/triple-e-class-container-ship/). These specifications are shown in Michaux 2021, Annex N.

Table C5. Shipping Class global proportion by number and Gross Tonnage.

Ship Class by GT	Number Proportion in 2018	Gross Tonnage (GT) in 2018
Small (100 GT to 499 GT)	46%	1%
Medium (500 GT to 24 999 GT)	38%	17%
Large (25 000 GT to 59 999 GT)	10%	33%
Very Large (>60 000 GT)	6%	49%
Total	100%	100%

Step 3 – Estimate the tonne-km of cargo for each commodity type moved by the global fleet in 2018

Shown in Table C3 the tonne-km of cargo for each commodity type moved by the global fleet in 2018 was estimated carried by each shipping class in appropriate units (tonne-km). The gross tonnage proportions from Table C3 were projected onto the cargo tonne-km to show the global maritime shipping activity for the year of 2018.

Table C6. World seaborne trade of each commodity in cargo tonne-miles -2018 (Source: UNCTAD 2018, The World Merchant Fleet in 2018 Statistics from Equasis 2024).

Commodity	Small Vessel Proportion (100 GT to 499 GT) (billions of tonne-km)	Medium Vessel Proportion (500 GT to 24 999 GT) (billions of tonne-km)	Large Vessel Proportion (25 000 GT to 59 999 GT) (billions of tonne-km)	Very Large Vessel Proportion (>60 000 GT) (billions of tonne-km)	Total (billions of tonne-km)
Chemicals	17,9	303,9	589,9	875,9	1 787,6
Gas	28,4	483,1	937,7	1 392,3	2 841,5
Oil	222,2	3 777,2	7 332,2	10 887,2	22 218,7
Other dry cargo	72,4	1 230,1	2 387,8	3 545,5	7 235,7
Containers	153,4	2 608,1	5 062,8	7 517,5	15 341,8
Main bulks	477,8	8 122,7	15 767,7	23 412,6	47 780,9
Sum	972,1	16 525,0	32 078,0	47 631,0	97 206,1

Step 4 – Estimate the fuel consumption of the global maritime fleet in 2018

In 2018, the global maritime fleet consumed 194 499 kT (1 481 million barrels) of bunker diesel fuel oil, which is a heavy grade of diesel (IEA 2019d). Use the proportions Gross Tonnage moved (Table C5) to adjust the commodities tonne-km, and annual fuel consumed, as a function of shipping class.

Table C7. Fuel consumption by ship class as a proportion of the global bunker fuel consumption in 2018.

Size Classification	World seaborne trade (billions of tonne-km)	World seaborne trade proportion of 194 499 kT of bunker fuel in 2018 (tonne)
Small (100 GT to 499 GT)	972,1	1 944 990,0
Medium (500 GT to 24 999 GT)	16 525,0	33 064 830,0
Large (25 000 GT to 59 999 GT)	32 078,0	64 184 670,0
Very Large (>60 000 GT)	47 631,0	95 304 510,0
Sum	97 206,1	194 499 000,0

Step 5 – Selection of appropriate economical speed for ship on a shipping route

Estimate the fuel consumption efficiency at a set speed (20 knots) of each shipping class per day at sea (tonnes per day)

The speed selected is classified as Extra slow steaming (15-18 knots; 27.8 – 33.3 km/hr), as discussed in Section 14 of (Michaux 2021). This is so known as super slow steaming or economical speed. A substantial decline in speed for the purpose of achieving a minimal level of fuel consumption while still maintaining a commercial service. It can be applied on specific short-distance routes. Figure C7 shows how fuel consumption at 20 knots was estimated for several shipping class sizes, used Table C8.

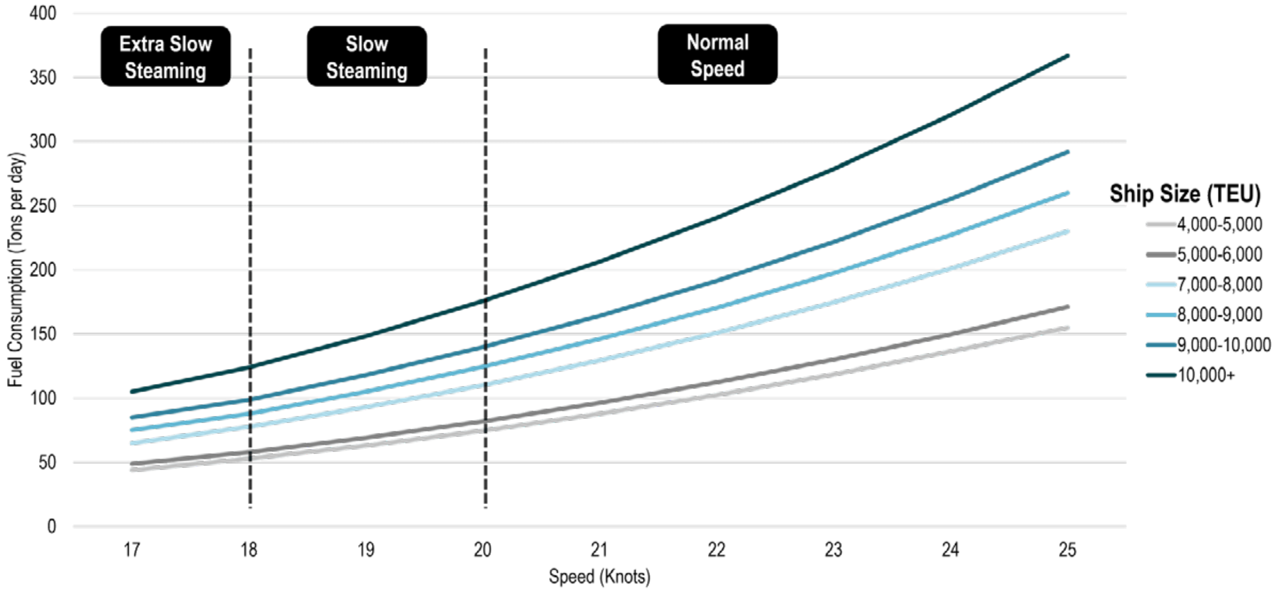


Fig. C7. Fuel Consumption by Containership Size and Speed (Source: adapted from Notteboom & Carriou 2009).

Step 6 – Estimate the fuel consumption efficiency at a set speed (20 knots) of each shipping class per day at sea (tonnes per day)

The energy consumption of each vessel size class was estimated, by calculating:

- Diesel bunker fuel oil consumption over a series of known international shipping routes.
- The true useful work done given an energy efficiency of the consumption of Diesel bunker fuel oil.
- An estimation of the electrical power required if electrical propulsion was used to do the same physical work done projected onto the commodity tonne-km globally in the year 2018.
- How much hydrogen would be needed to be supplied if that electrical propulsion system was fueled by a H_2-Cell.
- How much electricity would be required to produce that hydrogen with electrolysis.

Table C8. Fuel consumption by ship class across route Shanghai to Hamburg (Source: http://ports.com/, Shipping Trade Route Calculator. Notteboom & Carriou 2009).

Size Classification 	**Number of ships in Global Fleet (Source: The World Merchant Fleet in 2018 Statistics from Equasis)**	**Gross Tonnage** (GT)	**Fuel Consumption @20 knots** (tonnes per day)	**Diesel Oil consumption for whole route, Time at sea between Hamburg and Shanghai 25.6 days** (tonnes)
Small (100 GT to 499 GT)	53 854	300	9	220
Medium (500 GT to 24 999 GT)	44 696	12 300	27	691
Large (25 000 GT to 59 999 GT)	12 000	54 000	75	1 920
Very Large (>60 000 GT)	6 307	196 000	175	4 480
Total	116 857	262 600		7 311

As shown in Figure C7 and Table C8 in ICE, a Maersk's Triple-E class ship (capacity load of 18 340 TEUs) TEU diesel fuel oil consumption, while travelling at 20 knots (Slow Steaming speed), is estimated at 175 tons per day.

The energy density of diesel (marine gas oil) calorific content (kWh/kg) was determined (Lide 1991):

- Diesel (marine gas oil) calorific content (Lide 1991) 12.75 kWh/kg
- Energy content in diesel (joules) (Lide 1991) 45.9 MJ/kg
  45 900 000 J/kg

Step 7 – Estimate the quantity of the diesel fuel consumed in this route (kWh)

Map out multiple shipping routes and estimate fuel consumption. Then establish an average bunker fuel consumption by shipping class.

Table C9. Diesel fuel consumed in several shipping routes, by ship class – units of tonnes diesel (Source: http://ports.com/, Shipping Trade Route Calculator. Notteboom & Carriou 2009).

					Diesel fuel consumed in each shipping route			
Origin 	**Destination**	**Distance in kilometers** (km)	**Estimated time at sea** (days)	**Speed of Ship** (knots)	Small Vessel (100 GT to 499 GT) Fuel consumption @20 knots = 8,6 t/day (tonnes)	Medium Vessel (500 GT to 24 999 GT) Fuel consumption @20 knots = 27 t/day (tonnes)	Large Vessel (25 000 GT to 59 999 GT) Fuel consumption @20 knots = 75 t/day (tonnes)	Very Large Vessel (>60 000 GT) Fuel consumption @20 knots = 175 t/day (tonnes)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	25,6	20	219,9	690,5	1 918,1	4 475,6
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	27,8	20	239,3	751,3	2 086,9	4 869,4
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	27,1	20	232,8	731,0	2 030,6	4 738,1
Port of Hamburg (Germany)	Port Hong Kong	21 142	23,8	20	204,5	641,9	1 783,1	4 160,6
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	21,4	20	183,8	577,1	1 603,1	3 740,6
Port of Amsterdam (Holland)	Port of Singapore	17 368	19,6	20	168,3	528,5	1 468,1	3 425,6
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	40,1	20	345,1	1 083,4	3 009,4	7 021,9
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	19,3	20	165,8	520,4	1 445,6	3 373,1

Table C10. Diesel fuel consumption efficiency across each route.

Origin 	Destination	Diesel fuel consumed in each shipping route			
		Small Vessel (100 GT to 499 GT) Efficiency (tonnes/km)	**Medium Vessel (500 GT to 24 999 GT)** Efficiency (tonnes/km)	**Large Vessel (25 000 GT to 59 999 GT)** Efficiency (tonnes/km)	**Very Large Vessel (>60 000 GT)** Efficiency (tonnes/km)
Port of Shanghai (China)	Port of Hamburg (Germany)	0,0097	0,0304	0,0844	0,1968
Port of Hamburg (Germany)	Port of Melbourne (Australia)	0,0097	0,0303	0,0843	0,1966
Port of Hamburg (Germany)	Port of Osaka (Japan)	0,0097	0,0304	0,0843	0,1968
Port of Hamburg (Germany)	Port Hong Kong	0,0097	0,0304	0,0843	0,1968
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	0,0097	0,0303	0,0842	0,1965
Port of Amsterdam (Holland)	Port of Singapore	0,0097	0,0304	0,0845	0,1972
Port of Shanghai (China)	Port Los Angelas (United States)	0,0097	0,0304	0,0843	0,1968
Port of Shanghai (China)	Port of Cape Town (South Africa)	0,0097	0,0304	0,0844	0,1969
	Average	0,0097	0,0304	0,0843	0,1968

Use the average fuel consumption (Table C10) and the annual fuel consumption (Table C7) to estimate the distance traveled by each shipping class in 2018. Calculate the proportion of the maritime fleet fueled by hydrogen (17% from Table 3) to give Table C12.

Table C11. Fuel consumption and distance travelled by ship class.

Size Classification 	**World seaborne trade** (billions of tonne-km)	**World seaborne trade proportion of 194 499 kT of bunker fuel in 2018** (tonne)	**Average fuel consumption** (tonnes/km)	**Dsitance travelled in 2018** (km)
Small (100 GT to 499 GT)	972,1	1 944 990,0	0,0097	2,01E+08
Medium (500 GT to 24 999 GT)	16 525,0	33 064 830,0	0,0304	1,09E+09
Large (25 000 GT to 59 999 GT)	32 078,0	64 184 670,0	0,0843	7,61E+08
Very Large (>60 000 GT)	47 631,0	95 304 510,0	0,1968	4,84E+08
Total	97 206,1	194 499 000,0		2,54E+09

Table C12. Proportion of global maritime shipping by fuel, using the 2018 scope (Source: split taken from IEA 2021a).

	**Electric propulsion fueled by hydrogen fuel cell** 17% (km)	**ICE fueled with ammonia** 46% (km)	**ICE fueled with biodiesel** 37% (km)	**Total Distance travelled in 2018** 100% (km)
Small (100 GT to 499 GT)	3,42E+07	9,25E+07	7,44E+07	2,01E+08
Medium (500 GT to 24 999 GT)	1,85E+08	5,01E+08	4,03E+08	1,09E+09
Large (25 000 GT to 59 999 GT)	1,29E+08	3,50E+08	2,82E+08	7,61E+08
Very Large (>60 000 GT)	8,23E+07	2,23E+08	1,79E+08	4,84E+08
Total	4,31E+08	1,17E+09	9,38E+08	2,54E+09

Using the diesel (marine gas oil) calorific content (Lide 1991) of 12.75 kWh/kg, Table C9 is updated to Table C13.

Table C13. Energy consumed in several shipping routes, by ship class – units of kWh.

Origin	**Destination** 	**Distance in kilometers** (km)	**Estimated time at sea** (days)	**Energy consumed in this shipping route**			
				Small Vessel (100 GT to 499 GT) Fuel consumption @20 knots = 8,6 t/day of diesel, where energy density = 12.75 kW/kg (kWh)	**Medium Vessel (500 GT to 24 999 GT)** Fuel consumption @20 knots = 27 t/day of diesel, where energy density = 12.75 kW/kg (kWh)	**Large Vessel (25 000 GT to 59 999 GT)** Fuel consumption @20 knots = 75 t/day of diesel, where energy density = 12.75 kW/kg (kWh)	**Very Large Vessel (>60 000 GT)** Fuel consumption @20 knots = 175 t/day of diesel, where energy density = 12.75 kW/kg (kWh)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	25,6	2 804 299	8 804 194	24 456 094	57 064 219
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	27,8	3 051 011	9 578 756	26 607 656	62 084 531
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	27,1	2 968 774	9 320 569	25 890 469	60 411 094
Port of Hamburg (Germany)	Port Hong Kong	21 142	23,8	2 606 929	8 184 544	22 734 844	53 047 969
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	21,4	2 343 769	7 358 344	20 439 844	47 692 969
Port of Amsterdam (Holland)	Port of Singapore	17 368	19,6	2 146 399	6 738 694	18 718 594	43 676 719
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	40,1	4 399 706	13 813 031	38 369 531	89 528 906
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	19,3	2 113 504	6 635 419	18 431 719	43 007 344

Step 8 – Determine the work done energy efficiency of a diesel ICE system

Efficiency of an ICE diesel engine is 38% (Lide 1991).

Step 9 – Estimate the useful work done by the ship diesel engine during this shipping route (kWh)

Using the efficiency of an ICE diesel engine of 38%, Table C13 was updated to become Table C14 to show the useful work done by the propulsion system in each shipping route.

Table C14. Useful work done in each ship route, by shipping class.

Origin 	Destination	Distance in kilometers	Estimated time at sea	Useful work done in this route			
				Small Vessel (100 GT to 499 GT) Diesel work efficiency @38%	**Medium Vessel (500 GT to 24 999 GT)** Diesel work efficiency @38%	**Large Vessel (25 000 GT to 59 999 GT)** Diesel work efficiency @38%	**Very Large Vessel (>60 000 GT)** Diesel work efficiency @38%
		(km)	(days)	(kWh)	(kWh)	(kWh)	(kWh)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	25,6	1 065 633,5	3 345 593,6	9 293 315,6	21 684 403,1
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	27,8	1 159 384,3	3 639 927,4	10 110 909,4	23 592 121,9
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	27,1	1 128 134,0	3 541 816,1	9 838 378,1	22 956 215,6
Port of Hamburg (Germany)	Port Hong Kong	21 142	23,8	990 632,9	3 110 126,6	8 639 240,6	20 158 228,1
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	21,4	890 632,1	2 796 170,6	7 767 140,6	18 123 328,1
Port of Amsterdam (Holland)	Port of Singapore	17 368	19,6	815 631,5	2 560 703,6	7 113 065,6	16 597 153,1
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	40,1	1 671 888,4	5 248 951,9	14 580 421,9	34 020 984,4
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	19,3	803 131,4	2 521 459,1	7 004 053,1	16 342 790,6

Table C15. Useful work done by different shipping classes across example routes.

Origin 	**Destination**	**Useful work done in this route**			
		Small Vessel (100 GT to 499 GT) Efficiency (kWh/km)	**Medium Vessel (500 GT to 24 999 GT)** Efficiency (kWh/km)	**Large Vessel (25 000 GT to 59 999 GT)** Efficiency (kWh/km)	**Very Large Vessel (>60 000 GT)** Efficiency (kWh/km)
Port of Shanghai (China)	Port of Hamburg (Germany)	46,9	147,1	408,7	953,7
Port of Hamburg (Germany)	Port of Melbourne (Australia)	46,8	147,0	408,3	952,6
Port of Hamburg (Germany)	Port of Osaka (Japan)	46,9	147,1	408,7	953,6
Port of Hamburg (Germany)	Port Hong Kong	46,9	147,1	408,6	953,4
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	46,8	146,9	408,0	952,0
Port of Amsterdam (Holland)	Port of Singapore	47,0	147,4	409,5	955,6
Port of Shanghai (China)	Port Los Angelas (United States)	46,8	147,1	408,6	953,3
Port of Shanghai (China)	Port of Cape Town (South Africa)	46,9	147,2	408,9	954,0
	Average	46,9	147,1	408,7	953,5

Step 10 – Estimate the work done energy efficiency of an equivalent electric propulsion system

The work done energy efficiency of an electric propulsion system is taken at 73% (Malins 2017). Take the distance traveled from Table C12, the true efficiency from Table C15, calculated the total energy consumed doing useful work (Table C16). Then, given the efficiency of an electric propulsion system (73%), estimate the electrical power needed to be delivered to this proportion of the global maritime shipping fleet.

Table C16. Energy expended doing useful work for the proposed hydrogen fueled vessels, 17% of the 2018 global shipping industry.

Size Classification 	**Distance travelled by 17% of global shipping fleet fuled by hydrogen fuel cell (using 2018 scope)** (km)	**Useful work done efficiency** (kWh/km)	**Energy consumed doing useful work** (kWh)	**Electric power required given EV propulsion work efficiency @73%** (kWh)
Small (100 GT to 499 GT)	3,42E+07	46,9	1,60E+09	2,19E+09
Medium (500 GT to 24 999 GT)	1,85E+08	147,1	2,72E+10	3,73E+10
Large (25 000 GT to 59 999 GT)	1,29E+08	408,7	5,29E+10	7,24E+10
Very Large (>60 000 GT)	8,23E+07	953,5	7,85E+10	1,08E+11
Total	4,31E+08		1,60E+11	2,19E+11

Step 11 – Estimate the mass of hydrogen needed for 17% of the global shipping fleet annual consumption and the electrical power to produce it

Take the estimated electrical power needed to be delivered to electric propulsion systems in 17% of the global maritime fleet from Table C16 and determine how much hydrogen would be required if PEM fuel cell was the fuel source. The electrical power of 1 kg of hydrogen produced is 15 kWh (Thomas 2018). Thus, 1.46 x 10^{10} kg of hydrogen would be needed. If it is assumed that hydrogen production in a PEM cell is 50 kWh/kg, and to compress that hydrogen into a 700 bar storage fuel tank was 2.5 kWh/kg, then a total of 7.68 x 10^{11} kWh of electricity is required (Table C17).

Table C17. Electrical power needed to produce hydrogen for the H2-Cell powered maritime fleet (17% of the global fleet, using 2018 scope).

Size Classification 	**Electric power required given EV propulsion work efficiency @73%** (kWh)	**Hydrogen mass required @15 kWh/kg** (kg)	**Power required to produce hydrogen @50 kWh/kg** (kWh)	**Power required to compress hydrogen in 700 bar storage tanks @2.5 kWh/kg** (kWh)	**Total energy required to produce hydrogen for 17% of maritime shipping fleet** (kWh)	**Electrical power generated at station to account for 10% loss in transmission** (kWh)
Small (100 GT to 499 GT)	2,19E+09	1,46E+08	7,32E+09	3,66E+08	7,68E+09	8,45E+09
Medium (500 GT to 24 999 GT)	3,73E+10	2,49E+09	1,24E+11	6,22E+09	1,31E+11	1,44E+11
Large (25 000 GT to 59 999 GT)	7,24E+10	4,83E+09	2,41E+11	1,21E+10	2,53E+11	2,79E+11
Very Large (>60 000 GT)	1,08E+11	7,17E+09	3,58E+11	1,79E+10	3,76E+11	4,14E+11
Total	2,19E+11	1,46E+10			7,68E+11	8,45E+11
		14,6				844,9
		(million tonnes)				(TWh)

Electrical power required to produce the hydrogen to fuel 17% of the global shipping fleet is 7.68 x 10^{11} kWh. To produce the electrical power at the power station, assuming a 10% transmission loss, 8.45 x 10^{11} kWh, or **844.9 TWh** would need to be generated.

ANNEX D. STEEL MANUFACTURE

The global steel industry consumed 13.9% of coal in 2018, where 71% of steel was made using coal (World Coal Association 2024, World Steel Association 2019). About one-quarter of the world's steel is produced by the Electric-Arc Furnace method (EAF), which uses high-current electric arcs to melt steel scrap and convert it into liquid steel of a specified chemical composition and temperature (World Steel Association 2019).

The electric power used in EAF operation, however, is high, at 360 to 600 kWh per ton of steel, and the installed power system is substantial, where a 100-ton EAF facility often has a 70 MVA (megavolt ampere) transformer.

The production of steel is energy intensive (World Steel Association 2019, IEA 2020). The purpose of this Annex D is to assemble the calculations of energy consumption in steel production. Steel is low carbon content iron. Iron ore is smelted into pig iron. Currently, this is done predominantly with high grade coal (termed coking coal or coke).

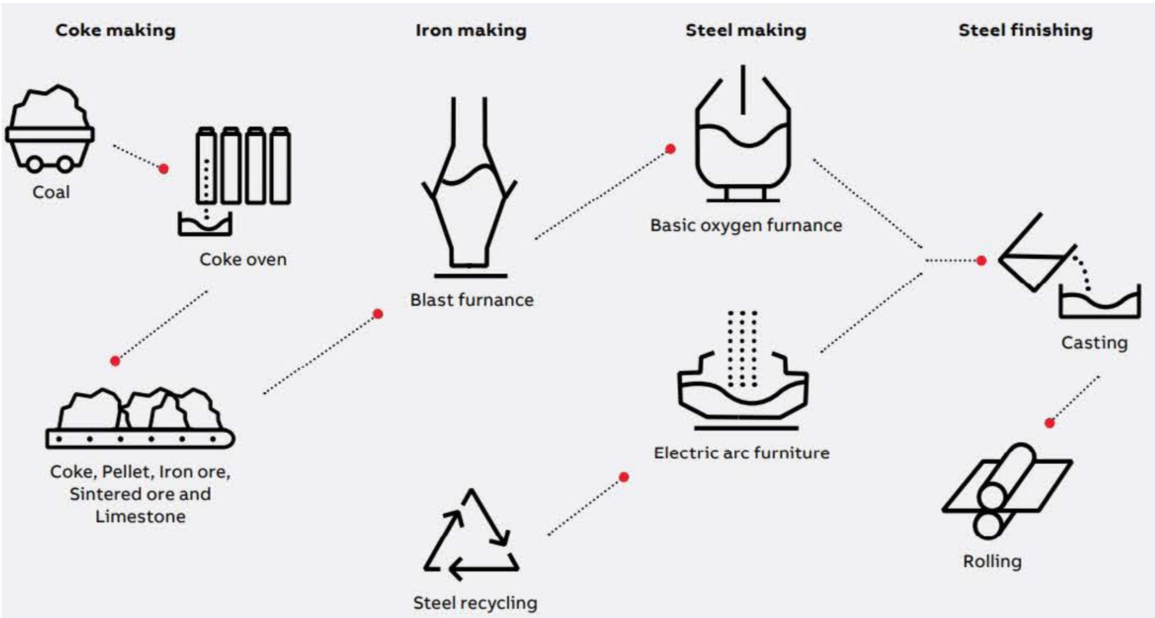


Fig. D1. Energy and coal use in iron and steel making processes (Source: ABB 2022).

The steel manufacturing process begins by smelting iron ore (Fe_2O_3 and/or Fe_3O_4) in an oxygen blast furnace. This smelting process melts out and separates iron from the original rock material, where the Fe melting temperature is less than the surrounding rock matrix. The iron ore is mixed with coke. The blast furnace burns the coke to heat the iron ore causing it to react into iron (Fe_2), nitrogen (N_2), and carbon dioxide (CO_2). The result is a liquid iron that flows from the bottom of the blast furnace. This product is termed "pig iron" or "hot metal". This iron can be used for ironworks or as the starting material for creating steel.

To produce steel carbon is released from the iron through either mechanical means or high temperatures. Mechanical means is what a blacksmith does when they pound the iron with a hammer. This forces the carbon from the iron to make steel, as it is shaped. Carbon can also be released through high temperatures (approximately 1800°C or higher), which are created by blowing air (with high oxygen content) through the furnace is operating. The oxygen raises the temperature of the furnace and reacts with carbon in the iron, creating carbon monoxide (CO). This reduces the carbon content of the iron, producing low carbon steel.

While the "Bessemer process" of steel production is widely known as the defining technology in the mass production of steel, modern steel is manufactured through two primary processes, the "Basic Oxygen Furnace" and "Electric Arc Furnace" (Cotter 1916).

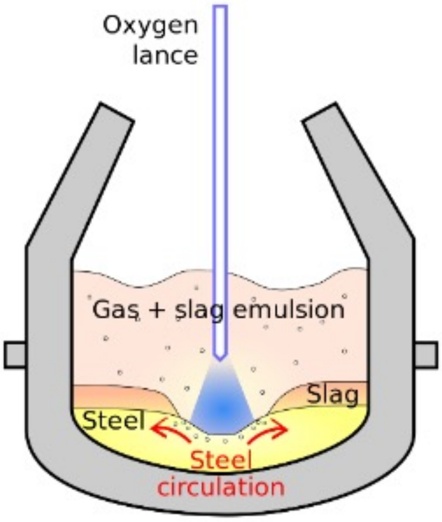


Fig. D2. Basic oxygen furnace (Source: Wikimedia Commons).

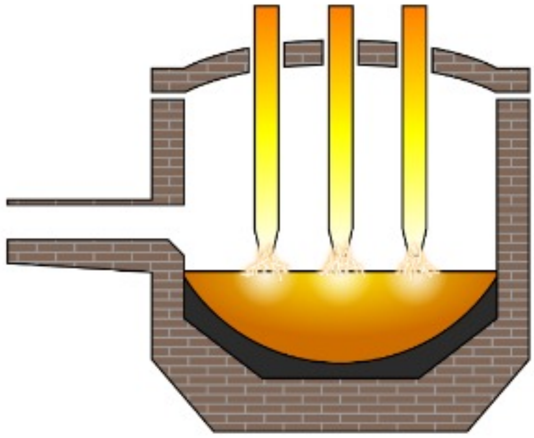


Fig. D3. Electric arc furnace (Source: Wikimedia Commons).

In a basic oxygen furnace (Fig. D2), oxygen is blown through liquid pig iron using the oxygen lance, increasing its temperature and releasing carbon (Martelaro 2016). Pure oxygen is often used as it improves the efficiency of the reaction between carbon and oxygen. Hydrocarbon fuel injection (coal, natural gas, oil, and tar) is also used to increase temperature and speed throughput.

In an electric arc furnace (Fig. D3), scrap steel and solid pig iron is melted using an electric arc (Martelaro 2016). The electric current passes through the steel, heating it a high degree. Since electricity is used to heat the metal, new steel can be created entirely from scrap steel. This avoids the step of creating pig iron from iron ore. Once the liquid steel is created it can then be cooled, rolled, cast, and formed into a wide variety of products.

Like all industrial processes, the production of steel consumes energy at each process stage (Desai 1986). This section gives an overview of the energy requirements of major production processes:

- the creation of pig iron,
- basic oxygen furnace production,
- and electric arc furnace production.

The theoretical minimum for creating steel, a practical minimum as and real-world energy use in American steel plants is shown in Table D1.

Table D1. Energy consumption in steel production (Source: Fruehan et al. 2000).

Steel Production Process	**Theoretical Absolute Minimum** (billion Joules / metric ton)	**Practical Minimum** (billion Joules / metric ton)	**Actual Average Requirement** (billion Joules / metric ton)	**% Over Practical Minimum** (%)
Liquid Metal "Pig Iron"	9,8	10,4	13,5	23%
Liquid Hot Metal: Basic Oxygen Furnace	7,9	8,2	11	25%
Liquid Hot Metal: Electric Arc Furnace	1,3	1,6	2,25	29%
Hot Rolling Flat	0,03	0,9	2,2	59%
Cold Rolling Flat	0,02	0,02	1,2	98%

Table D2. Energy consumption in steel production across whole process (Source: Fruehan et al. 2000).

	Average Energy Requirement to Produce Steel (billion Joules / metric ton)	**Average Energy Requirement to Produce Steel** (kWh/metric tonne)
Liquid Metal "Pig Iron"	13,5	3 750
Liquid Hot Metal: Basic Oxygen Furnace	11	3 056
Liquid Hot Metal: Electric Arc Furnace	2,25	625
Hot Rolling Flat	2,2	611
Cold Rolling Flat	1,2	333
Process path Pig Iron + Basic Oxygen Furnace + Hot Rolling Flat + Cold Rolling Flat	27,9	7 750
Process path Pig Iron + Electric Arc Furnace + Hot Rolling Flat + Cold Rolling Flat	19,2	5 319

Note: 1 billion joules = 277.777778 kilowatt hours

Taking data from Table D2, it requires between 7 750 and 5 319 kWh to produce a single tonne of steel, depending on what conventional process path is used. A non-fossil fuel alternative could be the use of hydrogen to produce steel.

In Sweden, an initiative which endeavors to revolutionize steel-making is being developed called HYBRIT, a collaboration between SSAB, LKAB and Vattenfall (HYBRIT 2019). HYBRIT aims to replace coking coal, traditionally needed for ore-based steel making, with hydrogen. The result will be the world's first fossil-free steel-making technology, with virtually no carbon footprint. During 2018, work started on the construction of a pilot plant for fossil-free steel production in Luleå, Sweden. The goal is to have a solution for fossil-free steel by 2035. While still in feasibility, this potentially could provide a way to manufacture steel without coal. According to the HYBRIT website, a tonne of steel could be produced with just 3 488 kWh. This lower energy consumption could be due to the use of an Electric Arc Furnace, which processes mostly un oxidated steel, it would need less energy to meet the same performance targets.

For the purposes of this study, it is assumed that the HYBRIT system works as shown (where production is much more energy efficient than the conventional process path at 3 488 kWh/tonne), and all steel production is transferred away from conventional coal fired production and using the hydrogen atmosphere process proposed by HYBRIT instead. For each tonne of steel, an estimated 52 kg of hydrogen would be needed as feedstock (HYBRIT).

Global crude steel production reached 1808.6 million tonnes (Mt) for the year 2018 (World Steel Association 2019). If it requires 3 488 kWh/tonne to produce steel (assumption that this is valid, giving a more conservative outcome), then 6 308.4 TWh of electrical power is needed to be generated annually to deliver this needed quantity of steel ([1.81 x 10^9 tonne] x [3.488 x 10^3 kWh/tonne] = [6.308 x 10^{12} kWh]). To produce the electrical power at the power station, assuming a 10% transmission loss, 6.94 x 10^{12} kWh, or **6 939.2 TWh** would need to be generated.

ANNEX E.
PRODUCTION OF AMMONIA

A proposed alternative to hydrogen fuel is ammonia. As it is a liquid at room temperature and pressure, ammonia does not have the same storage and transport logistical problems that hydrogen does. Ammonia (NH_3) is one of the most important and widely produced inorganic chemicals in the world, which can be used:

1. to produce agricultural fertilizers like ammonium nitrate, ammonium phosphate, and urea (Khademi & Sabbaghi 2017, IEA 2021b)
2. as a capturing agent in acid gas removal (AGR) processes (Akbari et al. 2018, IEA 2021b),
3. for large scale refrigeration and air-conditioning for buildings and industrial processes (Egenhofer et al. 2014, IEA 2021b),
4. to manufacture explosive materials, fibers, plastics, polymers, papers, and acids (Khademi & Sabbaghi 2017), and
5. as a potential fuel for internal combustion engines (ICE) due to a high octane rate of 110–130 (Zamfirescu & Dincer 2009) and fuel cells (e.g., solid-oxide fuel cells) for power generation with or without reforming (Aziz et al. 2017, Fuerte et al. 2009).

Ammonia is produced by using heat to force the combining of nitrogen (sourced from the air, and sometimes sourced from gasifying coal) with hydrogen to produce ammonia (NH_3), as shown in Equation 1. Ammonia is currently produced at an industrial scale through the synthesis of nitrogen and hydrogen, through the use of the Haber-Bosch process (Appl 1982), which is an artificial nitrogen fixation process and is the main industrial procedure for the production of ammonia. The hydrogen is sourced from natural gas, with the majority content being methane. The reaction is reversible, and the production of ammonia is exothermic.

$$N_2 + 3H_2 \xrightarrow{\text{yields}} 2NH_3 \qquad \text{Equation 1}$$

At each pass of the gases through the reactor, only about 15% of the nitrogen and hydrogen converts to ammonia (Appl 1982). Gases are cooled and ammonia turns into liquid. Liquid ammonia is separated, and rest of the gas is recycled. By continual recycling of the unreacted nitrogen and hydrogen, it is possible to produce ammonia from about 97 to 98% of the feedstock. This conversion requires to be conducted at pressures above 10 MPa (is often much higher for efficiency of output) and between 400 and 500 °C. The ammonia is then used to create other forms of nitrogen including ammonium nitrate and urea (ammonia + CO_2).

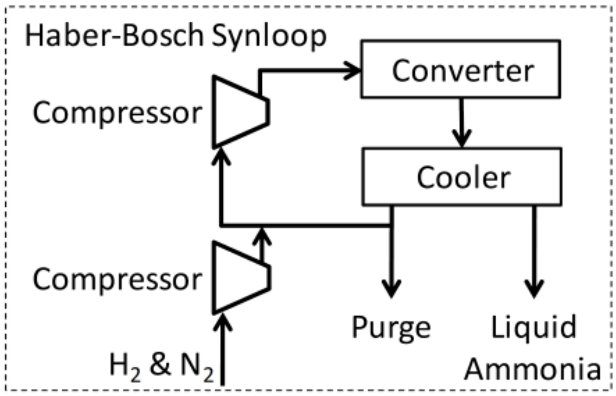


Fig. E1. Flow diagram of Haber-Bosch synthesis loop showing major components (Bartels 2008).

Table E1. Comparison of fuel properties (Source: IEA 2024a, fuel information Ammonia, https://www.iea-amf.org/content/fuel_information/ammonia).

	**Energy content (LHV)** (MJ/kg)	**Energy content (LHV)** (MJ/L)	**Density** (kg/m^3)	**Octane** (RON)	**Flame-velocity** (m/s)	**Flammability-limits** (vol/%)	**Minimum Ignition Energy** (mJ)
Cooled Ammonia (Liquefied)	18,6	12,69 (1 atm, -33°C)	682	>130	0,067	15-28	680
Compressed Ammonia (Liquefied)	18,6	11,65 (300 bar, 25°C)	626	>130	0,067	15-28	680
Cooled Hydrogen (Liquefied)	120	8,5 (1atm, -253°C)	70,85	>130	3,25	4.7-75	~0.016
Compressed Hydrogen (gaseous)	120	2.46 (300 bar, 25°C)	20,54	>130	3,25	4.7-75	~0.016
Diesel (n-dodecane)	44,11	32.89 (1 atm, 25°C)	745.7[12]	<20	~0.80	0.43-0.6	~0.23
Gasoline iso-octane)	44,34	(n-octane) (1 atm,25°C)	(n-octane) 697.6 30,93	100	0.41 ~0.58	0.95-6 (RON 90-98) (RON 90-98)	1.35 ~0.14 (RON 90-98) 0.6-8
Methanol	19.90	15.65 (1 atm,25°C)	786,3	108,7	0,56	6.7-36	~0.14
Ethanol	26,84	21.07 (1 atm,25°C)	785,1	108,6	0,58	3.3-19	0,6

Note: 1 MJ = 0.2778 kWh

The hydrogen used in commercial-scale ammonia synthesis processes comes mainly from natural gas, coal, and other fossil fuels (IEA 2021a). Therea re several other methods of producing ammonia with hydrogen (Rivarolo et al. 2019. Two-thirds of ammonia are currently synthesized from natural gas-derived hydrogen worldwide; while in China, 97% of ammonia is synthesized from coal-derived hydrogen (Xiang & Zhou 2018). However, to reduce fossil fuel consumption and greenhouse gas emissions, renewable energy derived green hydrogen is being promoted for ammonia production (IEA 2021b). Considering the application scale, potential alternatives for green hydrogen are biomass gasification and water electrolysis via renewable power, namely biomass-to-ammonia (BtA) and power-to-ammonia (PtA). Ammonia has a relatively low calorific value, and on top of that, characteristics like low cetane number and low flame speed make it difficult to apply in combustion engines. Ammonia's fuel properties are challenging when used in internal combustion engines (Table E1).

PRODUCTION OF AMMONIA FOR 46% OF THE MARITIME SHIPPING FLEET

In this study, it was assumed that 46% of the maritime shipping fleet would have ICE propulsion systems fueled with ammonia (Fig. E2), as per the prediction for 2050 (IEA 2021a) and as shown in Table 3 of the main report.

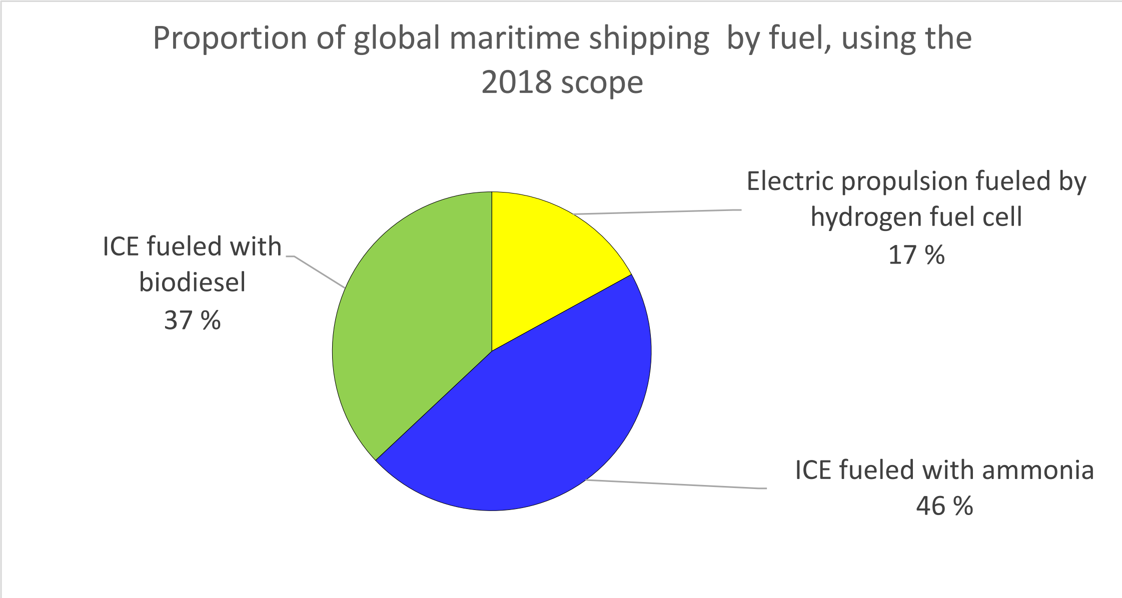


Fig. E2. Proportion of global maritime shipping by fuel, using the 2018 scope (Source: split taken from IEA 2021a).

Table E2. Petroleum product consumption in the year 2018 (Source: OECD Data Statistics Database).

Fossil Fuel	Fuel consumed in 2018	
	(bbls)	(Liters)
Petrol	9 307 500 000	1,48E+12
Diesel	10 439 000 000	1,66E+12
Marine fuel *	194 499 000 (tonne)	2,63E+11
Jet fuel	2 260 000 000	3,59E+11
	Annual total	3,76E+12

* Units of tonnes were converted to liters where:
1 tonne = 8.5 barrels
1 Barrel volume unit is equal to 158.98 Liters
Thus, scalar to convert tonne to liters = 1351.39

As such, of the 2.63 x 10^{11} liters (Table D2) of marine bunker fuel oil annual consumption in 2018 (OECD Data Statistics Database), 1.21 x 10^{11} liters of that bunker fuel oil would be replaced by an equivalent quantity of ammonia. Table D2 shows the fossil fuel petroleum product consumption. It is this fuel quantity that global annual ammonia production will be required to replace.

There are several technologies being considered to replace bunker fuel oil grade diesel in Internal Combustion (ICE) propulsion systems in the maritime shipping industry. Among these, anhydrous ammonia (NH_3) has been identified as a potential long-term fuel that could enter the market relatively quickly and offer a zero, or a near-zero, carbon solution (on a tank-to-wake basis and in some cases on a well-to-wake basis) irrespective of the origin of the fuel (European Maritime Safety Agency 2022).

Following a similar procedure as shown in Annex C, the amount of energy required to price enough ammonia to fuel 46% of the global shipping fleet. Some of the work done from Annex C is used again and developed. Table E3 is a repeat of Table C11 and shows an estimate of the distance travelled by the different shipping classes across 2018. Table E4 (a repeat of Table C12), shows an estimate of the distance travelled of each shipping class, as estimated by fuel, as predicted by the IEA (Table 3 and IEA 2021a). Table E5 (Table C16) shows an estimate of the total energy consumed doing useful work, given distance travelled by 46% of the fleet and energy efficiency as calculated in Annex C.

Table E3. Fuel consumption and distance travelled by ship class (Table D3).

Size Classification	**World seaborne trade** (billions of tonne-km)	**World seaborne trade proportion of ,194 499 kT of bunker fuel in 2018** (tonne)	**Average fuel consumption** (tonnes/km)	**Distance travelled in 2018** (km)
Small (100 GT to 499 GT)	972,1	1 944 990	0,0097	2,01E+08
Medium (500 GT to 24 999 GT)	16 525,0	33 064 830	0,0304	1,09E+09
Large (25 000 GT to 59 999 GT)	32 078,0	64 184 670	0,0843	7,61E+08
Very Large (>60 000 GT)	47 631,0	95 304 510	0,1968	4,84E+08
Total	97 206,1	194 499 000		2,54E+09

Table E4. Proportion of global maritime shipping by fuel, using the 2018 scope (Source: split taken from IEA 2021a) (Table D4).

Size Classification	**Electric propulsion fueled by hydrogen fuel cell** 17% (km)	**ICE fueled with ammonia** 46% (km)	**ICE fueled with biodiesel** 37% (km)	**Total Distance travelled in 2018** 100% (km)
Small (100 GT to 499 GT)	3,42E+07	9,25E+07	7,44E+07	2,01E+08
Medium (500 GT to 24 999 GT)	1,85E+08	5,01E+08	4,03E+08	1,09E+09
Large (25 000 GT to 59 999 GT)	1,29E+08	3,50E+08	2,82E+08	7,61E+08
Very Large (>60 000 GT)	8,23E+07	2,23E+08	1,79E+08	4,84E+08
Total	4,31E+08	1,17E+09	9,38E+08	2,54E+09

Table E5. Energy expended doing useful work for the proposed hydrogen fueled vessels, 17% of the 2018 global shipping industry (Table D5).

Size Classification	**Distance travelled by 46% of global shipping fleet fuled by ammonia (using 2018 scope)** (km)	**Useful work done efficiency** (kWh/km)	**Energy consumed doing useful work** (kWh)
Small (100 GT to 499 GT)	9,25E+07	46,9	4,33E+09
Medium (500 GT to 24 999 GT)	5,01E+08	147,1	7,37E+10
Large (25 000 GT to 59 999 GT)	3,50E+08	408,7	1,43E+11
Very Large (>60 000 GT)	2,23E+08	953,5	2,12E+11
Total	1,17E+09		4,33E+11

Shown in Table E5, is an estimate of quantity of ammonia needed to fuel these shipping vessels. The useful work established in Table E5 was adjusted to allow for the efficiency of an Internal Combustion Engine (ICE) of 38% (Lide 1991). Then the final quantity of ammonia was calculated, given an energy density of ammonia of 5.167 kWh/kg (18.6 MJ/kg) (IEA2024a, fuel information Ammonia, https://www.iea-amf.org/content/fuel_information/ammonia). Giving a total of 2.21 x 10^8 tonnes of ammonia to be produced.

Table E6. Estimation of the quantity of ammonia to fuel 46% of the global shipping fleet (2018 scope) (Table C6).

Size Classification	Energy consumed doing useful work (kWh)	Fuel consumption in an ICE engine, assuming 38% efficiency (kWh)	Mass of ammonia given energy density of ammonia = 5.167 kWh/kg (tonnes)
Small (100 GT to 499 GT)	4,33E+09	1,14E+10	2,21E+06
Medium (500 GT to 24 999 GT)	7,37E+10	1,94E+11	3,75E+07
Large (25 000 GT to 59 999 GT)	1,43E+11	3,76E+11	7,29E+07
Very Large (>60 000 GT)	2,12E+11	5,59E+11	1,08E+08
Total	4,33E+11	1,14E+12	2,21E+08

Table E7 shows the calculations for the energy required to produce the ammonia. Ammonia is produced from a combination of nitrogen and hydrogen (Equation D1), where to produce 1 tonne of ammonia, 177 kg of hydrogen is combined with 823 kg of nitrogen. The energy consumed to produce 1 tonne of ammonia using a Haber-Bosch process is 26 GJ (7 222.2 kWh) (Rouwenhorst et al. 2021).

The production of hydrogen requires 50 kWh/kg (or 50 MWh/tonne). To produce 177 kg of hydrogen would require 8 850 kWh (50 x 177), which is the hydrogen feedstock to produce 1 tonne of ammonia.

Table E7. Estimation of the energy required to produce hydrogen to produce ammonia fuel for 46% of the global shipping fleet (2018 scope).

Size Classification	Mass of ammonia given energy density of ammonia = 5.167 kWh/kg (tonnes)	Quantity of hydrogen given 1 tonne ammonia requries 177 kg of H_2 (kg)	Energy consumed to produce hydrogen @50 kWh/kg (kWh)	Electrical power generated at station to account for 10% loss in transmission (kWh)
Small (100 GT to 499 GT)	2,21E+06	3,91E+08	1,95E+10	2,15E+10
Medium (500 GT to 24 999 GT)	3,75E+07	6,64E+09	3,32E+11	3,65E+11
Large (25 000 GT to 59 999 GT)	7,29E+07	1,29E+10	6,45E+11	7,09E+11
Very Large (>60 000 GT)	1,08E+08	1,91E+10	9,57E+11	1,05E+12
Total	2,21E+08	3,91E+10	1,95E+12	2,15E+12
Total	220,8 (million tonnes)	39,1 (million tonnes)		2 149,2 (TWh)

Table E8. Estimation of the energy required to produce ammonia fuel in addition to hydrogen production.

Size Classification 	**Mass of ammonia given energy density of ammonia = 5.167 kWh/kg** (tonnes)	**Energy consumed to produce ammonia @7222.2 kWh/tonne** (kWh)	**Electrical power generated at station to account for 10% loss in transmission** (kWh)
Small (100 GT to 499 GT)	2,21E+06	1,59E+10	1,75E+10
Medium (500 GT to 24 999 GT)	3,75E+07	2,71E+11	2,98E+11
Large (25 000 GT to 59 999 GT)	7,29E+07	5,26E+11	5,79E+11
Very Large (>60 000 GT)	1,08E+08	7,81E+11	8,59E+11
Total	2,21E+08	1,59E+12	1,75E+12
Total	220,8 (million tonnes)		1 753,9 (TWh)

If it takes a further 7 222.2 kWh/tonne to produce the ammonia (Rouwenhorst et al. 2021) in the Haber-Bosch process (Appl 1982), then the full energy cost to produce ammonia would be:

1 tonne ammonia = 16 072.2 kWh (8850 + 7222.2)

Table E9. Estimation of the energy required to produce ammonia fuel for 46% of the global shipping fleet (2018 scope).

Size Classification 	**Mass of ammonia required to fuel 46% of maritime shipping** (tonnes)	**Electrical power generated to produce hydrogen** (kWh)	**Energy consumed to produce ammonia @7222.2 kWh/tonne** (kWh)	**Total energy required to produce Ammonia** (kWh)
Small (100 GT to 499 GT)	2,21E+06	2,15E+10	1,75E+10	3,90E+10
Medium (500 GT to 24 999 GT)	3,75E+07	3,65E+11	2,98E+11	6,64E+11
Large (25 000 GT to 59 999 GT)	7,29E+07	7,09E+11	5,79E+11	1,29E+12
Very Large (>60 000 GT)	1,08E+08	1,05E+12	8,59E+11	1,91E+12
Total	2,21E+08	2,15E+12	1,75E+12	3,90E+12
Total	220,8 (million tonnes)	2 149,2 (TWh)	1 753,9 (TWh)	3 903,1 (TWh)

The electrical power to produce 39.1 million tonnes of hydrogen, to in turn produce 220.8 million tonnes of ammonia to annually power 46% of the maritime shipping fleet (based on 2018 scope) is **3 903.1 TWh**.

ANNEX F. PRODUCTION OF BIODIESEL AND ETHANOL BASED JET FUEL

Corn and soy are high maintenance crops because they need a lot of pesticides to produce a good yield. Of global pesticide use on crops, corn's share is 39.5% and soybeans 22% (Mclaughlin & Walsh 1998, Padgitt et al. 2000, Pimentel 2003, Patzek 2004, Patzek 2005, Fernandez-Cornejo et al. 2014).

The production of biofuel from algae feedstock was examined in (Michaux 2021, Sections 21 & 22). It was found to not be viable as more energy was required to make the biofuel than was in the algae feedstock.

Table F1. Petroleum product consumption in the year 2018 (Source: OECD Data Statistics Database).

Fossil Fuel	Fuel consumed in 2018	
	(bbls)	(Liters)
Petrol	9 307 500 000	1,48E+12
Diesel	10 439 000 000	1,66E+12
Marine fuel *	194 499 000 (tonne)	2,63E+11
Jet fuel	2 260 000 000	3,59E+11
	Annual total	3,76E+12

* Units of tonnes were converted to liters where:
1 tonne = 8.5 barrels
1 Barrel volume unit is equal to 158.98 Liters
Thus, scalar to convert tonne to liters = 1351.39

PRODUCTION OF JET FUEL FROM CORN-BASED ETHANOL FOR 62% OF THE AVIATION FLEET

In this study, it was assumed that the aviation industry would contract in activity by 38%, as per the prediction for 2050 (IEA 2021a), as shown in Table 3. As such, the 3.59 x 10^{11} liters of jet fuel annual consumption in 2018 (OECD Data Statistics Database) would contract to 2.23 x 10^{11} liters of jet fuel.

Bioethanol is an alcohol made by fermentation, mostly from carbohydrates produced in sugar or starch crops such as corn, sugarcane, or sweet sorghum, where most bioethanol is produced using corn feedstock (FAO 2008a,b). Ethanol is an alcohol product produced from corn, wheat, sugar cane, and biomass and used as an additive in gasoline to increase its octane level. Cellulosic biomass, derived from non-food sources, such as trees and grasses, is also being developed as a feedstock for ethanol production (Neupane 2017). To date, commercialization of cellulosic ethanol production has been very challenging (Liu et al. 2013). Ethanol can be used as a fuel for vehicles in its pure form (E100), but it is usually used as a gasoline additive to increase octane and improve vehicle emissions (Griggs et al. 2014). Bioethanol is widely used in the United States and in Brazil (Biswas 2018). Biodiesel is not the same thing as raw vegetable oil or unaltered used frying grease (Fig. F1).

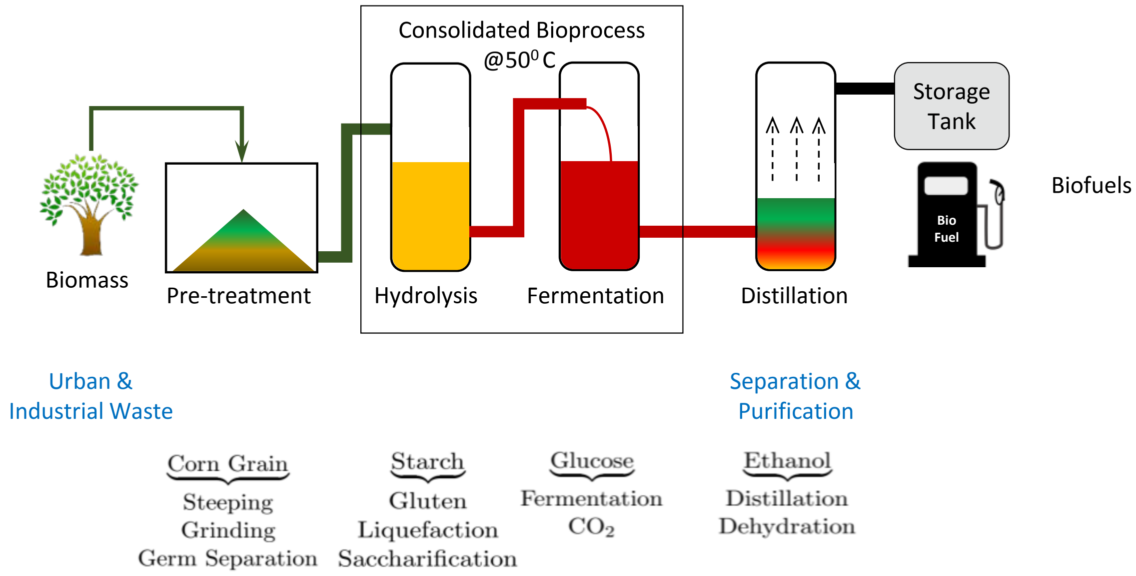


Fig. F1. Biofuel generation (Source: Liu et al. 2013, and https://paulvandecruys.files.wordpress.com/2014/03/blog-8.jpg) (Image: Simon Michaux, using some copyright free clipart).

In the United States in 2015, an average of 2.8 gallons of ethanol was produced per bushel of corn (IEA 2020b). The average corn yield in the Unites States was 167.5 bushels per acre in 2015, with a yield of 462 gallons per acre of bio ethanol produced (EIA 2024b, Monthly Biodiesel Production Report, https://www.eia.gov/biofuels/biodiesel/production/).

Given that:

- 1 bushel of corn = 0.022 metric tons of corn
- 1 US gallon = 3.79 liters
- 1 acre = 0.0041 km^2
- 1 btu = 0.000293 kilowatt hours

Converting the above units into standard S.I. units, resulting in:

- 1 km^2 of corn growing land produces about 41 372 bushels (1 acre produces 167.5 bushels)
- 1 km^2 of corn growing land can produce about 901 127 kg (or 901.13 tonne) of corn
- 1 km^2 of corn growing land produces 432 142 liters of bio-ethanol
- 2.08 kg of corn oil produces about 1 liters of ethanol

The average yield of anhydrous ethanol from corn is estimated to be 0.480 Liters of ethanol (EtOH) per kg of corn grain, or 2.085 kg of corn was consumed per liter of bioethanol produced. As part of the waste plume from producing ethanol from corn, for every liter of ethanol produced, 12 liters of noxious liquid sewage effluent are released which need to be treated (Schulz 2007, orginal units in gallons). An acre of sugar cane can produce approximate 35 ton yield or about 560 gallons of ethanol (Hofstrand 2009). A large proportion of the global corn, soy and sugar crop is already consumed to meet biofuel production demand.

In the United States, 40% of the corn crop is used to make ethanol biofuel (EIA Monthly Biodiesel Production Report, https://www.eia.gov/biofuels/biodiesel/production/). The water consumption footprint for food crop production is already quite high. In the United States, 70% of groundwater withdrawals is used to grow irrigated crops (Friedemann 2021), where the remaining 30% is used by livestock, aquaculture, industry, mining, and thermoelectric power plants (FAO 2015).

The water consumption footprint to grow corn is 2570 liters (680 gallons) of rainfall or irrigation water to produce enough corn to make just one liter of ethanol (Gerbens-Leenes et al. 2009). In some irrigated corn acreage in the United States Western regions, groundwater is being mined at a rate 25% faster than the natural recharge of its aquifer (Pimentel 2003, NRC 2003, Friedemann 2021).

Corn and soy are 50 or more times more prone to soil erosion than sod crops like wheat, barley, rye, and oats. After harvest, the corn fields are often left bare, where the unprotected soil is highly susceptible to erosion from wind and heavy rain. Large volumes of sediment, pesticides, and fertilizer are washed away into water ways. For each liter of ethanol produced, an estimated 2.40 to 4.79 kg of soil is lost to erosion (NRC 2014, Friedemann 2021)

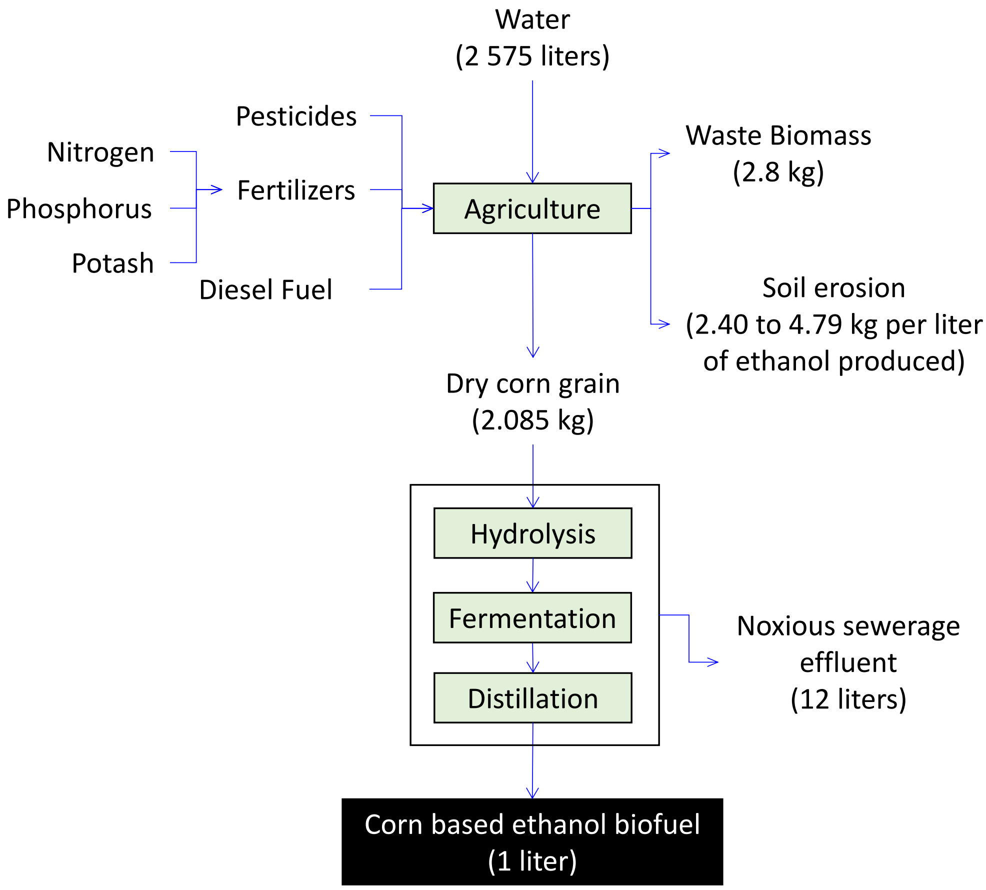


Fig. F2. Inputs and material flows to produce 1 liter of corn based ethanol (Source: based on data from IEA 2020b, EIA Monthly Biodiesel Production Report, https://www.eia.gov/biofuels/biodiesel/production/, Schulz 2007, Gerbens-Leenes et al. 2009, NRC 2014).

Global production of corn and soy, erode more topsoil, cause more pollution, global warming, acidification, eutrophication of water, water treatment costs, fish kills, and biodiversity loss than most other crops (Powers 2005, Troeh & Thompson 2005, Zattara & Aizen 2019). The cultivation of corn consumes more nitrogen based fertilizer than most other crops (Padgitt et al. 2000, Pimentel & Patzek 2005, NRC 2003), and significant quantities of phosphorus based fertilizers. Corn requires a lot of fertilizer because corn plants are natural adept at absorbing nitrogen and storing it in the corn grain. But unfortunately, much of the nitrogen fertilizer applied does not go into the grain but instead washes away into lakes, rivers, and the ocean (NRC 2014).

The Energy Returned on Energy Invested (ERoEI) ratio for corn based ethanol is 0.8 to 1.6:1 (Pimental et al. 2005). From a calorie count audit perspective, several studies have shown that it takes about one calorie of fossil fuel to make a calorie of ethanol (Pimentel 2003, Murphy et al. 2011). In this study, it was assumed that the aviation industry would contract in activity by 38%, as per the prediction for 2050 (IEA 2021a). As such, the 3.59 x 10^{11} liters of jet fuel annual consumption in 2018 (OECD Data Statistics Database) would contract to 2.23 x 10^{11} liters of jet fuel.

In order to substitute ICE jet turbine aircraft, the replacement technology would need to perform with the same specifications as the current standard aircraft. The Airbus A350 and the Boeing 777 are becoming the standard passenger transport aircraft. The A350-900 is a wide-body aircraft manufactured by Airbus (Airbus 2024). This jetliner accommodates between 300 and 350 passengers in a standard three-class configuration, with maximum seating of 440 passengers (https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a350-family). The A350-900 has an operational range of 15 000 km, maximum take-off weight of 280 tonnes, and a maximum jet fuel capacity of 141 000 liters.

Let us consider a thought experiment; that the global jet fuel annual consumption was to meet the production of biofuels. In this scenario, corn would be used as a feedstock to produce ethanol as a substitute biofuel, although to produce jet fuel, some extra distillation steps could be applied (not included here). The flowsheet shown in Figure E2 was used to estimate the mass flows required to produce 1 liter of ethanol. Where:

- 2.08 kg of corn grain produces 1 liter of ethanol
- To produce 1 liter of ethanol, 2 575 liters of water will be used to irrigate the corn
- To produce 1 liter of ethanol, 12 liters of noxious sewerage effluent are produced

This flowsheet is a composite from several sources of data (often in units of gallons and pounds, converted to liters and kg) that are discussed in (Michaux 2021a Section 21). This flowsheet was applied to the 2018 global annual demand for jet fuel (2.23 x 10^{11} liters) combined to a production target of bio ethanol produced from 464.5 million tonnes of corn biomass feedstock.

Table F2. Land use and water consumption in the production of ethanol biofuel for the aviation industry.

Liters of jet fuel to be produced from ethanol biofuel (liters)	Biomass feedstock dry corn to produce ethanol biofuel @2.08 kg/liter of fuel (kg)	Potable water consumed to produce ethanol biofuel @2 575 liters per liter of fuel (liters)	Arable land needed given 901 127 kg/km² of corn production (km²)	Soil erosion (3kg per litre of fuel produced assumed) (kg)
2,23E+11	4,64E+11	5,74E+14	515 445,3	6,68E+11
	464,5 (million tonnes)	573,6 (km³)		668,3 (million tonnes)

Note: 1 km² of corn growing land can produce about 901 127 kg (or 901.13 tonne) of corn
1 liters = 1.0 × 10-12 cubic kilometers

This was then used to estimate the biomass of dry corn, and area of arable land required to grow corn, assuming for every 1 km² of corn growing land produces 432 142 liters/km² of bio-ethanol. This resulted in a needed 0.83 million km² of arable land, and 573.6 km³ of fresh water would be needed in the global system to produce corn for bio-jet fuels.

Table F3. Biomass feedstock and waste in producing ethanol biofuel for the aviation industry.

Liters of jet fuel to be produced from ethanol biofuel (liters)	Biomass feedstock dry corn to produce ethanol biofuel @2.08 kg/liter of fuel (kg)	Waste biomass @2.8 kg/liter of fuel (kg)	Noxious sewerage effluent produced @12 liters per liter of fuel produced (liters)
2,23E+11	4,64E+11	6,24E+11	2,67E+12
	464,5 (million tonnes)	623,8 (million tonnes)	2,67 (km³)

Note: 1 liters = 1.0 × 10-12 cubic kilometers

Table F4. Estimated quantity of biomass and arable land required to grow corn to produce enough biofuels to substitute 2018 annual petroleum product consumption (OECD Data Statistics Database).

Jet fuel globally consumed in 2018 (Liters)	Jet fuel consumed after a 38% contraction in capacity (Liters)	Bioethanol to be produced (Liters)	Arable land needed to produce the same quantity of biofuel (km^2)	Biomass of dry corn required as feedstock (kg)	Generation of noxious sewerage effluent (Liters)
3,59E+11	2,23E+11	2,23E+11	831 465,8	4,63E+11	2,67E+12
Total		222,8 (billion liters)	0,83 (million km^2)	463,37 (million tonnes)	2,67 (km^3)

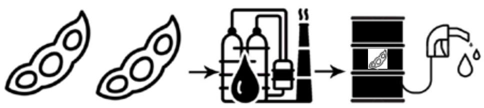
Table F5. Estimated water consumption footprint for 1 years production of corn feedstock to produce biofuel to substitute petroleum jet fuel (based on 2018 consumption).

Bio jet fuel production, given a 38% contraction on 2018 scope	Volume of fresh water (liters)	Volume of fresh water need to produce biomass (liters)	Volume of fresh water need to produce biomass (m^3)	Volume of fresh water need to produce biomass (km^3)
Corn ethanol liters to be produced annually	2,23E+11	5,74E+14	5,74E+11	573,6
Water needed per liter of fuel produced	2 575			

PRODUCTION OF BIODIESEL BIOFUEL FROM SOY FOR 37% OF THE MARITIME SHIPPING

Biofuel is fuel derived from biological sources such as soybean oil or animal fats and is produced by a chemical process that removes the glycerin from the oil. The majority of biodiesel is produced from soybean feedstock (FAO 2008a). Limited amounts of biodiesel can be used in any diesel vehicle without modification (Sadaka 2013).

Vehicles that are able to use biodiesel include buses, delivery trucks, waste disposal and recycling trucks, construction equipment, heavy-duty freight-hauling trucks, boats, passenger vehicles and tractors. Biodiesel can be blended at any ratio with petroleum diesel to achieve cost efficiency and improve cold weather performance.



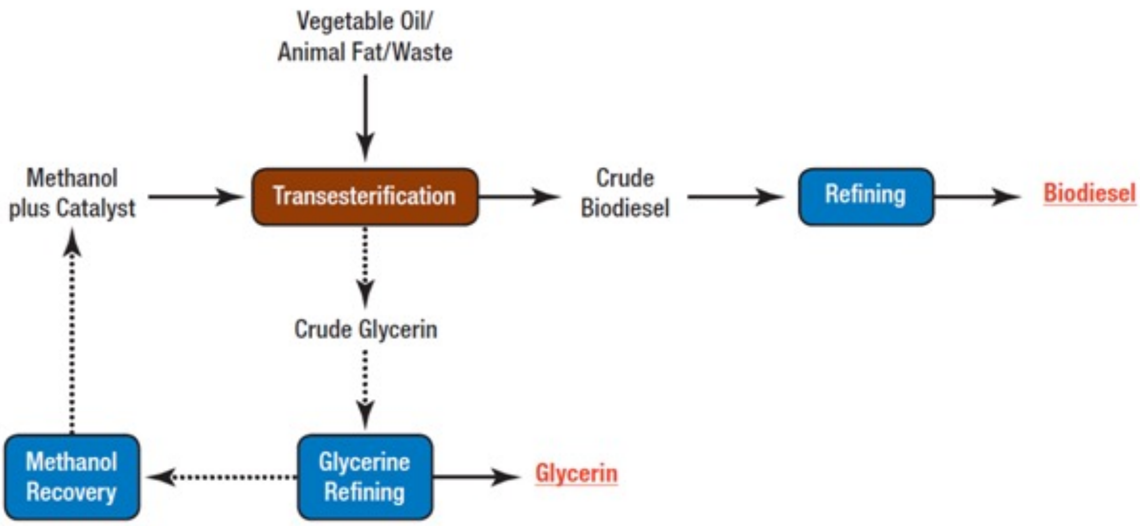


Fig. F3. Schematic production path for Biodiesel (Source: U.S. Department of Energy 2024, https://afdc.energy.gov/fuels/biodiesel_production.html) (Copyright License: https://www.energy.gov/about-us/web-policies).

The United States produces more than a billion gallons a year of biodiesel (Friedemann 2021). This biodiesel is made from 95% vegetable oils (68% soybean, 16% corn, 11.4% canola) and 4.6% animal fats and grease (EIA 2024b).

Soy is a much more productive feedstock to produce biodiesel compared to corn. Corn can yield 18 gallons of biodiesel per acre, where soybeans can yield 57 gallons of biodiesel per acre (NRC 2014). Corn yields 177 bushels per acre and soy just 39 bushels. This difference is related to the fat content of each plant feedstock. Corn is 4% fat whereas soy is 20% fat (Troeh & Thompson 2005, Friedemann 2021). Biobased fat is required to produce biodiesel. Despite its low-fat content (4%) and because of its high yield, corn contributes 16% of annual United States biodiesel production in 2019 (EIA 2024b).

A chemical conversion process known as trans-esterification is used for converting vegetable oils, animal fats, and greases into fatty acid methyl esters (FAME), which are used to produce biodiesel. This process is the reaction of oil or fat with an alcohol (methanol) to form biodiesel and glycerol (Sadaka 2013). A catalyst such as sodium or potassium hydroxide is required. Glycerol is produced as a byproduct. Biodiesel has a higher flash point than fossil diesel and so is safer for storage or in the event of an accident. From Sadaka 2013 (orginal units in acres, pounds, and gallons):

- 1 km^2 of soybean land produces about 9 637 bushels (1 acre produces 39 bushels)
- 1 bushel of soybeans weighs 27.2 kg
- 1 km^2 of soybean land can produce about 262 279 kg (or 262.3 tonne) of soybeans
- 1 bushel of soybeans produces 4.99 kg of oil
- 1 km^2 of soybean land produces 48 084 kg (or 48 tonne) of oil
- 1 kg of soybean oil produces about 0.973 kg of biodiesel
- 1 km^2 of soybean land produces 46 851.6 kg (or 46.9 tonne) of biodiesel
- 1 liter of biodiesel weighs 0.875 kg
- 1 km^2 of soybean land produces about 53 317.6 liters (57 gallons per acre) of biodiesel

Given that:

- 1 US gallon = 3.79 liters
- 1 acre = 0.0041 km^2
- 1 btu = 0.000293 kilowatt hours

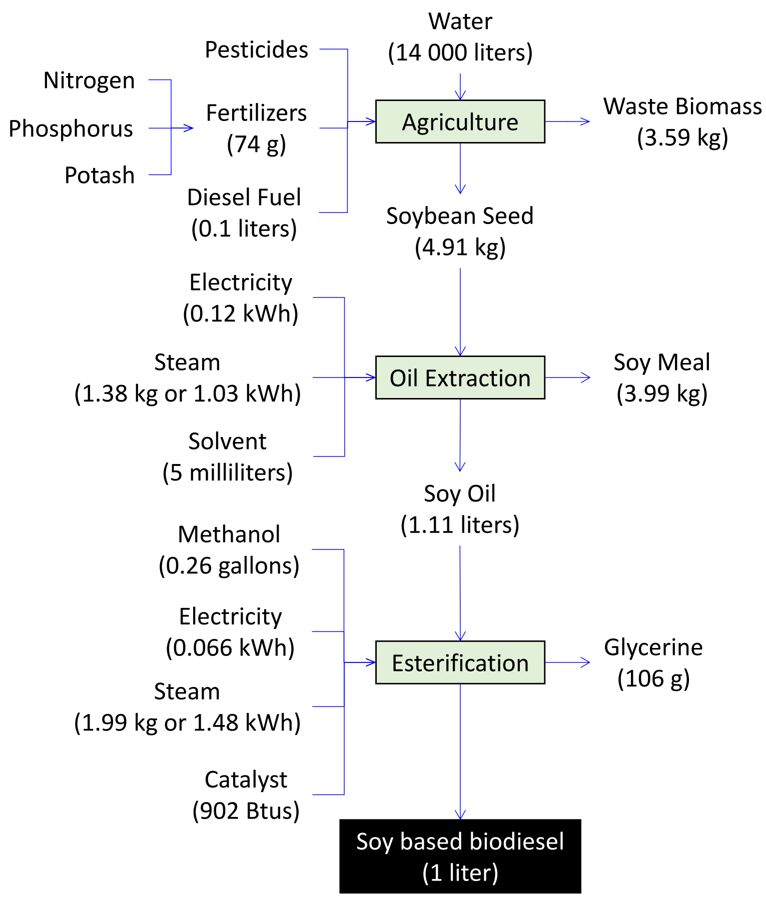


Fig. F4. Inputs and material flows to produce 1 liter of soy based biodiesel (Source: based on data from Sadaka 2013, Gerbens-Leenes et al. 2009).

The flowsheet in Figure F4 shows these numbers in a material flow sheet to produce 1 liter of biodiesel from a soybean feedstock. This flowsheet is a composite from several sources of data (often in units of gallons and pounds, converted to liters and kg) that are discussed in (Michaux 2021 Section 21).

Table F6. Biodiesel to fuel 37% of the global shipping transport fleet (based on 2018).

Liters of biodiesel to be produced (liters)	**Biomass feedstock of soybean seeds @4.91 kg/liter of fuel produced** (kg)	**Ferlizer @74 g per liter of fuel produced** (kg)	**Waste biomass @3.59 kg/liter of fuel** (kg)	**Glycerine produced @106 g per liter of fuel produced** (kg)
9,73E+10	4,78E+11	7,20E+09	3,49E+11	1,03E+10
Total	477,5 (million tonnes)	7,2 (million tonnes)	349,1 (million tonnes)	10,3 (million tonnes)

Table F7. Energy consumed in production of soybean feedstock biodiesel for 37% of the global aviation industry.

Liters of biodiesel to be produced (liters)	**Electricity consumed** (kWh)	**Steam consumed in production** (kWh)
9,73E+10	1,81E+10	2,44E+11
	18,1 (TWh)	244,1 (TWh)

To produce 1 liter of soy based biodiesel, 4.91 kg of soybean seed is required, resulting in 477.5 million tonnes of soybean biomass feedstock, and 1 361.5 km^3 of fresh water to annually produce enough biodiesel for 37% of the shipping fleet. It takes approximately 14 000 liters of water to produce enough soybeans to make a 1 liter of biodiesel (Gerbens-Leenes et al. 2009). The land use to grow soybeans can be quantified, where 53 317 liters of biodiesel could be produced on 1 km^2 of arable land used to grow soybeans (data taken from Sadaka 2013, then converted from imperial units to standard SI units).

Table F8. Water consumed and arable land required in production of biodiesel for 37% of the global shipping transport fleet.

Liters of biodiesel to be produced (liters)	**Potable water consumed to produce soybean biodiesel @14 000 liters per liter of fuel** (liters)	**Arable land needed given 1 km^2 of soybean production produces 53 317.6 liters of biodiesel** (km^2)
9,73E+10	1,36E+15	1 824 021,1
	1 361,5 (km^3)	1,82 (million km^2)

The Figure F4 flowsheet was applied to 37% of the 2018 global shipping annual demand for marine bunker fuel oil diesel (9.73 x 10^{10} liters) of biodiesel produced from soy feedstock. This was then adjusted to estimate the area of arable land required to grow soybeans, assuming for every 1 km^2 of soy growing land produces 53 317 liters/km^2 of bioethanol. This resulted in a needed 1.82 million km^2, and 1 361.5 km^3 of fresh water would be needed in the global system to produce soy for biofuels.

ANNEX G. MATERIAL PROPERTIES DATA AND EFFICIENCY OF POWER PLANTS OF DIFFERENT TYPES

Table G1. Higher and Lower Calorific Values of fuels (Source: Redrawn from The Engineering Toolbox https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html) (Lide 1991).

Fuel	**Density at temperature 0°C/32°F, 1 bar**		**Higher Heating Value (HHV) (Gross Calorific Value - GCV)**					**Lower Heating Value (LHV) (Net Calorific Value - NCV)**				
Gaseous fuels	**(kg/m³)**	**(g/ft³)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/m³)**	**(Btu/ft³)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/m³)**	**(Btu/ft³)**
at tempertaure of 0°C/32°F, and 1 bar of atmospheric pressure												
Acetylene	1,10	31,1	13,9	49,9	21 453	54,7	1 468					
Ammonia				22,5	9 690							
Hydrogen	0,09	2,6	39,4	141,7	60 920	12,7	341	33,3	120,0	51 591,0	10,8	290,0
Methane	0,72	20,3	15,4	55,5	23 874	39,8	1 069	13,9	50,0	21 496,0	35,8	964,0
Natural gas (US market)*	0,78	22,0	14,5	52,2	22 446	40,6	1 090	13,1	47,1	20 262,0	36,6	983,0
Town gas						18	483					
Liquid fuels	**(kg/l)**	**(kg/gal)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/l)**	**(Btu/gal)**	**(kWh/kg)**	**(MJ/kg)**	**(Btu/lb)**	**(MJ/l)**	**(Btu/gal)**
at tempertaure of 15°C/60°F, and 1 bar of atmospheric pressure												
Acetone	0,79	2,98	8,83	31,8	13 671	25	89 792	8,22	29,6	12 726	23,3	83 580
Butane	0,60	3,07	13,64	49,1	21 109	29,5	105 875	12,58	45,3	19 475	27,2	97 681
Butanol	0,81		10,36	37,3	16 036	30,2	108 359	9,56	34,4	14 789	27,9	99 934
Diesel fuel*	0,85	3,20	12,67	45,6	19 604	38,6	138 412	11,83	42,6	18 315	36,0	129 306
Dimethyl ether (DME)	0,67	2,52	8,81	31,7	13 629	21,1	75 655	8,03	28,9	12 425	19,2	68 973
Ethane	0,57	2,17	14,42	51,9	22 313	29,7	106 513	13,28	47,8	20 550	27,3	98 098
Ethanol (100%)	0,79	2,99	8,25	29,7	12 769	23,4	84 076	7,42		11 479	21,1	75 583
Diethyl ether (ether)	0,72	2,71	11,94	43	18 487	30,8	110 464					
Gasoline (petrol)*	0,74	2,79	12,89	46,4	19 948	34,2	122 694	12,06	43.4	18 659	32,0	114 761
Gas oil (heating oil)*	0,84	3,18	11,95	43	18 495	36,1	129 654	11,89	42.8	18 401	36,0	128 991
Glycerin	1,26	4,78	5,28	19	8 169	24	86 098					
Heavy fuel oil*	0,98	3,71	11,61	41,8	17 971	41	146 974	10,83	39.0	16 767	38,2	137 129
Kerosene*	0,82	3,11	12,83	46,2	19 862	37,9	126 663	11,94	43.0	18 487	35,3	126 663
Light fuel oil*	0,96	3,63	12,22	44	18 917	42,2	151 552	11,28	40.6	17 455	39,0	139 841
LNG*	0,43	1,62	15,33	55,2	23 732	23,6	84 810	13,50	48.6	20 894	20,8	74 670
LPG*	0,54	2,03	13,69	49,3	21 195	26,5	94 986	12,64	45.5	19 561	24,4	87 664
Marine gas oil*	0,86	3,24	12,75	45,9	19 733	39,2	140 804	11,89	42.8	18 401	36,6	131 295
Methanol	0,79	2,99	6,39	23	9 888	18,2	65 274	5,54		8 568	15,8	56 562
Methyl ester (biodiesel)	0,89	3,36	11,17	40,2	17 283	35,7	128 062	10,42	37.5	16 122	33,3	119 460

Table G1. Cont.

Liquid fuels	**(kg/l)**	**(kg/ gal)**	**(kWh/ kg)**	**(MJ/ kg)**	**(Btu/lb)**	**(MJ/l)**	**(Btu/ gal)**	**(kWh/ kg)**	**(MJ/kg)**	**(Btu/ lb)**	**(MJ/l)**	**(Btu/ gal)**
at tempertaure of 15°C/60°F, and 1 bar of atmospheric pressure												
MTBE	0,74	2,81	10,56	38	16 337	41,4	101 244	9,75	35.1	15 090	26,1	93 517
Oils vegetable (biodiesel)*	0,92	3,48	11,25	40,5	17 412	37,3	133 684	10,50	37.8	16 251	34,8	124 772
Paraffin (wax)*	0,90	3,41	12,78	46	19 776	41,4	148 538	11,53	41.5	17 842	37,4	134 007
Pentane	0,63	2,39	13,50	48,6	20 894	30,6	109 854	12,60	45.4	19 497	28,6	102 507
Petroleum naphtha*	0,73	2,75	13,36	48,1	20 679	34,9	125 145	12,47	44.9	19 303	32,6	116 819
Propane	0,50	1,89	13,99	50,4	21 647	25,1	89 963	12,88	46.4	19 927	23,1	82 816
Residual oil*	0,99	3,75				41,8	150 072	10,97	39.5	16 982	39,2	140 470
Tar*			10,00	36	15 477							
Turpentine	0,87	3,27	12,22	44	18 917	38,1	136 555					
Solid fuels*	**(kWh/ kg)**		**(kWh/ kg)**	**(MJ/ kg)**	**(Btu/lb)**			**(kWh/ kg)**	**(MJ/kg)**	**(Btu/ lb)**		
Anthracite coal			9,06	32,6	14 015							
Bituminous coal			8,39	30,2	12 984			8,06	29.0	12 468		
Carbon			9,11	32,8	14 101							
Charcoal			8,22	29,6	12 726			7,89	28,4	12 210		
Coke			7,22	26,0	11 178							
Lignite (brown coal)			3,89	14,0	6 019							
Peat			4,72	17,0	7 309							
Petroleum coke			8,69	31,3	13 457			8,19	29,5	12 683		
Semi anthracite			8,19	29,5	12 683							
Sub-Bituminous coal			6,78	24,4	10 490							
Sulfur (s)			2,56	9,2	3 955			2,55	9,2	3 939		
Wood (dry)	0,701		4,50	16,2	6 965			4,28	15,4	6 621		

Below is a list of common units used in thermodynamics and conversion formulae between them (Moran et al. 2014).

- 1 MJ = 0.2778 kWh
- 1 billion joules = 277.777778 kilowatt hours
- 1 tonne of oil = 8.5 barrels
- 1 Barrel volume unit = 158.98 Liters
- 1 Btu(IT)/lb = 2.3278 MJ/t = 2327.8 J/kg = 0.55598 kcal/kg = 0.000646 kWh/kg
- 1 kcal/kg = 1 cal/g = 4.1868 MJ/t = 4186.8 J/kg = 1.8 Btu(IT)/lb = 0.001162 kWh/kg
- 1 MJ/kg = 1000 J/g = 1 GJ/t = 238.85 kcal/kg = 429.9 Btu(IT)/lb = 0.2778 kWh/kg
- 1 kWh/kg = 1547.7 Btu(IT)/lb = 3.597 GJ/t = 3597.1 kJ/kg = 860.421 kcal/kg
- 1 Btu(IT)/ft^3 = 0.1337 Btu(IT)/gal(US liq) = 0.03531 Btu(IT)/l = 8.89915 kcal/m^3 = 3.7259x10^4 J/m^3
- 1 Btu(IT)/gal(US liq) = 0.2642 Btu(IT)/l = 7.4805 Btu(IT)/ft^3 = 66.6148 kcal/m^3 = 2.7872x10^5 J/m^3
- 1 MJ/m^3 = 26.839 Btu(IT)/ft^3 = 3.5879 Btu(IT)/gal(US liq) = 0.94782 Btu(IT)/l = 239.01 kcal/m^3
- 1 kcal/m^3 = 0.11237 Btu(IT)/ft^3 = 0.01501 Btu(IT)/gal(US liq) = 0.003966 Btu(IT)/l = 4186.8 J/m^3

THE EFFICIENCY OF POWER PLANTS OF DIFFERENT TYPES

Each of the methods used to industrially generate power in the quantities needed all have a range of advantages and disadvantages (Moran et al. 2014). The fuel used has a range of calorific density values. Then there are the relative efficiencies of generating power.

Table G2. Efficiency of electric power generation by fuel source (Some data from Grigsby 2006).

Power Generation System	**Fuel**	**Global Consumption in 2018** (BP Statistcis 2020, OECD Statistics)	**Energy Content of Fuel**	**Efficiency of Power Generation from Fuel**	**Installed Global Capacity** (Global Energy Observatory)	**Global Electricty Production in 2018** (Agora Energiewende and Sandbag 2019)
Coal	Coal	3772.1 Mtoe	30.2 MJ/kg	32-42%	1237.7 GW	10100.5 TWh
Gas	Gas	3309.4 Mtoe	40.6 MJ/m^3	32-38%	1207.5 GW	6182.8 TWh
Nuclear	Enriched Uranium	611.3 Mtoe	2000 MJ/Kg	0.27%	431.8 GW	2701.4 TWh
Hydroelectric	Moving water	948.8 Mtoe	-	85-90%	712.9 GW	4193.1 TWh
Wind	Moving air	-	-	35-45%	597 GW	1303.8 TWh
Solar PV	Sunlight	-	-	15-20%	580.14 GW Solar Thermal	579.1 TWh
Geothermal	Geological heat	-	-	10-35%	14.6 GW	93 TWh
Biowaste to energy	Biowaste	-	12-35 MJ/kg	13%	55 GW	60 TWh
Fuel Oil Diesel	Crude Oil	4662.1 Mtoe	45.6 MJ/kg	38%	225.8 GW	802.8 TWh

ANNEX H.
HYDROGEN AS POWER STORAGE SYSTEM

The purpose of Annex H is to calculate the numbers associated with using hydrogen as a power storage system. Electrical power is generated to produce hydrogen (Fig. H1), which is then stored. Later, this hydrogen is used to generate electrical power when it is needed, to balance intermittent supply of electrical power from wind and solar stations.

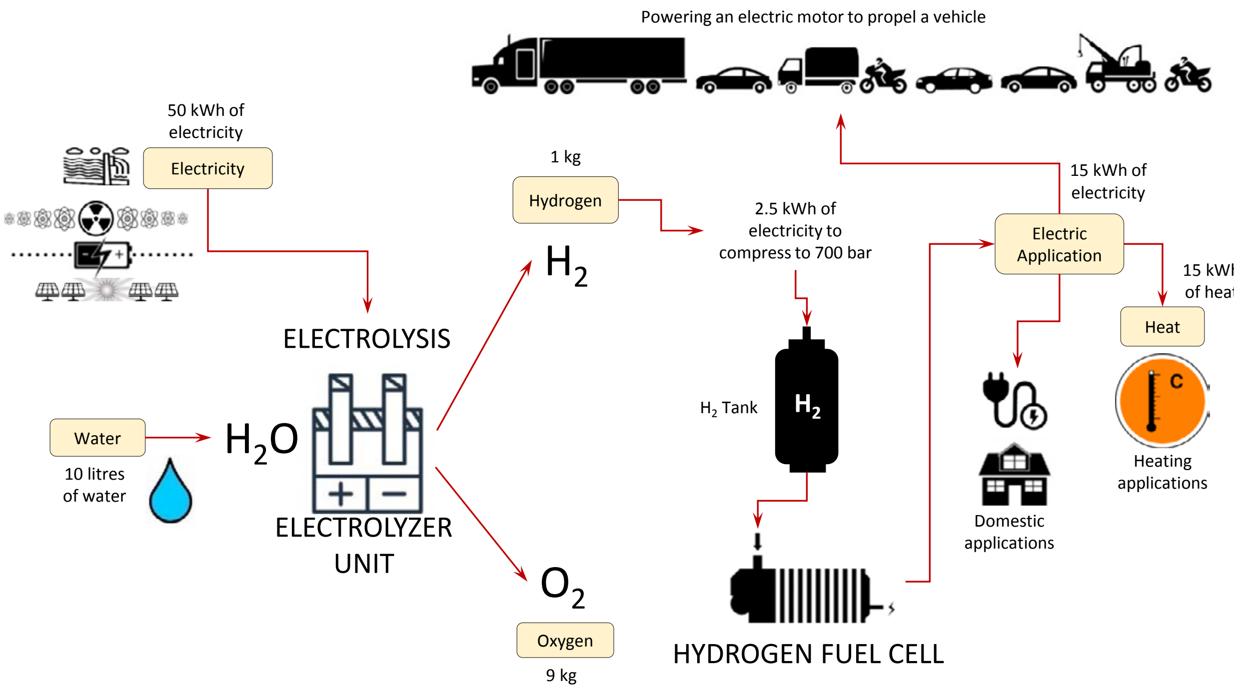


Fig. H1. Production and use of 1kg of hydrogen in the proposed Hydrogen Economy (Source: EIA 2024a, Thomas 2018).

Assumptions are as follows:

- Each 1 kg of H_2 can produce 15 kWh of electricity (IEA 2018, EIA 2024a, Thomas 2018)
- It requires 52.5 kWh to produce 1kg of hydrogen and compress it into 700 bar storage tanks (IEA 2018, EIA 2024a, Thomas 2018)

Table H1. Estimated number of new power stations and installed capacity to globally support stationary power storage with hydrogen production.

Power Generation System 	**Extra required annual capacity to phase out fossil fuels** (TWh)	**Proposed Proportion of Energy Split on new annual capacity** (%)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)
Nuclear	3 670,5	7,50%	12 803,2	287
Hydroelectric	6 538,4	13,36%	1 325,7	4 932
Wind	18 758,7	38,33%	81,2	230 899
Solar PV	16 884,3	34,50%	33,0	511 015
Solar Thermal	1 874,4	3,83%	77,0	24 352
Geothermal	362,2	0,74%	603,2	600
Biowaste to energy	851,6	1,74%	34,6	24 624
Total (kWh)	48 939,9	100,0%		796 709

Table H1 shows the required extra capacity of electrical power generation to phase out fossil fuels. Table H2 shows the estimated quantity of electrical power that needs to be stored to manage intermittent electricity supply from wind and solar stations, for four different capacities.

Table H2. Estimated stationary power storage buffer for a range of capacities.

Power Generation System 	**Expanded extra required annual global capacity to phase out fossil fuels** (TWh)	**Storage capacity for a 6 hour period to manage intermittent power supply from wind and solar** (Larson et al. 2021) (TWh)	**Storage capacity for a 48 hour +10% period to manage intermittent power supply from wind and solar** (Steinke et al. 2012) (TWh)	**Storage capacity for a 28 day period to manage intermittent power supply from wind and solar** (Droste-Franke 2015) (TWh)	**Storage capacity for a 12 week period to manage intermittent power supply from wind and solar** (Ruhnau & Qvist 2021) (TWh)
Wind	18 758,7	12,8	113,1	1 439,0	4 317,1
Solar PV	16 884,3	11,6	101,8	1 295,2	3 885,7
Solar Thermal	1 874,4	1,3	11,3	143,8	431,4
Total Power Storage Capacity	37 517,3	25,7	226,1	2 878,0	8 634,1

Table H3 shows the quantity of hydrogen needed to do this, and the electrical power required to produce that hydrogen.

Table H3. Production of hydrogen storage as a power buffer for different capacities.

Storage capacity to manage intermittent power supply from wind and solar	**Electrical power to be stored and then delivered back to the grid** (TWh)	**Quantity of hydrogen required, where energy density of H_2 is 15 kWh/kg** (kg)	**Quantity of hydrogen required, where energy density of H_2 is 15 kWh/kg** (million tonnes)	**Production of Hydrogen @52.5 kWh/kg** (TWh)	**Electicity production accounting for a 10% loss in transmission** (TWh)
6 hours	25,7	1,71E+09	1,7	89,9	98,9
48 hours +10%	226,1	1,51E+10	15,1	791,5	870,6
28 days	2 878,0	1,92E+11	191,9	10 073,1	11 080,5
12 weeks	8 634,1	5,76E+11	575,6	30 219,4	33 241,4

Tables H4 to H7 show the calculated number of power stations to deliver this electrical power shown in Table H3, according to the same energy split used in Table 38.

Table H4. Energy split of power stations to produce hydrogen for a 6 hour buffer storage.

Power Generation System 	**28.4 TWh capacity to phase out fossil fuels** (TWh)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)
Nuclear	1,9	12 803,2	0
Hydroelectric	3,4	1 325,7	3
Wind	9,8	81,2	121
Solar PV	8,9	33,0	268
Solar Thermal	1,0	77,0	13
Geothermal	0,2	603,2	0
Biowaste to energy	0,4	34,6	13
Total	25,7		418
Wind and solar power that will require further buffer support (TWh)	19,7		

Table H5. Energy split of power stations to produce hydrogen for a 48 hour +10% buffer storage.

Power Generation System 	**250.0 TWh capacity to phase out fossil fuels** (TWh)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)
Nuclear	17,0	12 803,2	1
Hydroelectric	30,2	1 325,7	23
Wind	86,7	81,2	1 067
Solar PV	78,0	33,0	2 361
Solar Thermal	8,7	77,0	113
Geothermal	1,7	603,2	3
Biowaste to energy	3,9	34,6	114
Total	226,1		3 681
Wind and solar power that will require further buffer support (TWh)	173,4		

Table H6. Energy split of powers stations to produce hydrogen for a 28 day buffer storage.

Power Generation System 	**3 182.2 TWh capacity to phase out fossil fuels** (TWh)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)
Nuclear	215,9	12 803,2	17
Hydroelectric	384,5	1 325,7	290
Wind	1 103,2	81,2	13 579
Solar PV	992,9	33,0	30 052
Solar Thermal	110,2	77,0	1 432
Geothermal	21,3	603,2	35
Biowaste to energy	50,1	34,6	1 448
Total	2 878,0		46 853
Wind and solar power that will require further buffer support (TWh)	2 206,3		

Table H7. Energy split of powers stations to produce hydrogen for a 12 week buffer storage.

Power Generation System	**9 546.7 TWh capacity to phase out fossil fuels** (TWh)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)
Nuclear	647,6	12 803,2	51
Hydroelectric	1 153,5	1 325,7	870
Wind	3 309,5	81,2	40 736
Solar PV	2 978,8	33,0	90 155
Solar Thermal	330,7	77,0	4 296
Geothermal	63,9	603,2	106
Biowaste to energy	150,2	34,6	4 344
Total	8 634,1		140 558
Wind and solar power that will require further buffer support (TWh)	6 618,9		

Table H8. Summary of mass of hydrogen needed and electrical power capacity to produce the hydrogen.

Storage capacity to manage intermittent power supply from wind and solar	**Electrical power to be stored and then delivered back to the grid** (TWh)	**Quantity of hydrogen required, where energy density of H_2 is 15 kWh/kg** (million tonnes)	**Electicity production accounting for a 10% loss in transmission (@52.5 kWh/kg to produce hydrogen)** (TWh)	**Increase in power generation assuming 54 112.5 TWh is required annualy** (%)	**Wind and solar power that will require further buffer support** (TWh)
6 hours	25,7	1,7	98,9	0,18%	19,7
48 hours +10%	226,1	15,1	870,6	1,61%	173,4
28 days	2 878,0	191,9	11 080,5	20,48%	2 206,3
12 weeks	8 634,1	575,6	33 241,4	61,43%	6 618,9

If it requires 52.5 kWh to produce 1 kg of hydrogen (then add 10% to account for transmission loss between powers station and application), and then getting 15 kWh of electrical energy in return, then using hydrogen as an energy storage has a round trip efficiency of 26%. This does not account for losses during storage or maintenance issues of infrastructure becoming brittle due to hydrogens storage. It does not account for hydrogen transport if it would be required. Hydrogen as an energy storage system may well have its place, like so many other renewable energy technologies, but it is unlikely to be scalable to become the primary energy storage system needed to manage wind and solar power generation systems.

ANNEX I. SENSITIVITY ANALYSIS PART 1

A sensitivity analysis was conducted on this data set. One parameter at a time was changed, then the full calculation was done again. This was done to assess the influence of each parameter. Some parameter changes were made to reflect a possible policy change. For example, if annual steel production increased 500% (Sensitivity Scenario R), to support the industrial reform of the fossil fuel technology system. The sum total of the additional annual electrical power generation requirement to be developed was compared to the baseline of 48 939.8 TWh. One parameter at a time was changed, then the full calculation was done again. All scenarios are described below.

Scenario A: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were reduced by 50% to a fleet size of 693.8 million vehicles, which would annually travel 7.13 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles.

Scenario B: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were reduced by 90% to a fleet size of 167.7 million vehicles which would annually travel 1.43 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles.

Scenario C: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were increased by 200% to a fleet size of 2.78 billion vehicles annually travelling 28.50 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles. This Scenario was developed to examine what impact a larger EV fleet might have on material demands. The size of the transport fleet is projected to grow 2.4 times between 2018 and 2050 (IEA 2021a).

Scenario D: The 28.9 million HCV Class 8 trucks were assumed to be EV, instead of H_2-Cell vehicles. The entire EV fleet now includes HCV Class 8 trucks + passenger cars + commercial vans/light trucks + buses + motorcycles (1.416 billion vehicles annually travelling 16.26 trillion km).

Scenario E: The existing fleet of 19 million buses, which annually travelled 560.8 billion km, was assumed to be expanded by 300% and were all assumed to be EV (58 million buses annually travelled 1.68 trillion km).

Scenario F: The existing fleet of 28.9 million HCV Class 8 trucks were assumed to be H_2-Cell vehicles and reduced by 50% in size (14.4 million H_2-Cell Class 8 trucks annually travelled 829 billion km).

Scenario G: The existing fleet of 28.9 million HCV Class 8 trucks were assumed to be H_2-Cell vehicles and increased by 200% in size (57.8 million H_2-Cell Class 8 trucks annually travel 3.31 trillion km). This Scenario was developed to examine the growth of the consumption of materials goods. The just-in-time supply grid would have to become large and more complex. Trucking transport would be just one input into a possible future study.

Scenario H: The existing rail transport network is expanded 300%. It was assumed that all new trains were H_2-Cell fueled electrical systems. One of the solutions to the challenge of phasing out fossil fuels is to restructure our society, where communal transport became much more important. Rail, metro, and buses would all significantly increase, and the use of personal vehicles would significantly decrease.

Scenario I: The maritime shipping fleet was reduced to by 10% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 10% fewer vessels and 10% less total distance travelled by shipping.

Scenario J: The maritime shipping fleet was reduced to by 50% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 50% fewer vessels and 50% less total distance travelled by shipping.

Scenario K: The maritime shipping fleet was reduced to by 90% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 90% fewer vessels and 90% less total distance travelled by shipping.

Scenario L: If Ammonia production was reduced by 50%, where in this study, it was tasked to fertilizer production, and ammonia fuel production for 46% of the maritime shipping fleet.

Scenario M: If Ammonia production was reduced by 90%, where in this study, it was tasked to fertilizer production, and ammonia fuel production for 46% of the maritime shipping fleet.

Scenario N: If Ammonia production was increased by 200%. This scenario was to examine the impact of a larger human population, that is increasingly dependent on petrochemical supported industrial agriculture, to supply food production.

Scenario O: The quantity of steel produced annually is reduced by 50%. It was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology (which is reported to be more efficient than conventional coking coal systems).

Scenario P: The quantity of steel produced annually is reduced by 90%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology.

Scenario Q: The quantity of steel produced annually is increased by 200%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology. Scenarios Q and R were assembled to examine what would happen if construction was stepped up in annual capacity. To phase out fossil fuels, a new system will have to be built around the replacement technology, using a completely different set of metrics. This would require an unprecedented demand for raw materials of all kinds, steel, and concrete in particualr (which are often used as proxies for industrialization).

Scenario R: The quantity of steel produced annually is increased by 500%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology.

Scenario S: Global building heating, now delivered with heat pumps, was reduced by 50%.

Scenario T: Existing conventional electricity demand was reduced by 50%. This includes all electrical demands (domestic and industrial) in 2018, where fossil fuel systems were fueling the vast majority of the transport fleet.

Scenario U: Existing conventional electricity demand was reduced by 90%.

Scenario V: Existing conventional electricity demand was increased by 200%. This Scenario was developed to see the impact of a significant increase in electrical demand. This study was founded in the paradigm to map the industrial system as it is currently (in 2018), then substituting with non fossil fuel technology to maintain the existing society. A non fossil fuel world will be different. If it will be founded in electrical technology (where we are currently founded in fossil fuel technology), then how that society will function will be different in form and complexity. It could be possible that an electrical non fossil fuel technology system would need more electrical power to service its many networks. We may need proportionally more electricity per capita than we do now.

Scenario W: Existing conventional electricity demand was increased by 300%.

Scenario Mu: Scenario Mu (μ) is a hybrid of different other scenarios. This scenario was to assemble a profile of data that shows the implications of sharp degrowth of societal footprint, in conjunction of a fundamental restructure of society and the construction of the post fossil fuel industrial society. This was to map out what a sharp degrowth of the system would look like as per recommendations from The Limits to Growth study (Meadows et al. 1972), and to fully replace all fossil fuel technology systems. Electricity demand for conventional applications would contract. The number of passenger cars and the distance they travelled would contract. Communal transport would become much more prominent and important (buses would expand greatly). Rail transport would become more important in the movement of physical goods, and the manufacture sector would relocate to be directly on a train line. So, rail would have to expand greatly. Manufacture would reduce its global dependency and become more regional. This resulted in a reduction in the maritime shipping transport of physical goods. In addition to this, society would reorganize itself around a different energy and transportation system. This means the retooling, and reconstruction of the industrial system across the full value chain, of the largest, most complex and sophisticated society the world has ever known. This will require the consumption of unprecedented quantity of raw materials and metal. Vast amounts of steel and concrete will be needed in quantities never seen before. To reflect this steel manufacture would greatly increase. The parameters selected for Scenario Mu may well be too small in size, and this Scenario really is a ranging shot to develop a more appropriate study. The parameters changed for Scenario Mu were as follows:

- Class 8 HCV trucks reduced by 50%. So, the existing fleet of 28.9 million H_2-Cell fueled HCV Class 8 semi-trailer trucks that traveled 1.66 trillion km (in 2018), would contract to 14.5 million H_2-Cell fueled HCV Class 8 semi-trailer trucks that would annually travel 828.7 billion km.
- Delivery trucks (Rigid) reduced by 50%. So, the existing fleet of 9.6 million delivery trucks, which annually travelled 250 billion km, reduces to 4.8 million buses which would annually travel 127 billion km, and were all assumed to be EV's.
- Rail transport increased by 300%.
- Buses increased by 300%. The existing fleet of 19 million buses, which annually travelled 560 billion km, expands to 58 million buses which would annually travel 1.68 trillion km, and were all assumed to be EV's.
- Commercial vans and light trucks reduced by 40%. The existing fleet of 601.3 million commercial vans and light trucks, which annually travelled 8.07 trillion km, contracted to 360.8 million vehicles that would instead annually travel 4.84 trillion km, and were all assumed to be EV's.
- Passenger cars reduced by 70%. The existing fleet of 695.2 million passenger cars, which annually travelled 5.6 trillion km, contracted to 208.6 million vehicles that would instead annually travel 1.67 trillion km, and were all assumed to be EV's.
- Motorcycles reduced by 70%. The existing fleet of 62.1 million motorcycles, which annually travelled 163.7 billion km, contracted to 18.6 million vehicles that would instead annually travel 49.1 billion km, and were all assumed to be EV's.
- Maritime shipping reduced by 60%. The existing base line study had a maritime fleet of 116 857 vessels where 17% were fueled by hydrogen (needing 844.9 TWh annually, reduced to 338 TWh), 46% fueled by ammonia (needing 3903.1 TWh annually, reduced to 1 561.3 TWh), and 37% biofuels (needing 477.5 million tonnes of soy biomass, reduced to 191 million tonnes of soy biomass).
- Steel production increased by 300%. Existing annual production of steel (1 808.6 million tonnes for the year 2018) in a hydrogen atmosphere would require an estimated 6 939.2 TWh, where each tonne of steel requires 3 488 kWh, giving a total of 20 817.6 TWh.
- Conventional electrical power reduced by 50%, from 17 086.1 TWh to 8543.1 TWh
- Nuclear power accounts for 20% of the energy power generation mix.

Table I1.1. Sensitivity Analysis of applications for power consumption.

Application Task Sensitivity Scenario	Base Case (TWh)	If EV's were reduced by 50% A (TWh)	If EV's were reduced by 90% B (TWh)	If EV's increased by 200% C (TWh)	If Class 8 trucks were also EV D (TWh)	If buses were increased 300% E (TWh)
Electrical power required to charge EV batteries	4 354,0	2 177,0	435,4	8 708,1	7 015,7	6 827,9
Electric power required to produce hydrogen for existing applications (excluding hydrogen used to refine petroleum products)	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5
Electric power required to produce hydrogen produce hydrogen for a H2-Cell HCV Class 8 truck fleet	7 676,0	7 676,0	7 676,0	7 676,0		7 676,0
Electric power required to produce hydrogen produce hydrogen for a H2-Cell rail network	793,1	793,1	793,1	793,1	793,1	793,1
Electric power required to produce hydrogen produce hydrogen for a H2-Cell in 17% of maritime shipping	844,9	844,9	844,9	844,9	844,9	844,9
Electric power to produce steel in a hydrogen atmosphere	6 939,2	6 939,2	6 939,2	6 939,2	6 939,2	6 939,2
Produce ammonia to fuel 46% of the maritime shipping fleet	3 903,1	3 903,1	3 903,1	3 903,1	3 903,1	3 903,1
Produce ammonia for agricultural fertilizer	2 545,8	2 545,8	2 545,8	2 545,8	2 545,8	2 545,8
Electrical power required to produce biodiesel for 37% of maritime shipping	18,1	18,1	18,1	18,1	18,1	18,1
Electrical power required to power heat pumps for building heating	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0
Electrical power required to phase out coal, gas, oil power generation	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1
Total	**48 939,8**	**46 762,8**	**45 021,2**	**53 293,9**	**43 925,5**	**51 413,7**
Change from baseline (%)		**-4,45%**	**-8,01%**	**8,90%**	**-10,25%**	**5,06%**

Table I1.2. Sensitivity Analysis of applications for power consumption.

Application Task	If trucks were reduced by 50%	If trucks were increased by 200%	If the rail network increased by 300%	If maritime shipping was reduced by 10%	If maritime shipping was reduced by 50%	If maritime shipping was reduced by 90%
Sensitivity Scenario	F	G	H	I	J	K
	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)
Electrical power required to charge EV batteries	4 354,0	4 354,0	4 354,0	4 354,0	4 354,0	4 354,0
Electric power required to produce hydrogen for existing applications (excluding hydrogen used to refine petroleum products)	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5
Electric power required to produce hydrogen produce hydrogen for a H2-Cell HCV Class 8 truck fleet	3 838,0	15 007,5	7 676,0	7 676,0	7 676,0	7 676,0
Electric power required to produce hydrogen produce hydrogen for a H2-Cell rail network	793,1	793,1	2 379,3	793,1	793,1	793,1
Electric power required to produce hydrogen produce hydrogen for a H2-Cell in 17% of maritime shipping	844,9	844,9	844,9	760,4	422,4	84,5
Electric power to produce steel in a hydrogen atmosphere	6 939,2	6 939,2	6 939,2	6 939,2	6 939,2	6 939,2
Produce ammonia to fuel 46% of the maritime shipping fleet	3 903,1	3 903,1	3 903,1	1 935,5	1 075,3	215,1
Produce ammonia for agricultural fertilizer	2 545,8	2 545,8	2 545,8	2 545,8	2 545,8	2 545,8
Electrical power required to produce biodiesel for 37% of maritime shipping	18,1	18,1	18,1	18,1	18,1	18,1
Electrical power required to power heat pumps for building heating	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0
Electrical power required to phase out coal, gas, oil power generation	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1
Total	**45 101,8**	**56 271,3**	**50 526,0**	**46 887,7**	**45 689,5**	**44 491,4**
Change from baseline (%)	**-7,84%**	**14,98%**	**3,24%**	**-4,19%**	**-6,64%**	**-9,09%**

Table I1.3. Sensitivity Analysis of applications for power consumption.

Application Task	**If Ammonia production reduced by 50%**	**If Ammonia production reduced by 90%**	**If Ammonia production increased by 200%**	**If Steel production reduced by 50%**	**If Steel production reduced by 90%**	**If Steel production increased by 200%**	**If Steel production increased by 500%**
Sensitivity Scenario	L	M	N	O	P	Q	R
	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)
Electrical power required to charge EV batteries	4 354,0	4 354,0	4 354,0	4 354,0	4 354,0	4 354,0	4 354,0
Electric power required to produce hydrogen for existing applications (excluding hydrogen used to refine petroleum products)	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5
Electric power required to produce hydrogen produce hydrogen for a H2-Cell HCV Class 8 truck fleet	7 676,0	7 676,0	7 676,0	7 676,0	7 676,0	7 676,0	7 676,0
Electric power required to produce hydrogen produce hydrogen for a H2-Cell rail network	793,1	793,1	793,1	793,1	793,1	793,1	793,1
Electric power required to produce hydrogen produce hydrogen for a H2-Cell in 17% of maritime shipping	844,9	844,9	844,9	844,9	844,9	844,9	844,9
Electric power to produce steel in a hydrogen atmosphere	6 939,2	6 939,2	6 939,2	3 469,6	693,9	13 878,4	34 696,0
Produce ammonia to fuel 46% of the maritime shipping fleet	3 903,1	3 903,1	3 903,1	3 903,1	3 903,1	3 903,1	3 903,1
Produce ammonia for agricultural fertilizer	1 272,9	254,6	5 091,7	2 545,8	2 545,8	2 545,8	2 545,8
Electrical power required to produce biodiesel for 37% of maritime shipping	18,1	18,1	18,1	18,1	18,1	18,1	18,1
Electrical power required to power heat pumps for building heating	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0
Electrical power required to phase out coal, gas, oil power generation	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1	17 086,1
Total	**47 666,9**	**46 648,6**	**51 485,7**	**45 470,2**	**42 694,5**	**55 879,0**	**76 696,6**
Change from baseline (%)	**-2,60%**	**-4,68%**	**5,20%**	**-7,09%**	**-12,76%**	**14,18%**	**56,72%**

Table I1.4. Sensitivity Analysis of applications for power consumption.

Application Task	**If building heating reduced by 50%**	**If conventional electrical power reduced by 50%**	**If conventional electrical power reduced by 90%**	**If conventional electrical power increased by 200%**	**If conventional electrical power increased by 300%**	**Hybrid Scenario Mu**
Sensitivity Scenario	**S**	**T**	**U**	**V**	**W**	**μ**
	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)	(TWh)
Electrical power required to charge EV batteries	4 354,0	4 354,0	4 354,0	4 354,0	4 354,0	4 178,8
Electric power required to produce hydrogen for existing applications (excluding hydrogen used to refine petroleum products)	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5	1 963,5
Electric power required to produce hydrogen produce hydrogen for a H2-Cell HCV Class 8 truck fleet	7 676,0	7 676,0	7 676,0	7 676,0	7 676,0	3 838,0
Electric power required to produce hydrogen produce hydrogen for a H2-Cell rail network	793,1	793,1	793,1	793,1	793,1	2 379,3
Electric power required to produce hydrogen produce hydrogen for a H2-Cell in 17% of maritime shipping	844,9	844,9	844,9	844,9	844,9	338,0
Electric power to produce steel in a hydrogen atmosphere	6 939,2	6 939,2	6 939,2	6 939,2	6 939,2	20 817,6
Produce ammonia to fuel 46% of the maritime shipping fleet	3 903,1	3 903,1	3 903,1	3 903,1	3 903,1	1 561,2
Produce ammonia for agricultural fertilizer	2 545,8	2 545,8	2 545,8	2 545,8	2 545,8	2 545,8
Electrical power required to produce biodiesel for 37% of maritime shipping	18,1	18,1	18,1	18,1	18,1	7,2
Electrical power required to power heat pumps for building heating	1 408,0	2 816,0	2 816,0	2 816,0	2 816,0	2 816,0
Electrical power required to phase out coal, gas, oil power generation	17 086,1	8 543,1	1 708,6	34 172,2	51 258,3	8 543,1
Total	**47 531,8**	**40 396,8**	**33 562,3**	**66 025,9**	**83 112,0**	**48 988,5**
Change from baseline (%)	**-2,88%**	**-17,46%**	**-31,42%**	**34,91%**	**69,82%**	**0,10%**

ANNEX J.
TEXAS WINTER STORM OF FEB 2021 POWER SUPPLY FAILURE CASE STUDY

In February 2021, a severe winter storm hit the state of Texas in the United States (Penney 2021). This storm coincided with a cold wave, with a record low temperature at Dallas/Fort Worth International Airport of –2 °F (–19 °C) on February 16th. This was the coldest temperature record in North Texas in 72 years. The electrical power generation stations in Texas were unprepared to operate in such cold temperatures and were subject to operational shutdowns. Natural gas, coal, and nuclear plants (which normally provide the bulk of Texas' power in the winter) were taken offline. Some wind turbines froze and ceased to operate. Electrical power supplied to the Texas grid was disrupted and millions of residents were without power in very cold temperatures.

This purpose of Annex J was to show the data and analysis of the power production in Texas through this unusual circumstance. The analysis and data presented was done by Art Berman of Labyrinth Consulting (Berman 2023, https://www.artberman.com/).

The electrical power generation for Texas during this period was ERCOT (Texas Comptroller 2022). The Electric Reliability Council of Texas (ERCOT), the state's electric grid operator, managed an electricity infrastructure consisting of more than 1,030 generating units and almost 53,000 miles of high-voltage transmission lines. ERCOT's breakdown of energy use by fuel source in 2021 is shown in Figure J1. A diverse Texas energy profile is needed to ensure demand is met and that the electric load curve is maintained. The term SARA, is The Seasonal Assessment of Resource Adequacy report conducted by the Texas Comptroller.

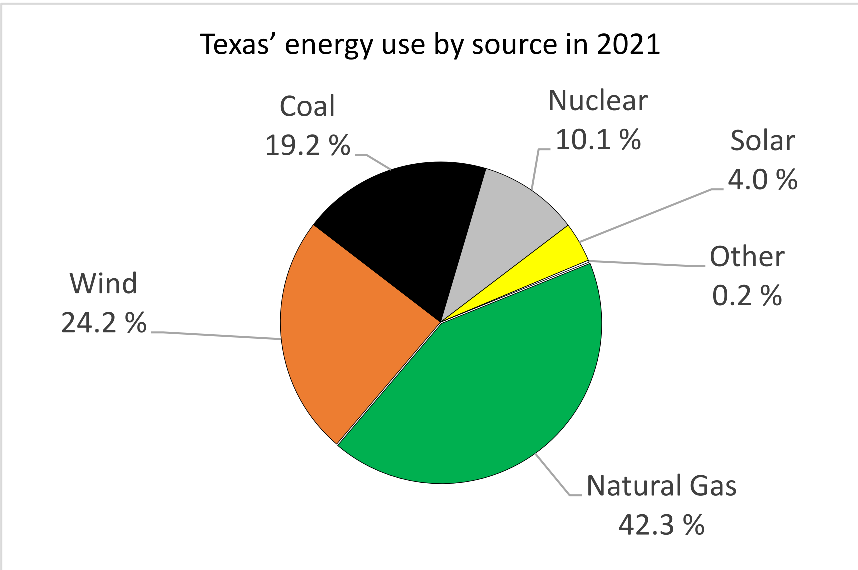


Fig. J1. Texas' energy use by source in 2021 (Source: drawn from Texas Comptroller 2022).

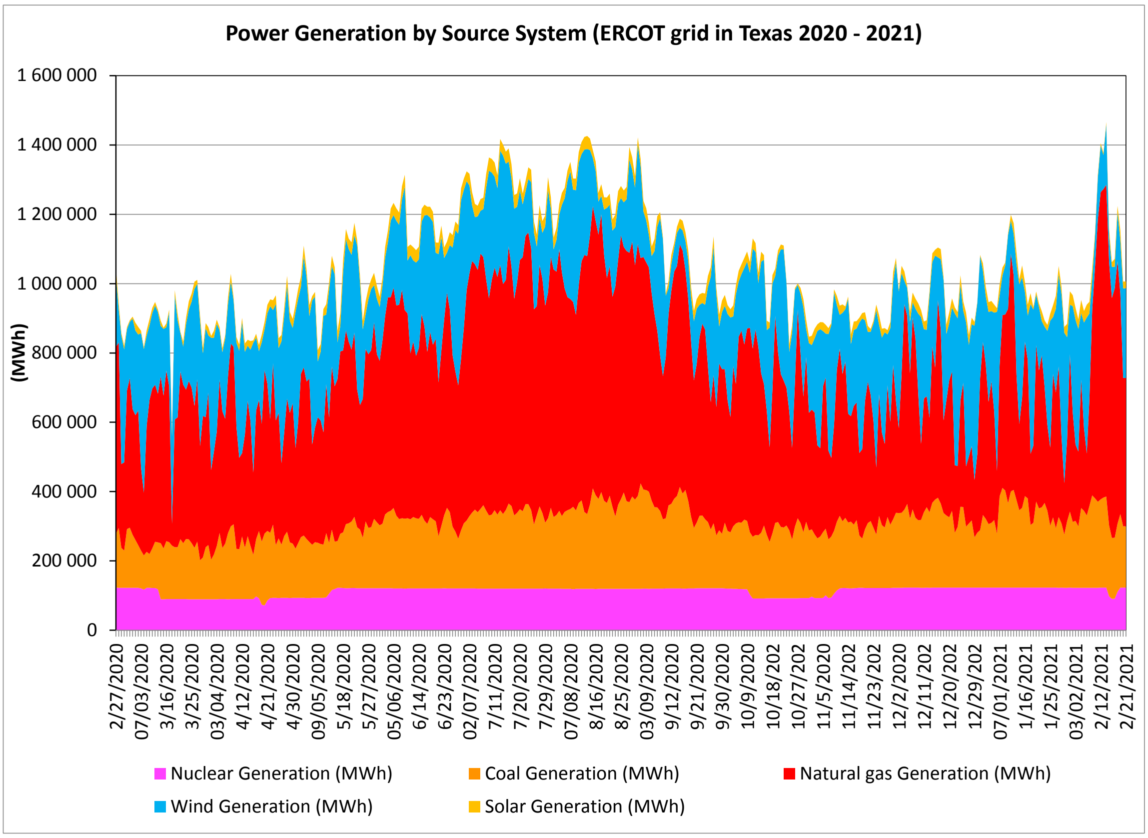


Fig. J2. Power Generation by Source System, ERCOT grid in Texas 2020–2021 (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

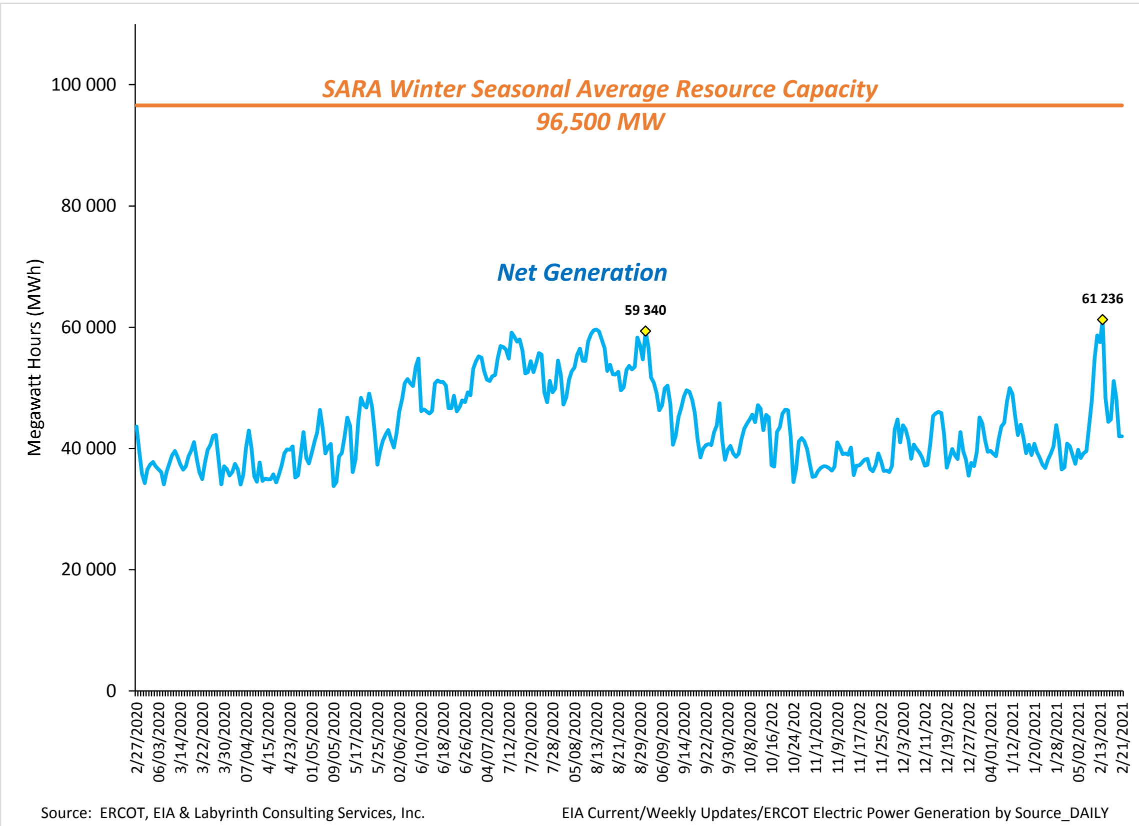
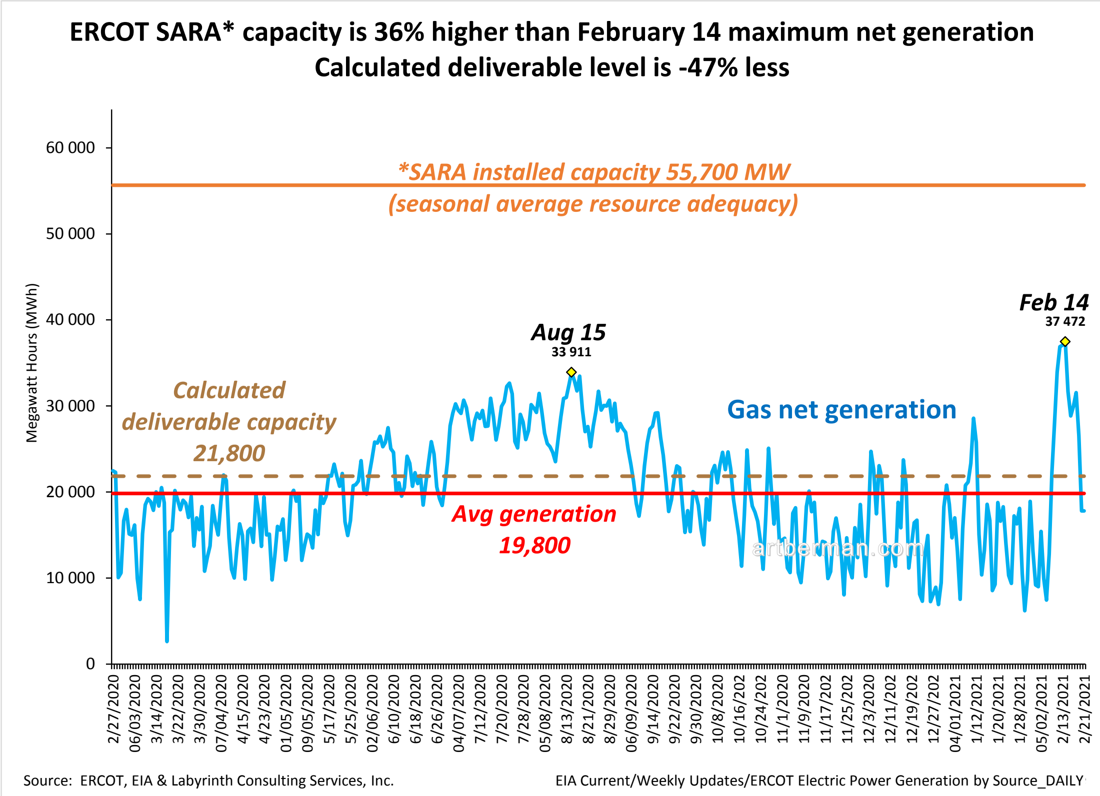


Fig. J3. ERCOT's resource capacity estimate exceeds maximum net electrical power generation by 37% (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).



* Note: SARA, is The Seasonal Assessment of Resource Adequacy report

Fig. J4. ERCOT SARA capacity is 36% higher than February 14 maximum net power generation for gas Calculated deliverable level is -47% less (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

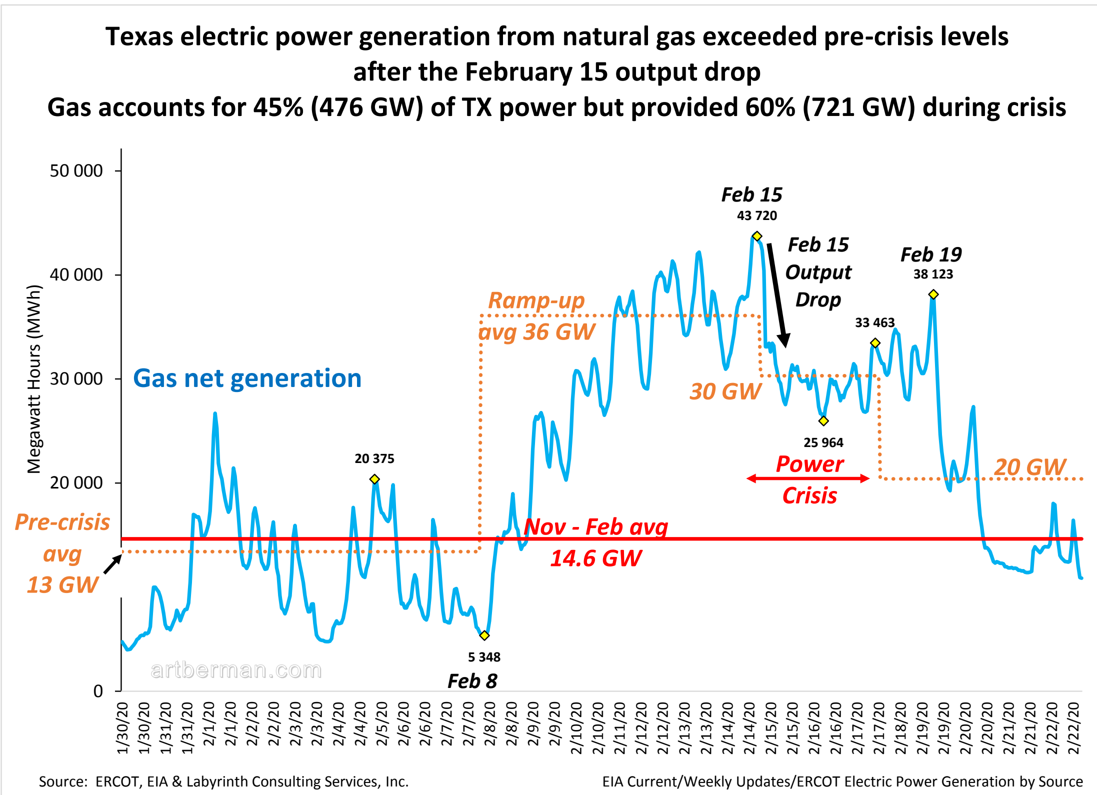


Fig. J5. Texas electric power generation from natural gas exceeded pre-crisis levels after the February 15 output drop Gas accounts for 45% (476 GW) of TX power but provided 60% (721 GW) during crisis (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

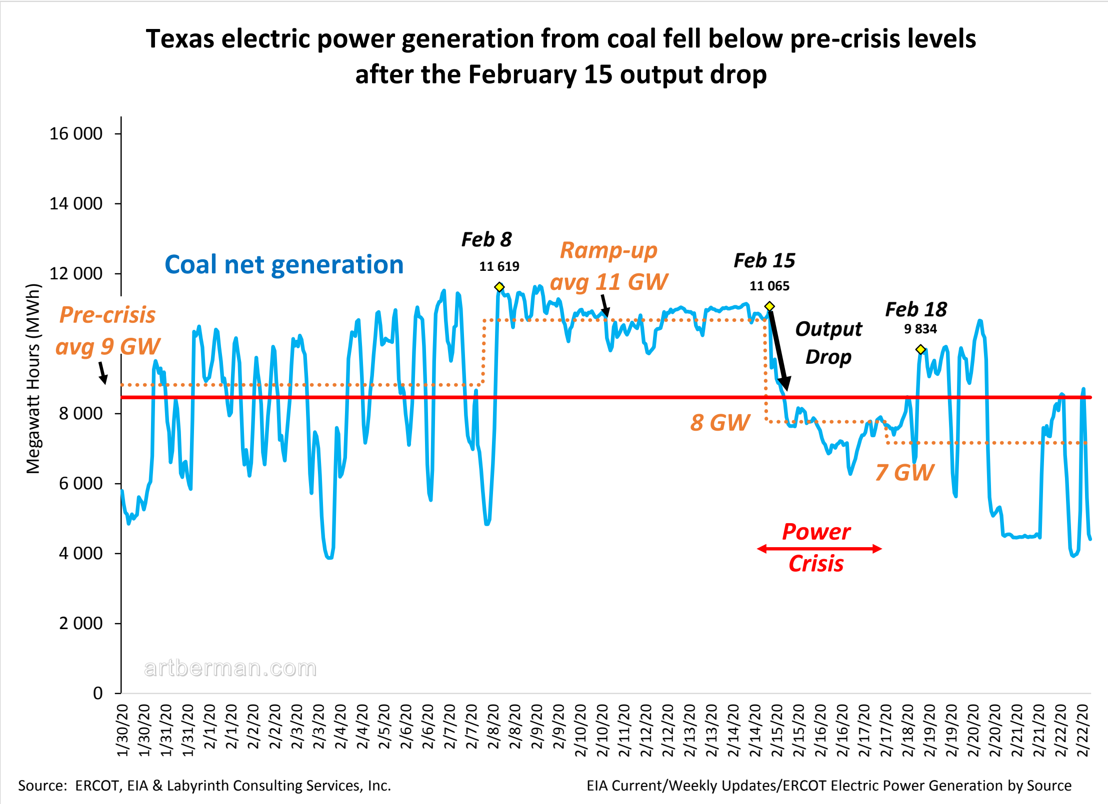


Fig. J6. Texas electric power generation from coal (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

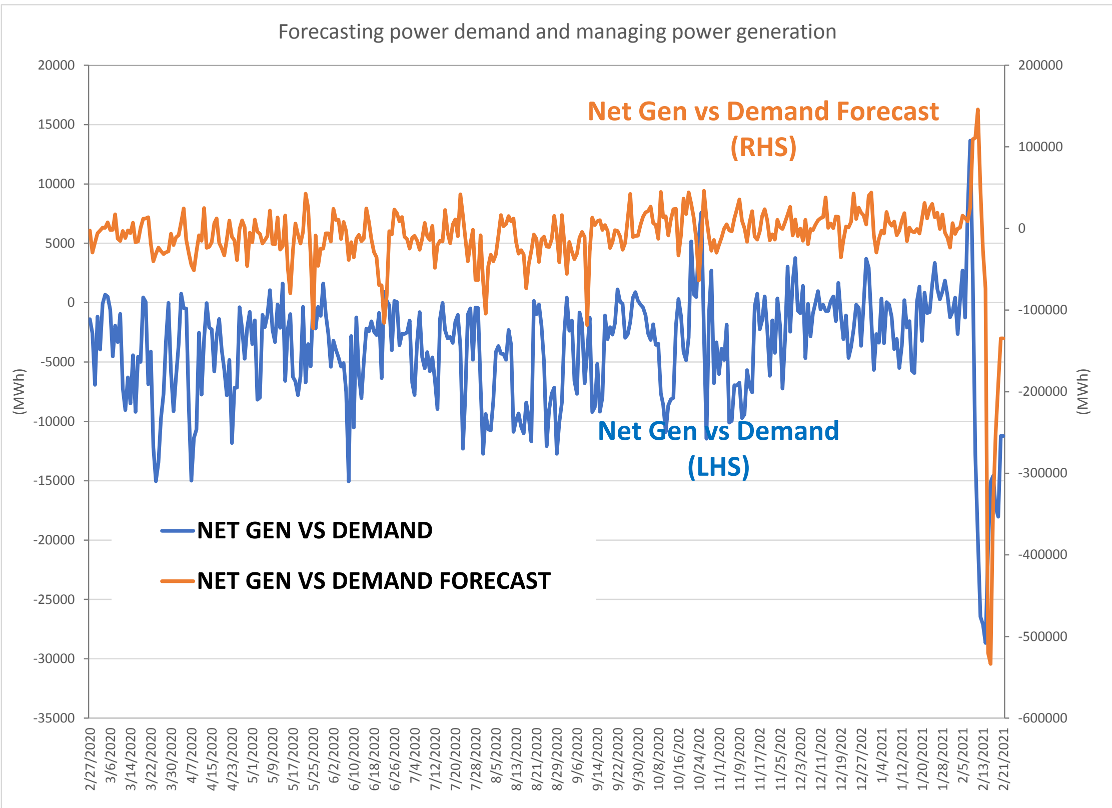


Fig. J7. Forecasting power demand and managing power generation (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

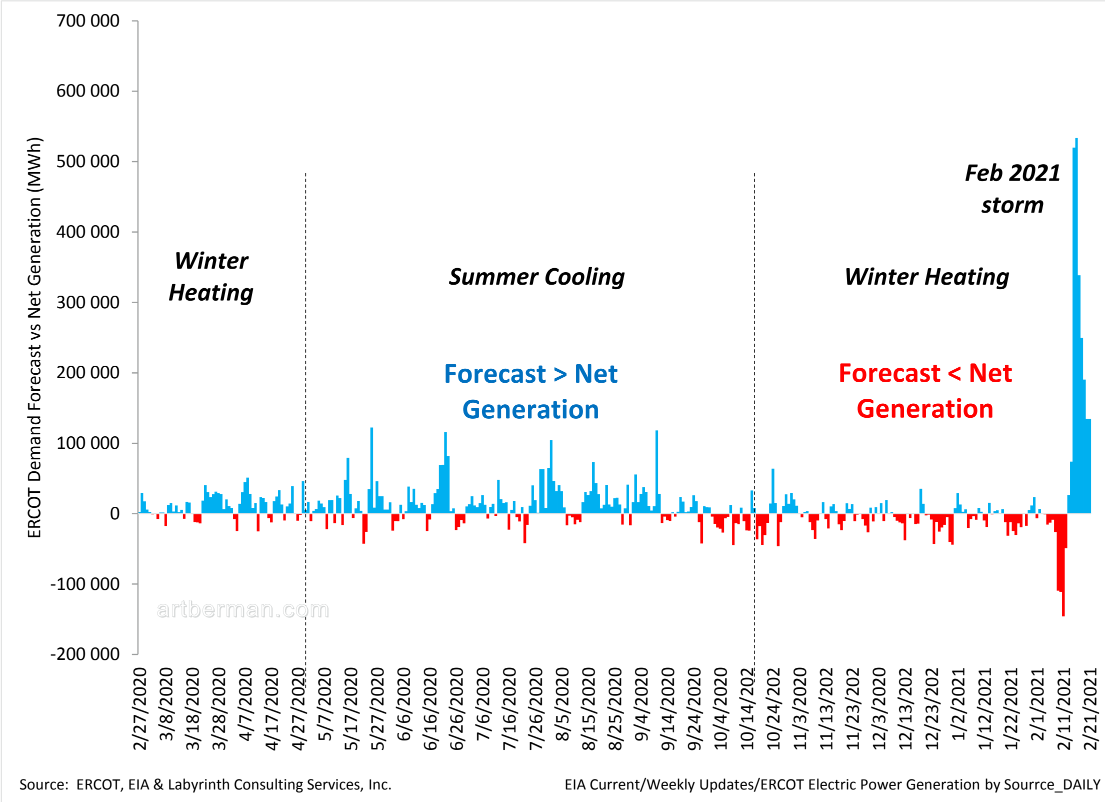


Fig. J8. ERCOT over-estimated Texas electric power demand in summer and under-estimated demand in winter before the February 2021 winter storm (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

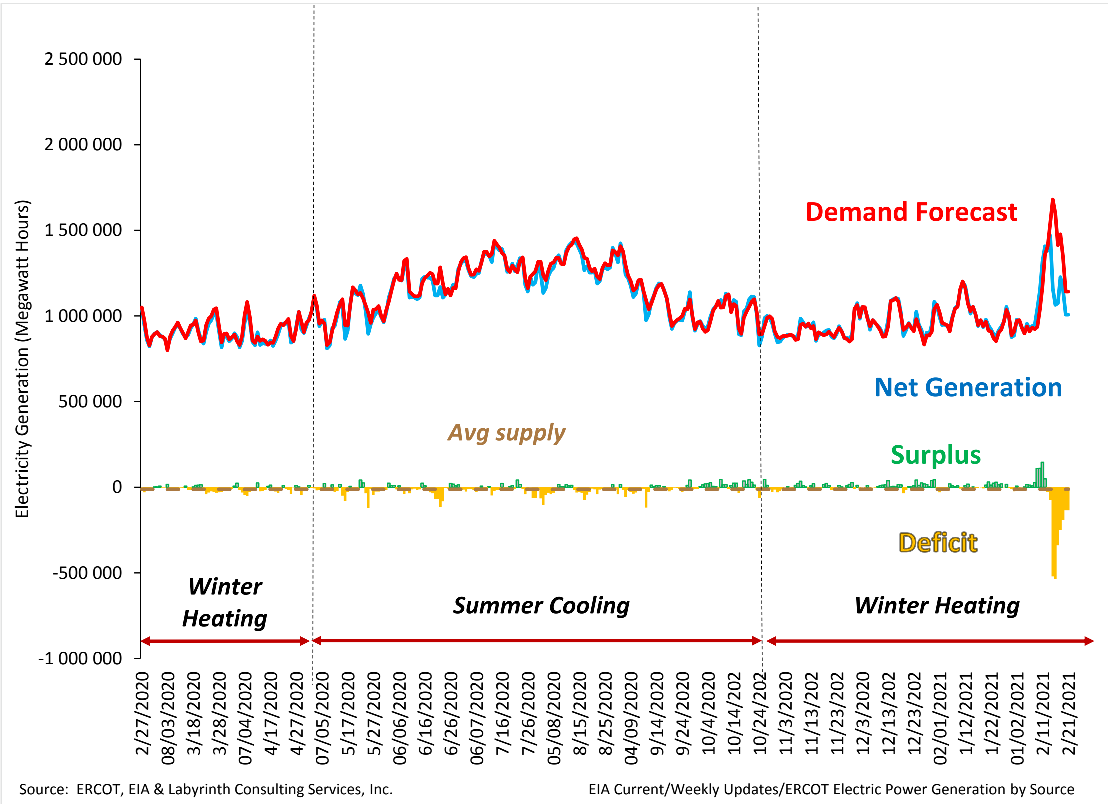


Fig. J9. Summer electric power demand in Texas built more gradually than recent winter power demand and did not reach same extreme level (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

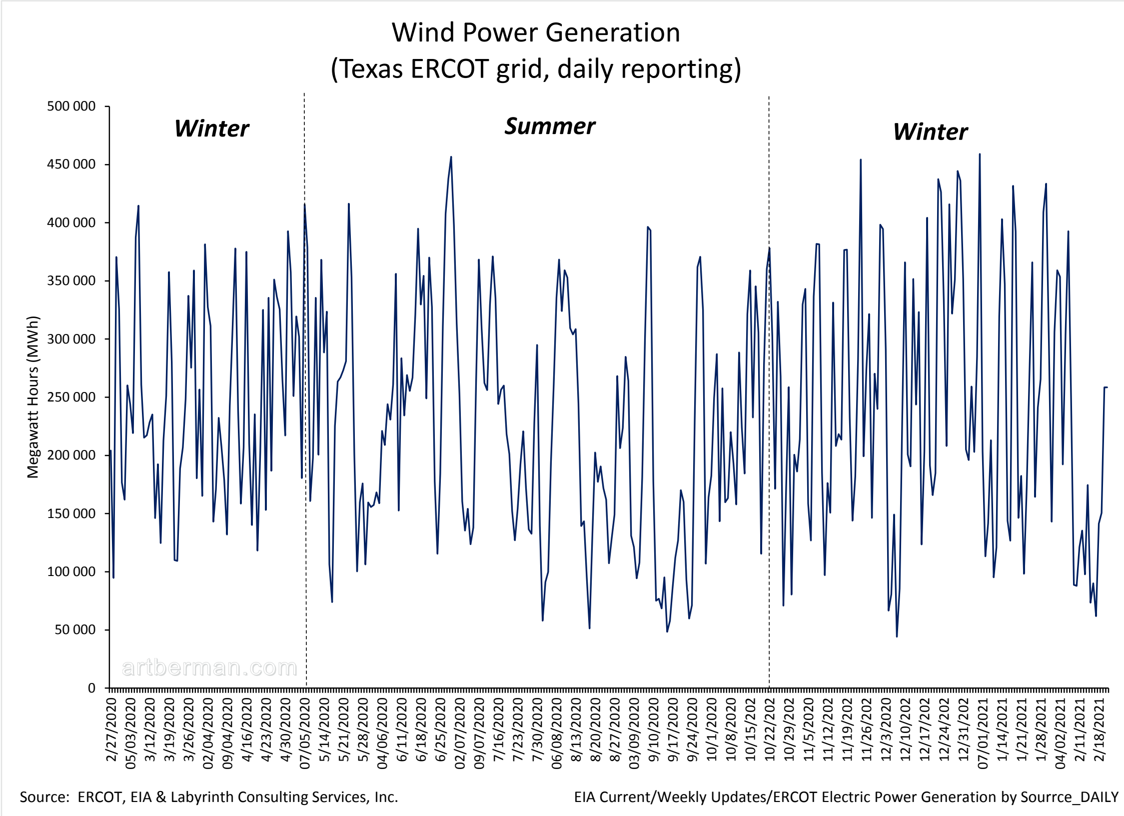


Fig. J10. Texas electric power generated from wind is cyclic Peak-to-peak cycles are approximately 5 days in winter and 7 days in summer (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

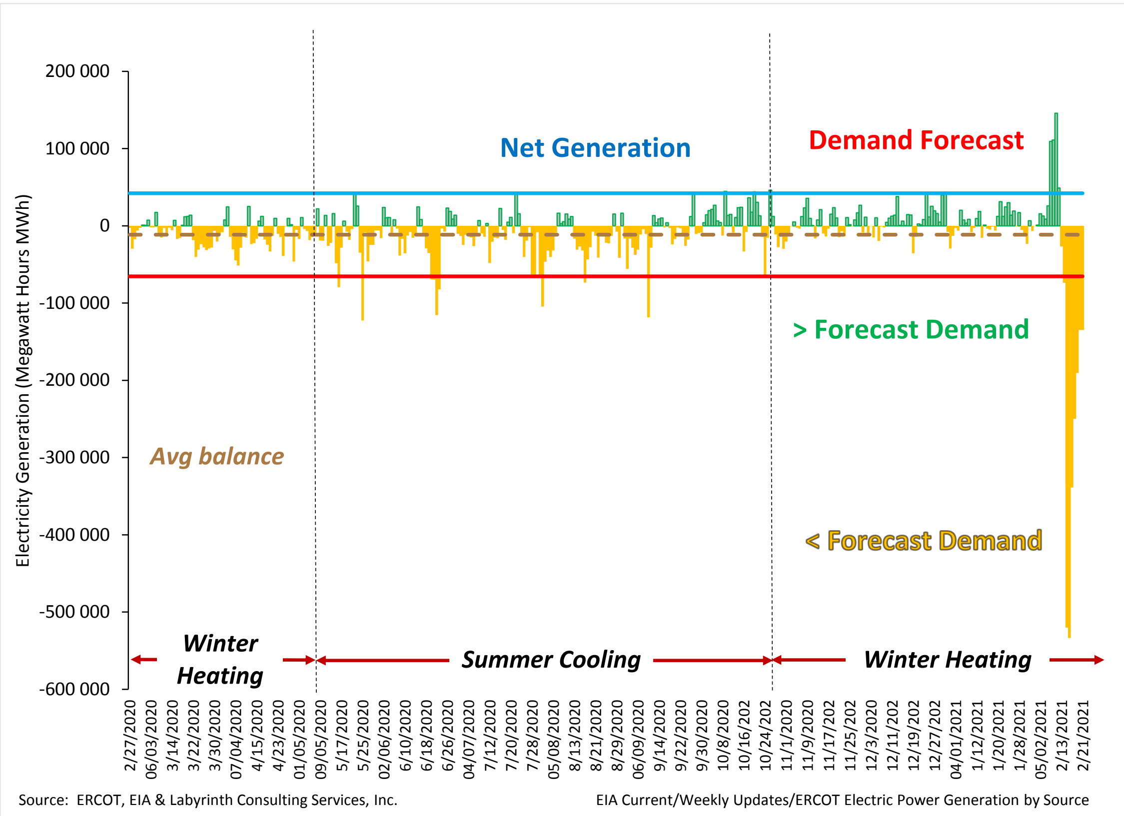


Fig. J11. Summer electric power demand in Texas built more gradually than recent winter power demand and did not reach same extreme level (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

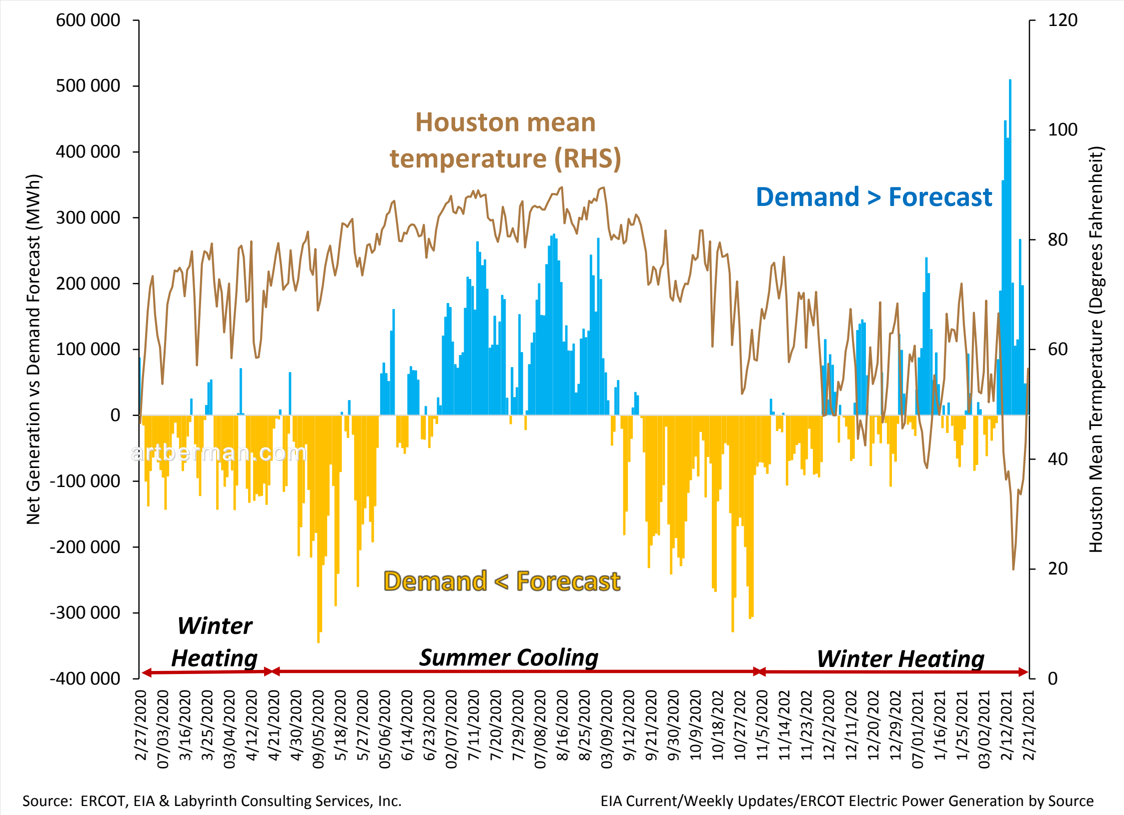


Fig. J12. ERCOT Texas demand forecast averaged 10% too high or 10% too low in 2020 & 2021 Incorrect demand forecasts most pronounced during 2021 cold weather periods (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

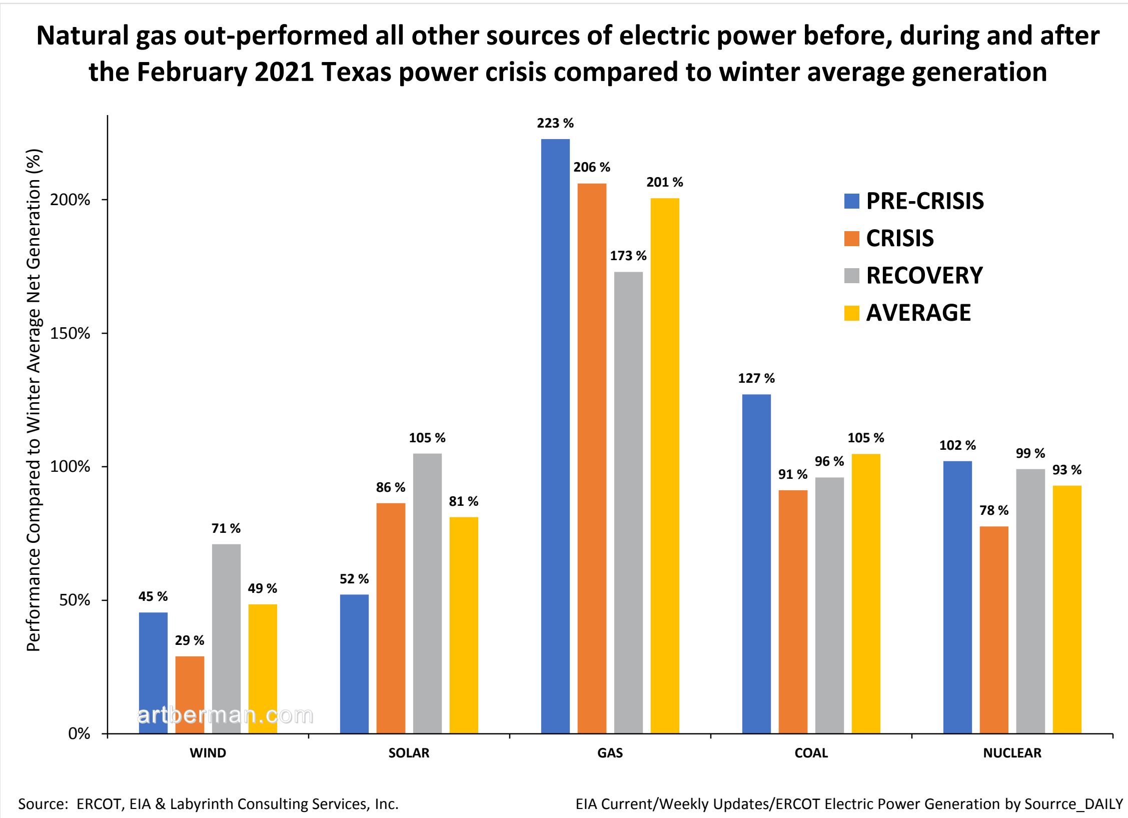


Fig. J13. Natural gas out-performed all other sources of electric power before, during and after the February 2021 Texas power crisis compared to winter average generation (Source: Art Berman of Labyrinth Consulting) (Copyright granted: Art Berman of Labyrinth Consulting).

QUANTITY OF METALS REQUIRED TO MANUFACTURE ONE GENERATION OF RENEWABLE TECHNOLOGY UNITS TO PHASE OUT FOSSIL FUELS

by

Simon P. Michaux[1*)]

Michaux, S. P. 2024. Quantity of metals required to manufacture one generation of renewable technology units to phase out fossil fuel. *Geological Survey of Finland, Bulletin 416,* 173–293, 38 figures, 60 tables and 2 annexes.

An estimate is presented for the total quantity of raw materials required to manufacture a single generation of renewable technology units (solar panels, wind turbines, etc.) sufficient to replace energy technologies based on combustion of fossil fuels. This estimate was derived by assembling the number of units needed against the estimated metal content for individual battery chemistries, wind turbines, solar panels, and electric vehicles. The majority of the metals needed were to resource the construction of stationary power storage to act as a buffer for wind and solar power generation.

This study uses four stationary power buffer capacities as modelled in a previous study: 6 hours, 48 hours + 10%, 28 days and 12 weeks. This power buffer is assumed to be supplied through the use of large battery banks (in line with strategic policy expectations). Metal quantities were calculated for all four capacities and compared with mining production, mineral reserves, mineral resources, and known under sea resources. It was also assessed whether recycling could deliver this metal quantity by comparing calculations against the sum total mined metal between 1990 and 2023. The quantity of metal mined over the last 34 years was inadequate, which means recycling cannot deliver the needed capacity, and the mining of minerals would have to be the primary source of metals for at least the first generation of non-fossil fuel technology. If a metal has not yet been mined, then that metal cannot be recycled.

It was shown that both 2019 global mine production, 2022 global reserve estimates, 2022 mineral resources, and estimates of undersea resources, were manifestly inadequate for meeting projected demand for copper, lithium, nickel, cobalt, graphite, and vanadium. Comprehensive analysis of these calculations suggest that lithium-ion battery chemistry (on its own) is not a viable option for upscaling to meet anticipated global market demand. This then implies that battery banks would not be viable as a power buffer for wind and solar in the quantities needed. As previous work had shown that pumped hydro storage and hydrogen storage face logistical issues in scale up, the belief of strategic policy makers was that battery banks were the solution. As all of these technologies face scale up issues, wind and solar may not be viable as the primary energy source to support the next generation of industrialization.

Consequently, the development of alternative battery chemistries is recommended. The calculated shortfall in copper and nickel production was also of concern, as both metals are vital to the existing economy and there is no known viable substitute or alternative for either commodity. Another alternative would be to develop an entirely new form of electrical power generation that did not need such heavy resource supply in construction or operation.

Keywords: metals, renewable energy sources, recycling, minerals, production, reserves, resources, batteries, wind, solar energy

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CONTENTS

ANNEX A.

ANNEX B.

1 INTRODUCTION

The need to phase out fossil fuels as an energy source is imminent, as the urgency of the task is increasingly acknowledged. However, the scale and scope of complexity of this task has been underestimated by strategic planners (Michaux 2021a, 2024). Until quite recently, scant consideration has been given to the quantity of metal and materials required to replace the use of fossil fuels in energy production. This paper presents a rudimentary, yet comprehensive estimate of the quantity of specific/relevant metals needed to manufacture just one generation of renewable, non-fossil fuel technology units (batteries, wind turbines, solar panels, etc.), in order to completely replace (globally) all Internal Combustion Engine (ICE) and fossil fuel technologies. This estimate was derived by examining global data figures from 2018 in order to determine the requirements for complete replacement of the existing global system of fossil fuel technologies (drawn from Michaux 2024). This gave the needed number of different technology units. An estimate of what the future market share of the different technologies might be was developed from an IEA market prediction for 2050 (IRENA 2022). Based on this estimation, a calculation of the metal content of each renewable technology and battery chemistry type was conducted (IEA 2021a), which was then projected onto the market share and number of units. What is clear, is that the current plan to phase out fossil fuels (often referred to as The Green Transition), will need metals and materials that are different to the metals and materials that were used to construct the existing fossil fuel industrial system (Kleijn et al. 2011, Jowitt & McNulty 2021).

2 DETERMINATION OF CALCULATIONS

The calculation flow for this paper was as follows:

1. Use the results and conclusions of (Michaux 2024) to determine the required quantity of electrical power required to substitute for electrical energy produced from combustion of fossil fuels completely. The global vehicle transport fleet was replaced with the required number and size of Electric Vehicles (EV's) and Hydrogen Fuel cell vehicles (H-Cell), and the required extra annual electrical power to support them. This study was based on 2018 data, to model the scope of physical activities over one calendar year. So, the objective of the first part of this study (Michaux 2024), was to map out the physical size, scope, and activities for the global system in the calendar year 2018. The objective of the second part of this study (this paper), was to take the outcomes of the first part and estimate the quantity of metals to produce the required number of renewable non-fossil fuel technological units.
2. Estimation of the energy split between various electrical power generation system alternatives (based on an IEA study, IRENA 2022) to deliver the required new annual capacity.
3. Estimation of how many average sized power stations of different kinds would be needed, then how many technology units like wind turbines and solar panels, and how much stationary power storage buffer would need to be provided. An effort was made to collect data as close to the source as possible, and still be practical.
4. Estimation of the metal content of each renewable technology unit.
5. Determination of the type and total volume of metals needed for all renewable technology units summed together for the global system. This calculation applies to the production of a single generation of renewable technology units and does not consider additional metal requirements for their subsequent replacement, nor the role of material reuse, recycling, or grid infrastructure.

6. Comparison of the total volumes of metals needed with net global mining production in 2019 (the last year before the global supply chain disruption resulting from quarantine measures introduced during the COVID-19 pandemic, the several years following 2019 have all sorts of data artefacts that are inconsistent with the previous 40 years).
7. Comparison of total volume of metals needed against stated global reserves in 2022, estimated conventional resources on land, and estimated resources under the sea (the most current data).

In this analysis, there were no time-based targets set for achieving replacement of energy systems based on fossil-fuel combustion. The focus of this study was on estimating the metal quantities required to replace the existing fossil fuel system with alternative technologies. Calculations for greenhouse gas emissions (GHG) and market price projections were not considered. This study differs to others in that it directly links the number of physical units of technology to the quantity of metals required to phase out fossil fuels. In doing so, an audit of the existing capability and existing scope of physical tasks is conducted. The size and scope of the physical task to phase out fossil fuels was estimated in (Michaux 2024). The numbers developed in that study are used in this paper.

3 SCOPE OF TASKS TO PHASE OUT FOSSIL FUELS

The size of the global fossil fuel system to be replaced was estimated for the year 2018 (Michaux 2024, Michaux 2021a), where the use of fossil fuels was quantified, and the size of the transport fleet was estimated. In 2018, the global system was still 84.7% dependent on fossil fuels, where renewables (including solar, wind, geothermal and biofuels) accounted for 4.05% of global energy generation (the remaining 11.25% being nuclear and hydro) (BP Statistical Review of World Energy 2020).

The global resources consumed to produce energy are shown since the beginning of the industrial revolution in Figure 1. Note the majority have always been fossil fuels and still is. Also note that the sum of all the demand for energy resources has been increasing consistently in a near exponential fashion (as opposed to society becoming more efficient and reducing fossil fuel resources as technology developed). Note the radical increase in global energy consumption from 28 564 TWh in 1950 to 172 884 TWh in 2018, an increase of more than 600%. Energy consumption in 2050 is projected to be much larger than it is in 2018. This paper does not account for economic growth but will map and study the calendar year 2018 only.

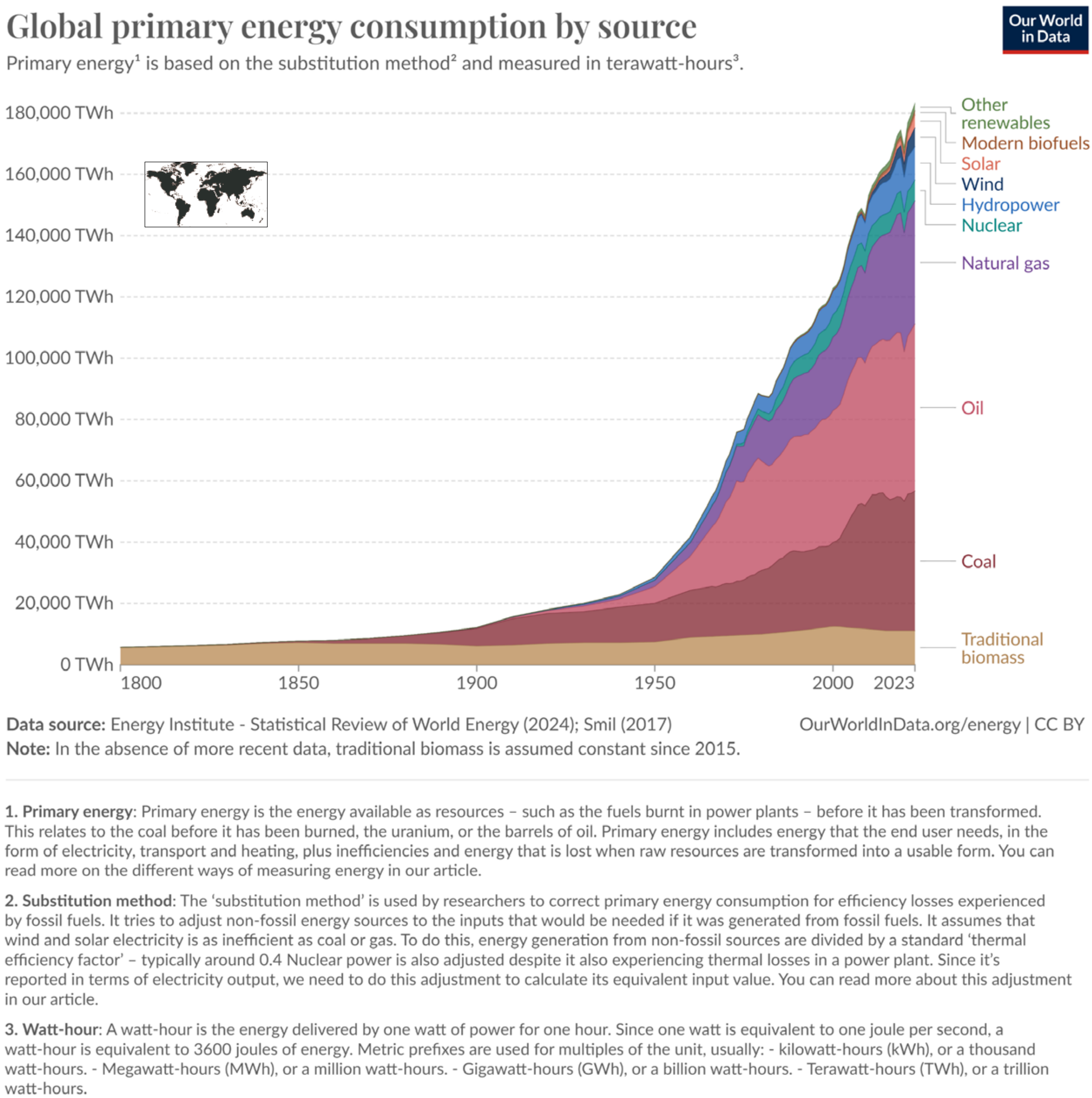

Fig. 1. Global Primary energy consumption. Units measured in terawatt-hours (TWh) per year. Classification 'other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels (Source: Our World in Data 2024, BP Statistical review of World Energy 2019, 2022) (Copyright Our World in Data, permission to reproduce granted).

The estimated total number of vehicles in the global fleet was 1.42 billion (Michaux 2021a), which travelled an estimated total distance of 16.26 trillion km (Table 1). Table 2 shows how the transport fleet may be split up into renewable technology units.

Table 1. Number of vehicles and estimated km driven in global fleet (Source: Michaux 2024).

Vehicle Class 	**Number of Self Propelled Vehicles in Global Fleet in 2018** (number)	**Total km driven by class in Global Fleet in 2018** (billion km)
Class 8 Truck	28 929 348	1 657,3
Refuse Truck + Delivery Truck	9 645 529	253,1
Transit Bus + School Bus + Paratransit Shuttle	19 356 724	560,8
Light Truck/Van + Light-Duty Vehicle	601 327 324	8 066,6
Passenger Car	695 160 429	5 562,1
Motorcycle	62 109 261	163,7
Total	**1 416 528 615**	**16 263,7**
	1.42 billion vehicles	Travelled 16.26 trillion km in 2018

* A Class 8 Truck is a heavy duty truck or semi trailer. Weight 14 969–36 287 kg (and above).

To phase out diesel fuel, all rail activity would have to become EV-based technology (powered by hydrogen fuel cells: Michaux 2021a, 2024). In a global context, 45% of passenger rail transport and 85% of rail freight is driven by diesel fuel locomotives (IEA 2019). If the number of million passengers carried per year in diesel fueled trains, on a global scale was 45%, then 1 720 billion passenger-kilometers was in trains powered by diesel (45% of 3 823 billion passenger-kilometers = 1 720 billion passenger-kilometers). The data for the number of passenger train locomotives in the global fleet was unavailable at the time of writing. If the number of tonne-kilometers (tkm) of rail freight transport per year in diesel fueled trains, on a global scale was 85%, then 9407 billion tkm were transported by locomotives powered by diesel. This study (Michaux 2024) assumed that all new rail transport should be hydrogen cell powered. Thus, phasing out fossil fuels in the rail network was assumed to be part of the hydrogen economy (Michaux 2024).

It was assumed that the most practical way to maintain capability in the aviation industry would be with biofuel (Michaux 2021a). In 2018, the global aviation industry consumed 359.3 billion liters of jet fuel (OECD 2024, Data Statistics Database). If this petroleum jet fuel was substituted by biofuel produced from ethanol, 747.37 billion tonnes of dry corn would be needed to be produced each year (Michaux 2024). This would require 831 465 km^2 of arable land dedicated to growing biomass for biofuel production, which in turn would require 925.2 km^3 of fresh water for irrigation. It was not clear whether this was environmentally sustainable to produce this quantity of biomass. There is significant pressure on available arable land mass to grow food in agriculture (United Nations 2019). As such, the aviation industry was not included in Tables 1 and 2.

Table 2. Estimated number of EV and H-Cell vehicles in the future global transport fleet (Michaux 2024).

TF20:J48ransport Vehicle	Number of EV Units (number)	Estimated average battery capacity (kWh)	Estimated total fleet battery capacity (TWh)	Number of H-Cell Hydrogen Powered Units (number)
Maritime Ship Size Classification ঃ				
Small (100 GT to 499 GT*)				9 155
Medium (500 GT to 24 999 GT*)				7 598
Large (25 000 GT to 59 999 GT*)				2 040
Very Large (>60 000 GT*)				1 072
Rail Freight Transport Fleet				
Passenger Locomotive**				data unavailable
Freight Locomotive**				104 894
Vehicle Transport Fleet				
HCV Class 8 Truck				28 929 348
Delivery Truck	9 645 529	206,1	1,99	
Bus	19 356 724	227,5	4,40	
Light Truck/Van + Light-Duty Vehicle	601 327 324	42,1	25,32	
Passenger Car	695 160 429	46,8	32,53	
Motorcycle	62 109 261	12,7	0,79	
Total	1 387 599 267		65,05	29 054 107

* Note. Gross tonnage (GT, G.T. or gt) is a nonlinear measure of a ship's overall internal volume. Gross tonnage is different from gross register tonnage. Neither gross tonnage nor gross register tonnage should be confused with measures of mass or weight such as deadweight tonnage or displacement. Gross tonnage (GT) is a function of the volume of all of a ship's enclosed spaces (from keel to funnel) measured to the outside of the hull framing. The numerical value for a ship's GT is always smaller than the numerical values of gross register tonnage (GRT).

ঃ Note. 17% of the maritime shipping fleet is to be powered with hydrogen in a H2-Cell unit

** Note. 45% of passenger rail transport and 85% of rail freight is driven by diesel fuel locomotives (IEA 2019). Number of freight locomotoves was able to be estimated. However, data for the number of diesel passenger locomotives was unavailable. All new locomotives were for freight and were assumed to be H2-Cell powered electric systems. Extra power cacpaicty from the electrical power grid for passenger trains and freight trains was included in calculations for Michaux 2021a.

Note. Aviation was not included in this table. For this study, it was found that aviation might be powered with biofuel.

The outcome of the comparison of all EV transport systems against all H-Cell transport systems doing the same physical work over one year, was that the electrical power to produce the needed hydrogen was approximately 3.3 times required to charge the battery of an equivalent EV system (Michaux 2024 and Michaux 2021a). It was also found that the mass of the required EV battery was approximately 3.2 times the mass of the equivalent H-Cell hydrogen fuel tank.

These two findings were used to recommend that all long-range, or heavy application transport vehicles (HCV Class 8 trucks, rail, and maritime shipping be H-Cell hydrogen fueled propulsion systems). All other vehicles were recommended to be EV's (passenger cars, buses, commercial vans, and light trucks).

The total energy requirements of the macro-scale tasks for replacing fossil fuels in a global context is as follows (Figs. 2, 3, Michaux 2024, Michaux 2021a):

In summary:

Electrical energy required to charge EV batteries	4 354.0 TWh
	+
Electric power required to produce hydrogen for existing applications (excluding hydrogen used to refine petroleum products)	1 963.5 TWh
	+
Electric power to produce hydrogen for a H_2-Cell HCV Class 8 truck fleet	7 676.0 TWh
	+
Electric power to produce hydrogen for a H_2-Cell rail network	793.1 TWh
	+
Electric power to produce hydrogen for a H_2-Cell in 17% of maritime shipping	844.9 TWh
	+
Electric power to produce steel in a hydrogen atmosphere	6 939.2 TWh
	+
Electric power required to produce ammonia production	
To fuel 46% of the maritime shipping fleet	3 903.1 TWh
	+
To produce agricultural fertilizer	2 545.8 TWh
	+
Electrical energy required to produce biodiesel for 37% of maritime shipping	18.1 TWh
+	
Electrical energy required to phase out coal, gas, oil power generation	17 086.1 TWh
	+
Electrical energy required to power heat pumps for building heating	2 816.0 TWh
	=
Total power requirements	**48 939.8 TWh**

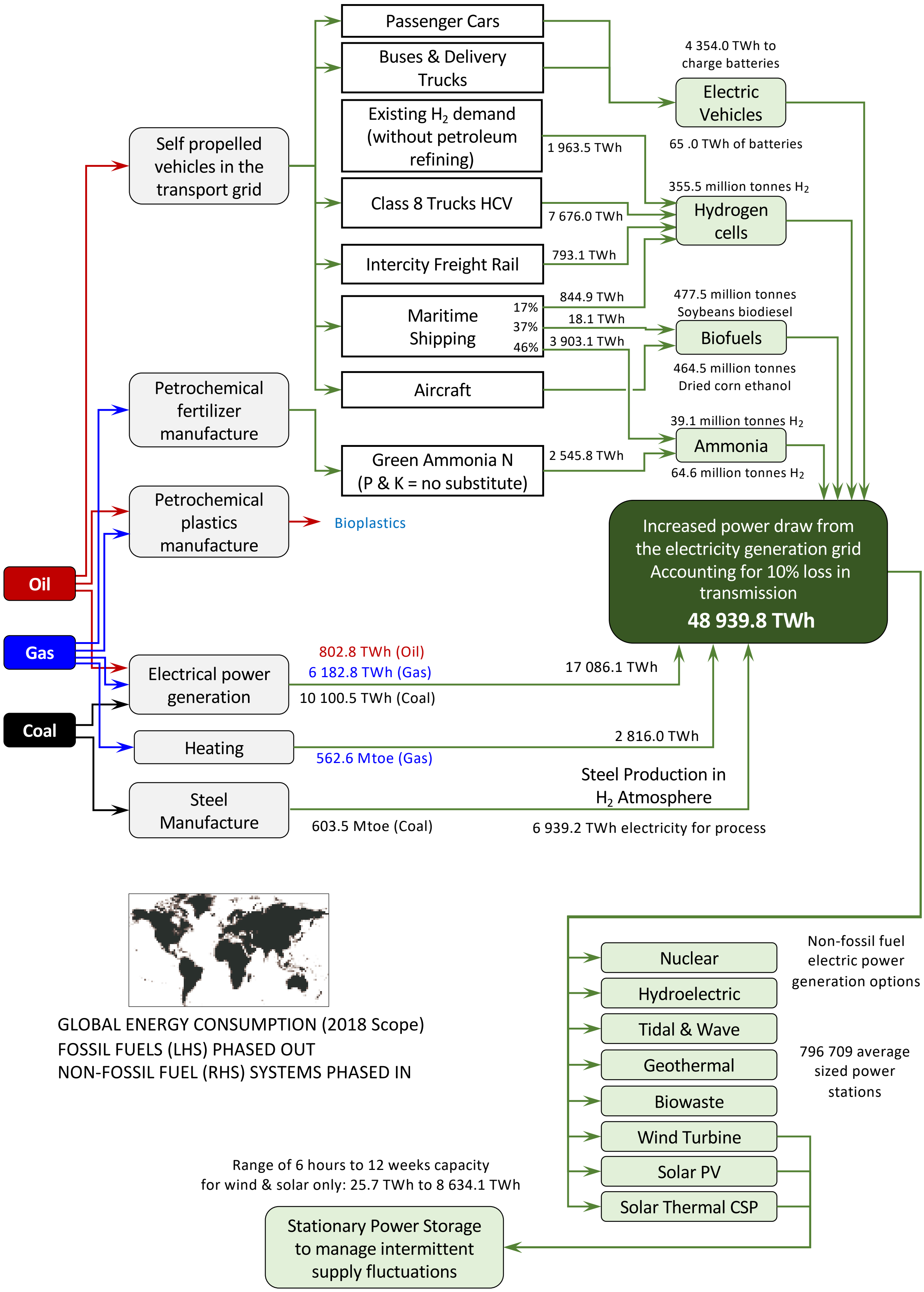

Fig. 2. Fossil fuel energy consumption by application and proposed substitution systems (Michaux 2024).

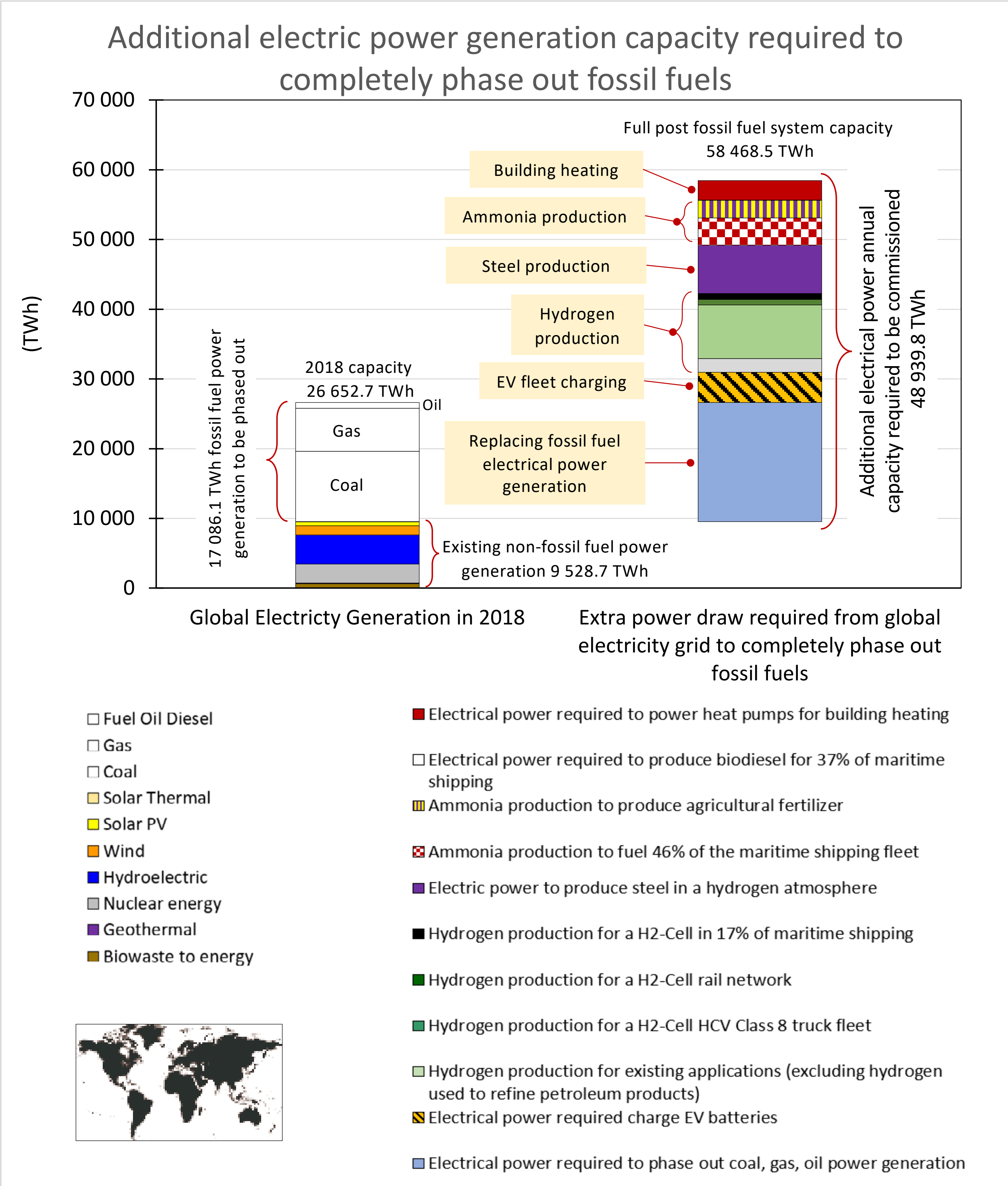

Fig. 3. The estimated additional electrical power required globally to phase out fossil fuels (Michaux 2024).

Figures 4 and 5 show a calculation flowchart that this study has followed. The reader could use them as a map.

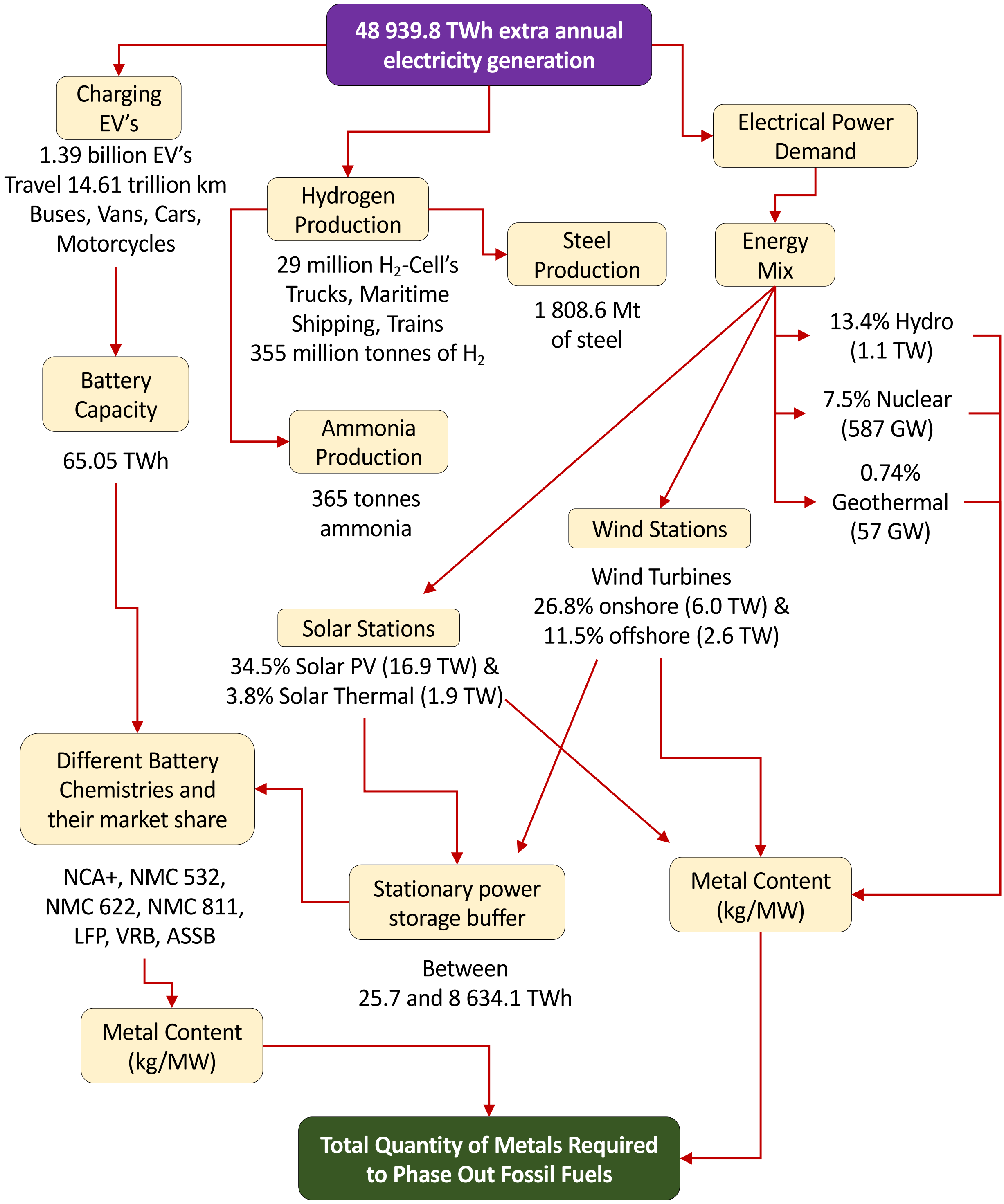

Fig. 4. Quantity of metal required to phase out fossil fuels calculation flowchart for this study.

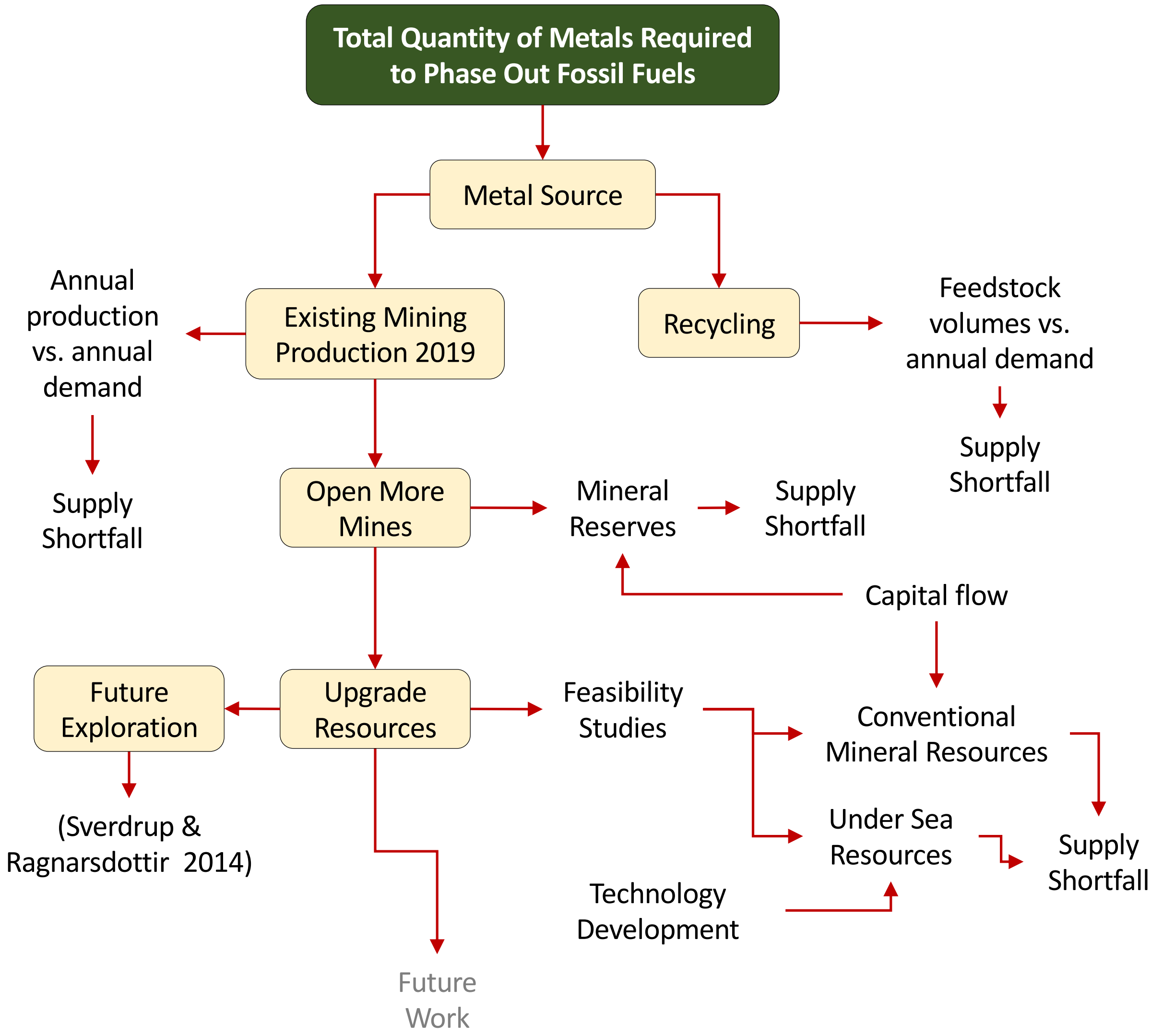

Fig. 5. Metal supply from mineral reserves and resources calculation flowchart for this study.

4 THE ENERGY SPLIT IN ELECTRICAL POWER GENERATION SYSTEMS

To source the required extra annual 48 939.8 TWh of electrical energy, an estimate was made of the energy split between non-fossil fuel electrical power generation systems. The International Renewable Energy Agency published a road map report (IRENA 2022) that proposed an energy split in 2050, where wind and solar dominated, and overall electricity generation had tripled in size between 2018 and 2050 (Fig. 6). Figure 6 was developed to provide a road map for the global system to phase out fossil fuels in accordance with the climate mitigation goal – to limit global average temperature increase by the end of the present century to 1.5°C, relative to pre-industrial levels (European Commission 2019a).

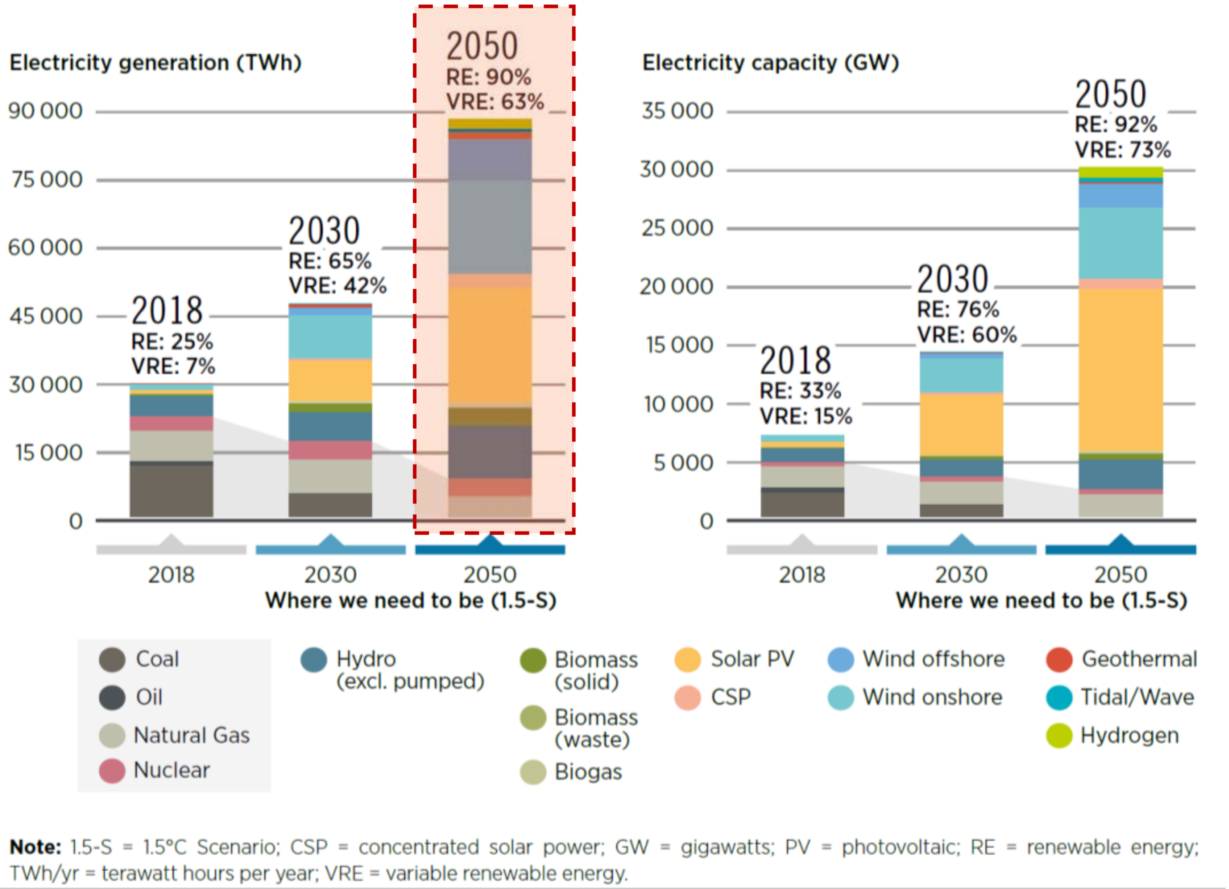

Fig. 6. Global total power generation and the installed capacity of power generation sources in 1.5°C Scenario in 2018, 2030 and 2050 (Source: IRENA 2022, Fig. 2.3, pg 61) (Copyright IRENA) (Copyright IEA, permission to reproduce granted).

Table 3 shows the predicted energy split for 2050 in Figure 6 (inside the red rectangle with the dotted border), which in conjunction with learnings from previous work (Michaux 2021a) became the developed energy split for this study. This was used to estimate what extra capacity of new power systems and what type would be required to phase out fossil fuels. The energy split in Figure 3 has some assumptions which were not used in this study. Figure 6 and Table 3 show that natural gas still is part of the energy mix. While this may be sensible in that gas power generation could be used as a power buffer, senior policy makers who develop strategic plans in Europe prefer to phase out fossil fuels completely (personal observation by the author in strategic development meets held in Brussels). So, this paper assumes gas, like all other fossil fuels will be removed entirely. While Europe is not the entire global system, this observed opinion has proven to be quite useful.

Table 3. Proposed energy split electrical power generation systems in 2050 (IRENA 2022, Fig. 2.3).

Power Generation System	**Proposed energy split electrical power generation systems in 2050 (IRENA 2022, Figure 2.3)** (%)
Gas	5,0%
Nuclear	3,8%
Hydroelectric	12,9%
Biomass (solid)	4,0%
Biomass (biogas)	1,3%
Solar PV	30,0%
Solar Thermal	2,7%
Wind onshore	24,8%
Wind offshore	10,7%
Geothermal	1,3%
Tidal/Wave	0,7%
Hydrogen	2,7%

It was assumed in this study that biowaste to energy systems cannot be expanded beyond what it is now, as planetary environmental sustainability limits may be exceeded. What is considered a sustainable harvest rate from the environment compared against what might be demanded for consumption should be the subject of future work to be done. Work done in Finland shows that the Finnish forestry industry is close to the sustainable limits of what should be harvested, and expansion of that harvest could be challenging (Michaux 2022). Any extra biomass harvest capacity should be tasked to generate biofuel for the aviation industry, feedstock for bioplastics and feedstock for the organic fertilizer industry. So, for this study, the biowaste power generation (Combined Heat and Power CHP) was to stay as it was in 2018.

A simulation to expand the nuclear power plant (NPP) fleet was conducted (Scenario E in Michaux 2021a). It was found that the logistics to expand nuclear value chain could not happen fast enough (assuming a net increase of 25 new plants a year from 2025, and a 5 year build time) to fully replace fossil fuel systems. It was postulated that the industrial system could not expand the nuclear fuel cycle infrastructure so quickly, assuming if done appropriately. That being stated, nuclear power could well become the power source that keeps heavy industry viable. Nuclear power should be expanded but valued much more highly than it is now.

The potential for geothermal power is good, but dependent on scientific breakthroughs. Low temperature geothermal could be used for building heating if heat reservoirs were available (shallow enough to access). A breakthrough in deep well drilling could revolutionize this power source. Available geothermal resources in the desired quantities could be a bottleneck though. Most known heat resources are not mapped to the level of precision that could be used for geothermal power. It is proposed that geothermal power will expand in capacity (Michaux 2024).

Consistent data was not available for wave or tidal energy systems in a form that could be used in this study, so it was not included. Hydroelectricity will expand in a similar proportion to shown in Figure 6.

It was assumed that wind and solar power would become the primary electric power source for the global industrial system, with an energy mix proportion of approximately 68.2% in context of the previous assumptions. Proportions of onshore/offshore wind turbines were taken directly from the IEA (IRENA 2022) where onshore wind turbines were 70% of the fleet, and offshore turbines were 30% of the fleet. Proportions of solar PV/solar CSP systems were also taken directly from the IEA (IRENA 2022) where solar PV systems represent 90% of the solar capacity and solar CSP thermal systems represent 10%.

Using the proportions shown in Figure 6, Table 3, and the assumptions just stated, the energy mix used in this paper were developed and listed below:

- All fossil fuels will be completely phased out
- Hydro will expand by adding 115% capacity compared to 2018 production rates
- Nuclear will double in capacity from 2018 production rates
- Biowaste to energy was to remain the same in energy split proportion
- Geothermal power generation will triple in producing capacity compared to 2018 production rates
- After the above calculations, all remaining new required capacity will be split equally between wind and solar
- New wind capacity will be a split between 70% onshore wind turbine site to 30% offshore wind turbine
- New solar power capacity will be split between 90% solar PV and 10% solar thermal

Tables 4 and 5 were developed in (Michaux 2024) and show the proposed energy split based on the above assumptions used in this paper.

Table 4. Estimated number of new power stations and installed capacity to globally phase out fossil fuels (Michaux 2024, Michaux 2021a).

Power Generation System 	**Global non-fossil fuel electricity production in 2018 (Agora Energiewende and Sandbag 2019)** (GWh)	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Proposed Proportion of Energy Split on new annual capacity** (%)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)
Nuclear	2 701 400	3 670 491	7,50%	12 803,2	287
Hydroelectric	4 193 100	6 538 368	13,36%	1 325,7	4 932
Wind Onshore (70% share)	1 303 800	13 131 060	26,83%	81,2	161 629
Wind Offshore (30% share)		5 627 597	11,50%		69 270
Solar PV (90% share)	579 100	16 884 259	34,50%	33,0	511 015
Solar Thermal (10% share)	5 500	1 874 397	3,83%	77,0	24 352
Geothermal	93 000	362 155	0,74%	603,2	600
Biowaste to energy	652 800	851 554	1,73%	34,6	24 624
Total (GWh)	9 528 700	48 939 882			796 709
Total (TWh)	9 528,7	48 939,9			

Table 5. Estimated energy split between non fossil fuel powered electricity generation systems (Michaux 2021a).

Power Generation System 	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)	**Power produced by a single average plant in 2018** (GWh)	**Average installed plant capacity in 2018 (Global Energy Observatory)** (MW)	**Total new annual installed capacity required** (MW)
Nuclear	287	12 803,2	2 046,5	586 702,5
Hydroelectric	4 932	1 325,7	225,4	1 111 636,4
Wind Onshore	161 629	81,2	37,2	6 012 611,3
Wind Offshore	69 270		37,2	2 576 833,4
Solar PV	511 015	33,0	33,1	16 914 581,6
Solar Thermal	24 352	77,0	77,0	1 874 397,5
Geothermal	600	603,2	94,7	56 854,5
Biowaste to energy	24 624	34,6	31,7	780 591,1
Total	796 709			29 914 208,3

5 WIND POWER

According to Table 6, this study projects that 1.3 million wind turbines (each one assumed to be a 6.6 MW (Megawatt capacity) will need to be operational as part of the task to completely phase out fossil fuels. Onshore units will account for 70% of this number, corresponding to 910 000 wind turbines. Offshore units will account for 30%, requiring 390 429 wind turbines. Each wind turbine is connected to the power grid with a cable consisting predominantly of copper (approximately 250 mm in diameter). Offshore turbines would require a much longer connecting cable, requiring proportionately more copper.

Table 6. Estimated number of new 6.6MW wind turbines and 450 MW solar panels (Michaux 2024, Michaux 2021a).

Power Generation System 	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Power produced by a single average plant in 2018** (GWh)	**Estimated number of required new power plants of average size to phase out fossil fuels** (number)	**Average installed plant capacity in 2018 (Global Energy Observatory)** (MW)	**Total new annual installed capacity required** (MW)	**Number of 6.6 MW wind turbines** (number)	**Number of 450 Watt Commercial grade solar panels** (number)
Wind Onshore (70% share)	13 131 060	81,2	161 629	37,2	6 012 611	911 002	
Wind Offshore (30% share)	5 627 597	81,2	69 270	37,2	2 576 833	390 429	
Solar PV (90% share)	16 884 259	33,0	511 015	33,1	16 914 582		37 587 959 078
Solar Thermal (10% share)	1 874 397	77,0	24 352	77,0	1 874 397		
						1 301 431 total wind turbines	

There are four main types of wind turbines (IEA 2021a): gearbox double-fed induction generator (GB-DFIG), gearbox permanent magnet synchronous generator (GB-PMSG), direct-drive permanent magnet synchronous generator (DD-PMSG) and direct-drive electrically excited synchronous generator (DD-EESG). Figure 7 shows a projection of what the split between the different wind turbines could be (based on the Sustainable Development Scenario in IEA 2021a).

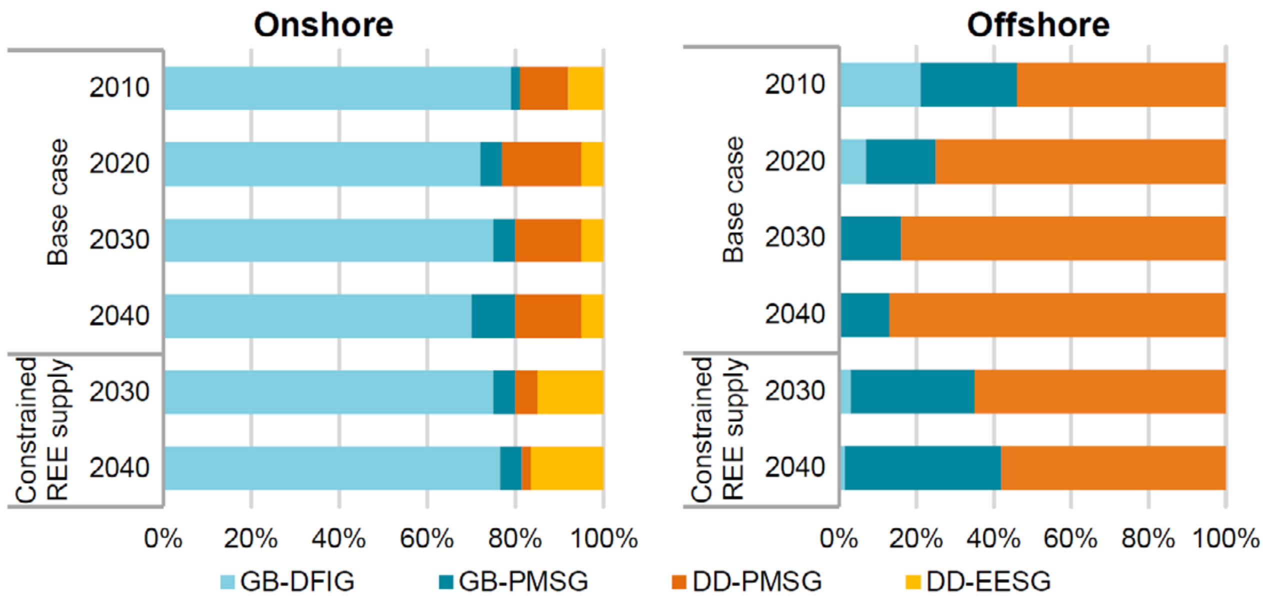

Fig. 7. Projected wind turbine global market share (Source: IEA 2021a) (Copyright IEA, permission to reproduce granted).

Figure 8 shows the metal content of different wind turbine units. Figure 8 shows some of the metal content needed for wind turbine manufacture, but not all the different types of metals. For example, steel and cement are not included in Figures 7 and 8. Calculations were made in this study for the concrete (and cement) and steel for wind turbines (shown in Tables 10 and 11).

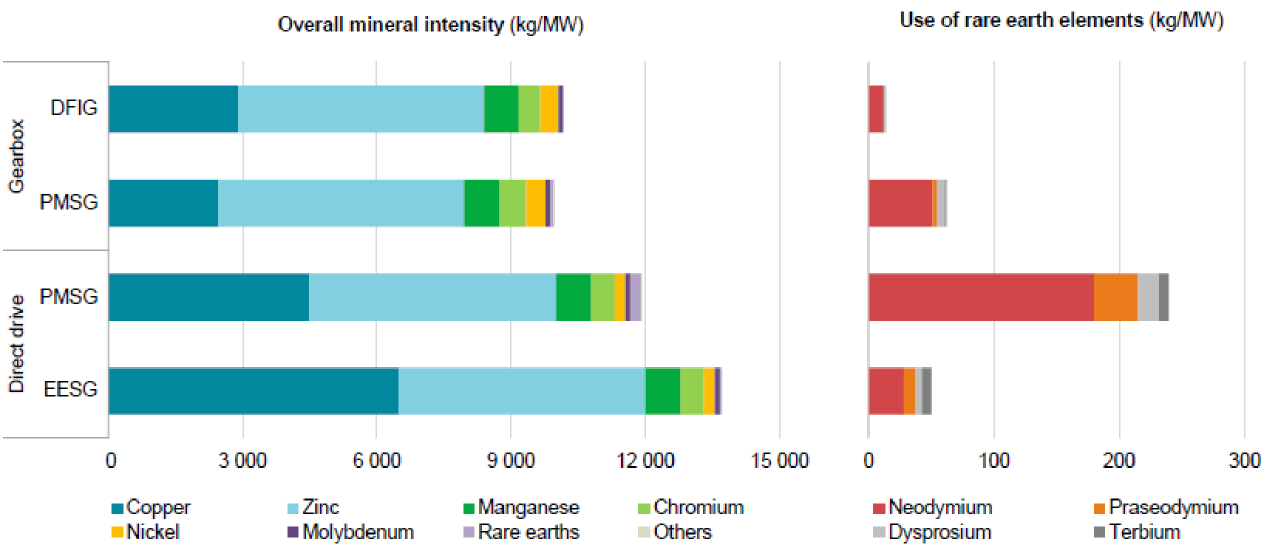

Fig. 8. Metal content of different wind turbine units. Note: that the metal content intensity numbers are based on the onshore installation environment. More copper is needed in offshore applications due to much longer cabling requirements Also, not all metals used are shown, for example the amount of iron (steel) and concrete are not shown (Source: IEA 2021a) (Copyright IEA) (Copyright IEA, permission to reproduce granted).

After examining the projected market share of wind turbines in Figures 7, 8, Tables 3 and 5, the assumed projected market share for wind turbines to be used in this study was calculated in Tables 7 and 8. There were no logistics, or time required for construction estimated for the required new installed power generation capacity in Tables 6, 7 and 8. This study just presents the long-term target for full system replacement (using a 2018 industrial activity footprint).

Table 7. Projected market share of onshore wind turbine types used in this study.

Onshore Wind Turbine Type	Acronym	Projected market share in 2040 (%)	Required new annual installed capacity required (6 012 611 MW*) (MW)
Gearbox double-fed induction generator	GB-DFIG	69,0%	4 147 385
Gearbox permanent magnet synchronous generator	GB-PMSG	11,7%	702 203
Direct-drive permanent magnet synchronous generator	DD-PMSG	14,6%	877 753
Direct-drive electrically excited synchronous generator	DD-EESG	4,7%	285 270

* from Table 5

Table 8. Projected market share of offshore wind turbine types used in this study.

Offshore Wind Turbine Type	Acronym	Projected market share in 2040 (%)	Required new annual installed capacity required (2 576 833 MW*) (MW)
Gearbox double-fed induction generator	GB-DFIG	-	
Gearbox permanent magnet synchronous generator	GB-PMSG	13,1%	337 565
Direct-drive permanent magnet synchronous generator	DD-PMSG	86,9%	2 239 268
Direct-drive electrically excited synchronous generator	DD-EESG	-	

* from Table 6

The metal content for each wind turbine type was estimated in Table 9. Combining Tables 6 to 9, the metal content for the global fleet of wind turbines was estimated in Table 10 (Onshore units) and Table 11 (Offshore units). Cast iron, steel, and concrete quantity (kg per installed capacity MW) was averaged from data for a 1 MW, 2 MW and 2.3 MW wind turbine materials construction list (Source: Chipindula et al. 2018, Carrara et al. 2020).

Table 9. Estimated metal content in wind turbines by technology unit per MW.

Metal Content in a Wind Turbine by Type	**Gearbox double-fed induction generator** GB-DFIG (kg/MW)	**Gearbox permanent magnet synchronous generator** GB-PMSG (kg/MW)	**Direct-drive permanent magnet synchronous generator** DD-PMSG (kg/MW)	**Direct-drive electrically excited synchronous generator** DD-EESG (kg/MW)
Cast Iron (onshore unit) ‡	14 218	14 218	14 218	14 218
Cast Iron (offshore unit) ‡	23 643	23 643	23 643	23 643
Steel (onshore unit) ‡	113 519	113 519	113 519	113 519
Steel (offshore unit) ‡	450 065	450 065	450 065	450 065
Concrete (onshore unit) *	421 000	421 000	421 000	421 000
Concrete (offshore unit) **	650 000	650 000	650 000	650 000
Aluminium [₫]	1 560	1 560	1 560	1 560
Copper (Onshore unit)	2895,8	2432,4	4459,5	6486,5
Copper (Offshore unit) ⊚	7895,8	7432,4	9459,5	11486,5
Zinc	5501,9	5501,9	5501,9	5501,9
Manganese	752,9	781,9	747,1	752,9
Chromium	463,3	532,8	521,2	521,2
Nickel	463,3	463,3	231,7	231,7
Molybdenum	104,2	115,8	104,2	104,2
Rare Earth Metals				
Neodymium	12,4	49,7	180,0	22,8
Praseodymium	4,1	34,1	6,2	
Dysprosium	6,2	16,6	4,1	
Terbium		2,1	6,2	4,6

‡ Cast iron, steel quantity (kg per installed capacity MW) was averaged from data for a 1 MW, 2 MW and 2.3 MW wind turbine materials construction list (Source: Chipindula et al. 2018)

* The concrete content of wind onshore technology was determined by averaging the concrete contents of wind turbines with and without precast concrete towers of respectively 2.3 and 2 MW capacities. (Source: Hache et al. 2020, EcoInvent 2017, Chipindula et al. 2018)"

** The concrete content of wind offshore was determined through the UNEP data, of offshore wind turbine with 5MW capacity. (Source: Hache et al. 2020, UNEP 2016)

₫ Source: United States Department of Energy 2015

⊚ An offshore wind turbine would require a much longer connecting cable to the power grid resulting in more copper required in manufacture. This is assumed to add 5 000 kg/MW (Source: estimated from Bobba et al. 2020). So metal content for an onshore wind turbine is assumed to be the same as an offshore wind turbine, with the exception of copper.

Table 10. Total metal content in onshore wind turbines to globally phase out fossil fuels.

Combined Metal Content in an onshore wind turbine by Type	Gearbox double-fed induction generator GB-DFIG (tonnes)	Gearbox permanent magnet synchronous generator GB-PMSG (tonnes)	Direct-drive permanent magnet synchronous generator DD-PMSG (tonnes)	Direct-drive electrically excited synchronous generator DD-EESG (tonnes)	Metal quantity required for onshore wind turbines (tonnes)	Metal quantity required for onshore wind turbines (million tonnes)
Cast Iron (Onshore unit)	58 968 713	9 984 121	12 480 151	4 056 049	85 489 033	85,49
Steel (Onshore unit)	470 807 120	79 713 375	99 641 718	32 383 558	682 545 771	682,55
Concrete (Onshore unit)	1 746 049 169	295 627 372	369 534 216	120 098 620	2 531 309 377	2 531,31
Copper (Onshore unit)	12 009 803	1 708 061	3 914 306	1 850 399	19 482 569	19,48
Aluminium	6 469 921	1 095 436	1 369 295	445 021	9 379 674	9,38
Zinc	22 818 625	3 863 471	4 829 339	1 569 535	33 080 970	33,08
Manganese	3 122 549	549 020	655 773	214 778	4 542 120	4,54
Chromium	1 921 568	374 147	457 516	148 693	2 901 924	2,90
Nickel	1 921 568	325 345	203 341	66 086	2 516 340	2,52
Molybdenum	432 353	81 336	91 503	29 739	634 931	0,63
Rare Earth Metals						
Neodymium	51 485	34 868	157 996	6 492	250 841	0,25
Praseodymium		2 906	29 965	1 771	34 641	0,035
Dysprosium		4 359	14 528	1 180	20 067	0,020
Terbium		1 453	5 448	1 298	8 199	0,008

Table 11. Total metal content in offshore wind turbines to globally phase out fossil fuels.

Combined Metal Content in an offshore wind turbine by Type	**Gearbox permanent magnet synchronous generator** GB-PMSG (tonnes)	**Direct-drive permanent magnet synchronous generator** DD-PMSG (tonnes)	**Metal quantity required for offshore wind turbines** (tonnes)	**Metal quantity required for onshore wind turbines** (tonnes)
Cast Iron (Offshore unit)	7 981 158	52 943 715	60 924 874	60,92
Steel (Offshore unit)	151 926 285	1 007 816 347	1 159 742 632	1159,74
Concrete (Offshore unit)	219 417 367	1 455 524 365	1 674 941 732	1674,94
Copper (Offshore unit)	2 508 930	21 182 267	23 691 198	23,69
Aluminium	526 602	3 493 258	4 019 860	4,02
Zinc	1 857 260	12 320 298	14 177 558	14,18
Manganese	263 926	1 672 967	1 936 893	1,94
Chromium	179 861	1 167 186	1 347 047	1,35
Nickel	156 401	518 749	675 150	0,68
Molybdenum	39 100	233 437	272 537	0,27
Rare Earth Metals				
Neodymium	16 762	403 068	419 830	0,420
Praseodymium	1 397	76 444	77 841	0,078
Dysprosium	2 095	37 064	39 159	0,039
Terbium	698	13 899	14 597	0,015

6 SOLAR POWER

Electricity generated with solar powered photovoltaic cells is projected to account for a large proportion of the global energy market in the future (Table 4). Several technologies are used to manufacture solar PV panels.

Crystalline silicon solar panels (cells are made of silicon atoms connected to one another to form a crystal lattice) are the most common technology used currently and is projected to account for 90% of the market in 2040 (Figs. 9, 10, IEA 2021a).

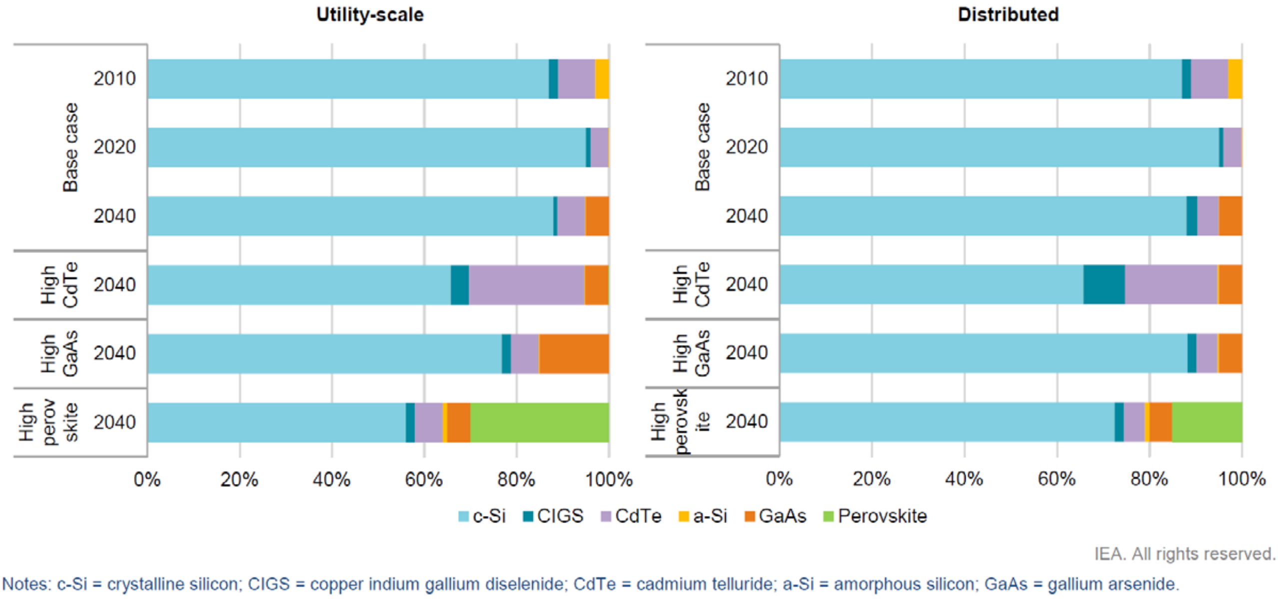

Fig. 9. Share of annual capacity additions by PV technology under different technology evolution scenarios (Source: IEA 2021a) (Copyright IEA, permission to reproduce granted).

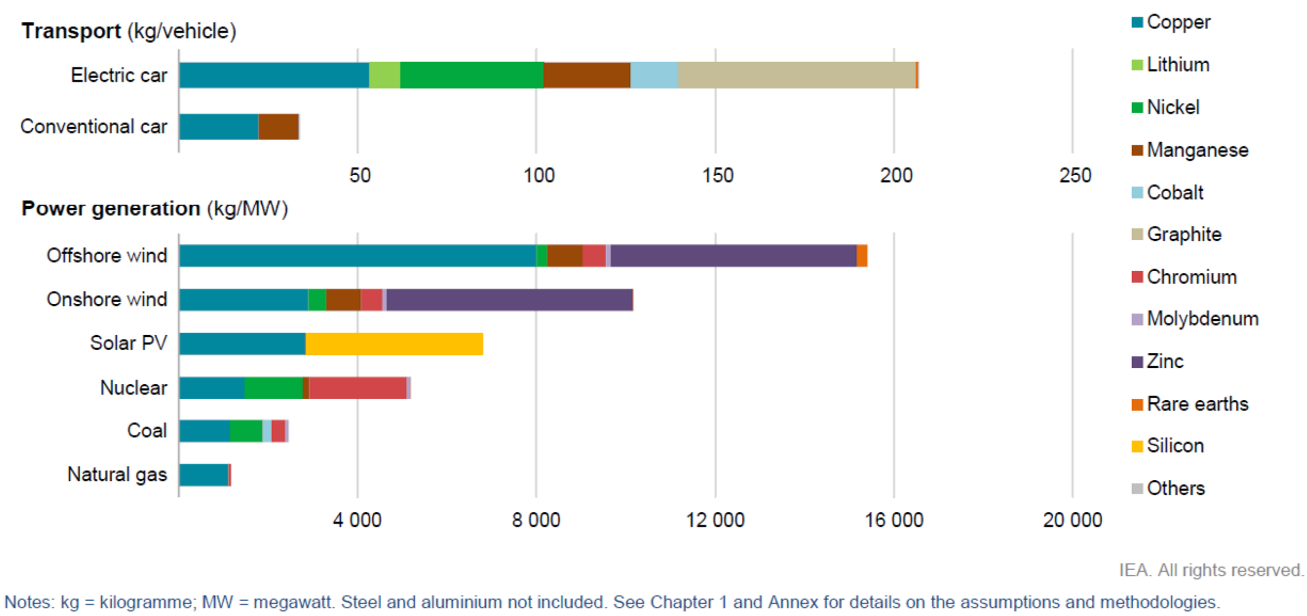

Fig. 10. Estimated metal content for various energy technology systems (Source: IEA 2021a). Note: not all metals used are shown, for example the amount of iron (steel) and concrete are not shown (Copyright IEA, permission to reproduce granted).

Thin film photovoltaic technology will also have a share of the market. There are two main types of thin-film PV semiconductors in production at present: cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). Both materials can be deposited directly onto either the front or back of the module surface. CdTe is the second-most common PV material after silicon (EIA). For the purpose of this study, it was assumed that all extra solar PV capacity would be based on crystalline silicon solar cells, because the data was not available to estimate the metal content of thin film photovoltaics. Given that all solar panels were to be crystalline silicon, it was assumed that 2 841 kg of copper and 3 984 kg of metallurgical grade silicon was required per MW of power generation capacity with crystalline silicon photovoltaic (PV) panels (IEA 2021a). Metallurgical grade Silicon is roughly 98 to 99% pure Silicon with Aluminium and iron being the major source of impurities (USGS 2024).

The amount of silver paste used per unit of crystalline silicon photovoltaic cell was on average 100 mg/cell, with a projected reduction to 50 mg/cell by 2029 (ITRPV 2019). In this calculation, it was assumed that there would be 50 mg of silver for each PV cell, which was assumed to have a typical cell efficiency of 4.27 W/cell (ITRPV 2019). This resulted in an estimate of 11.7 kg of silver per megawatt of solar PV power generation.

The total metal content required in solar panel capacity to phase out fossil fuels was 48 million tonnes of copper, 67.4 million tonnes of metallurgical silicon, and 197 901 tonnes of silver (Table 12). Table 12 does not show all the different metals required to manufacture solar panel systems.

Table 12. Metal content in crystalline silicon solar PV panels per MW (Source: IEA 2021a, ITRPV 2019).

Metal	**Mass in 1 MW of Solar Panels** (kg/MW)	**Metal content in 16 903 977.3 MW of solar panels** (kg)	**Metal content in 16 903 977.3 MW of solar panels** (tonnes)
Steel [đ]	5 000	8,46E+10	84 572 908
Concrete*	10 000	1,69E+11	169 145 816
Aluminium	12 000	2,03E+11	202 974 979
Silicon (Metallurgical)	3 984	6,74E+10	67 387 693
Copper	2 841	4,81E+10	48 054 326
Silver	11,7	1,98E+08	197 901

[đ] Source: U.S. Department of Energy 2015

* Source: Hache et al. 2020

7 STATIONARY POWER STORAGE BUFFER

Wind and solar electrical power generation are highly intermittent in supply. The moving path of the sun and the weather conditions drastically alter the incident solar radiation, especially across the winter season. Solar power generation efficiency varies in a day/night cycle and is also highly seasonal. Figure 11 shows the annual variation in daily solar radiation in Germany (Wesselak & Voswinckel 2016). Amount of solar radiation has a direct influence on the efficiency and effectiveness for solar photovoltaic panels to generate electricity. This also makes solar power highly intermittent in supply. This problem is more extreme closer to the geographical poles as compared to the planetary equator.

Wind power has shown to be highly intermittent (Fares 2015, EIA 2015), as power generation depends on wind conditions. Furthermore, wind power is considered non-dispatchable because it is a variable power source, meaning that its electrical output depends on many factors, such as wind speed, air density, turbine characteristics, and more. All these factors also change depending on location of the site. Wind speed must also be in a certain range (depending on the turbine), above 3.5 m/s to generate electricity, and below 25 m/s to avoid damage to the turbine (Huang et al. 2014). For example, between October 2006 and February 2007 there were 17 days when the output from Britain's 1632 windmills was less than 10% of their capacity. During that period there were five days when output was less than 5% and one day when it was only 2% (McKay 2008). Wind power generation efficiency can vary greatly minute to minute, but also can vary greatly in a month-to-month scale.

Existing power systems currently rely on changing the generation of fossil fuel-based and hydro plants to cope with the fluctuations in the demand (Grigsby 2006). Intermittent power supply from wind and solar generation systems is also balanced up in the same manner, with most variation mitigation coming from gas power fired systems. This means that to replace the gas industry, electrical power generation and the ability to buffer between electricity supply and demand will need to be substituted. A buffer power storage system will be required.

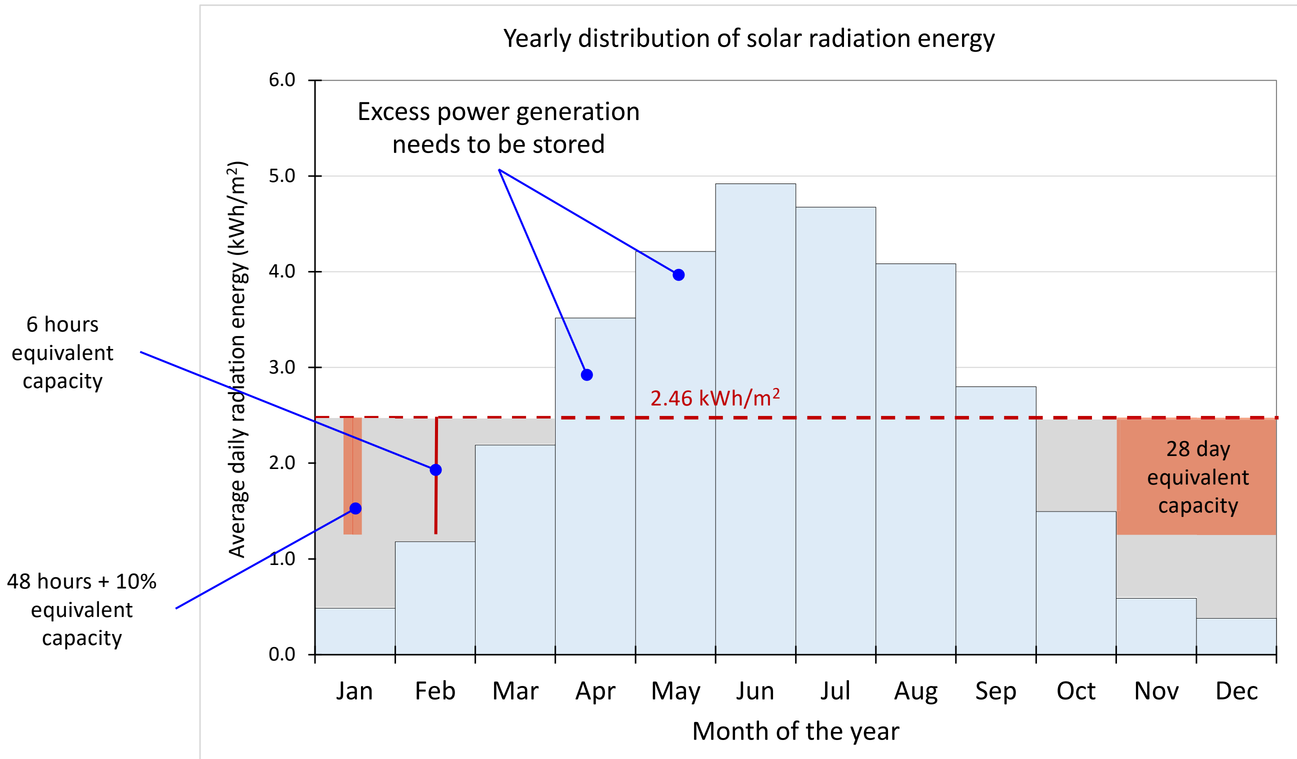

Fig. 11. Distribution of the sun's radiation energy over the year in Germany (Wesselak & Voswinckel 2016).

Power storage systems are mostly required to ensure consistent supply to the grid during the long periods of reduced sunlight hours and reduced wind where it is needed, for solar and wind turbine stations. The difficulty associated with integrating variable sources of electricity stems from the fact that the current power grid was generally designed around the concept of large, controllable, steady supply electric generators (Hanania et al. 2017). Many industrial applications like smelting require a stable and reliable power source, where if there was any change, several weeks' notice would be required to facilitate a shutdown.

The most flexible storage in application is a large battery storage power station (U.S. Department of Energy 2020). This is a type of energy storage power station that uses a group of batteries to store electrical energy. In addition, there are many other options, including gravity-based (pumped) storage, storing energy as heat, and so on. While there are many ways to store energy, there is a school of thought that grid scale battery banks may be the most practical to use at scale for time periods longer than a few days (Fekete et al. 2023).

7.1 Size of power storage buffer

Steinke et al. 2012 put forward the recommendation for a fully renewable powered Europe to have 2 days of power storage, plus 10%. This study was to examine all power requirements for Europe to be 100% renewable. Another study (Droste-Franke 2015) examined the possibility of a 'supergrid' across the European Union, North Africa, and the Mediterranean. This study found that there would still need to be 28 days (1 month) of energy storage to keep the grid up during seasonal variations (Droste-Franke 2015). Palmer & Floyd (2020) proposed that up to 7 weeks of storage would be required as well as large amounts of renewable capacity overbuild. (Ruhnau & Qvist 2021) proposed 12 weeks of power buffer. A study done in the United Kingdom (Fragaki et al. 2019) proposed a 30 day power buffer for a 100% renewable energy generation system, provided there was a 115% overbuild in renewable energy generation capacity.

In the literature, there are a number of opinions with regard to how much of a buffer is required. None of the studies examined worked to the assumption that the power grid would deliver the same current, voltage and frequency in clean sinusoidal power at the same quantity of energy, 365 days a year, 24 hours a day, to a resolution of a millionth of a second (Grigsby 2006). This is what is required to protect delicate electronic equipment like computers from black outs, brown outs, and power spikes. At this time power grids can achieve this by balance off against each other, usually sing fossil fuel power generation. In a fully Green Transition scenario, a large solar or wind power generation system would not have the access of fossil fuel power generation systems and would have to be internally self-sufficient. In the projected energy split shown in Figure 30 (the IEA prediction for 2050), wind and solar represent about 70% of the generation of electricity. These renewable grids would be so large and so intermittent, that they could not be stabilized by an external power source.

Tables 13 to 18 show a case study in the form of the power produced by wind and solar in the PJM regional electrical power transmission organization (RTO). These tables were assembled by assessing data from PJM reporting (Monitoring Analytics LLC 2023, Monitoring Analytics LLC 2024, PJM 2024). This is a multi-fuel electrical power generation grid that services approximately 100 million people in the United States. Tables 13 and 14 shows the installed capacity of wind and solar systems, for the years 2022 and 2023.

Table 13. 2022 Capacity Factors for the PJM power grid per PJM installed capacities, September 2023 (Source: Table 12-1, 12-2 in Monitoring Analytics LLC 2023).

PJM renewable power system	**Capacity in 2022** (MW)	**MWh potential** (MWh)	**Actual MWh** (MWh)	**Capacity Factor** (%)
Solar	6 220	54 482 820	9 242 961	17,0%
Wind	10 996	96 323 208	31 518 036	32,7%

Table 14. 2023 Capacity Factors for the PJM power grid per PJM installed capacities, September 2023 (Source: Table 12-1, 12-2 of Monitoring Analytics LLC 2024).

PJM renewable power system	**Capacity in 2023** (MW)	**MWh potential** (MWh)	**Actual MWh** (MWh)	**Capacity Factor** (%)
Solar	9 005	78 880 296	11 131 150	14,11%
Wind	12 072	105 751 596	28 991 982	27,42%

Table 15. PJM electrical power generation grid monthly wind and solar capacity factors 2022 (Source: Monitoring Analytics LLC 2024, PJM 2024).

2022	**Solar 6 220 MW Capacity**			**Wind 10 996 MW Capacity**			**Blended renewables monthly and annual capacity factors**
	MWh Potential (MWh)	**Actual power generated** (MWh)	**Reported capacity factor** (%)	**MWh Potential** (MWh)	**Actual power generated** (MWh)	**Reported capacity factor** (%)	(%)
Jan	4 627 308	426 958	11,7%	8 180 875	3 072 620	36,4%	27,3%
Feb	4 179 504	564 995	17,2%	7 389 178	3 256 337	42,8%	33,0%
Mar	4 627 308	754 201	20,7%	8 180 875	3 386 619	40,2%	32,3%
Apr	4 478 040	956 146	26,8%	7 916 976	3 298 157	40,4%	34,3%
May	4 627 308	945 079	25,5%	8 180 875	2 676 674	31,7%	28,3%
Jun	4 478 040	1 103 444	30,8%	7 916 976	1 830 399	21,9%	23,7%
Jul	4 627 308	998 653	26,7%	8 180 875	1 473 974	17,3%	19,3%
Aug	4 627 308	989 814	26,1%	8 180 875	1 242 872	14,6%	17,4%
Sep	4 478 040	877 827	23,6%	7 916 976	1 655 009	20,1%	20,4%
Oct	4 627 308	689 760	17,9%	8 180 875	2 945 520	34,6%	28,4%
Nov	4 478 040	523 884	13,8%	7 916 976	3 584 422	43,5%	33,1%
Dec	4 627 308	412 200	10,2%	8 180 875	3 095 434	36,4%	27,4%
Total	54 482 820	9 242 961	17,0%	96 323 208	31 518 036	32,7%	**27,0%**

Table 16. PJM electrical power generation grid monthly wind and solar capacity factors 2023 (Source: Monitoring Analytics LLC 2024, PJM 2024).

2023	Solar 9 005 MW Capacity			Wind 12 072 MW Capacity			Blended renewables monthly and annual capacity factors
	MWh Potential (MWh)	Actual power generated (MWh)	Reported capacity factor (%)	MWh Potential (MWh)	Actual power generated (MWh)	Reported capacity factor (%)	(%)
Jan	6 699 422	417 821	9,9%	8 981 642	2 913 721	34,3%	21,2%
Feb	6 051 091	598 408	15,2%	8 112 451	3 440 914	44,8%	28,5%
Mar	6 699 422	927 132	21,1%	8 981 642	3 573 935	42,1%	28,7%
Apr	6 483 312	1 062 635	24,9%	8 691 912	2 798 644	33,6%	25,4%
May	6 699 422	1 244 371	28,1%	8 981 642	2 063 557	23,8%	21,1%
Jun	6 483 312	1 172 403	25,0%	8 691 912	1 661 900	18,8%	18,7%
Jul	6 699 422	1 332 825	26,2%	8 981 642	1 001 020	10,9%	14,9%
Aug	6 699 422	1 203 178	23,1%	8 981 642	1 470 474	15,9%	17,1%
Sep	6 483 312	970 014	18,1%	8 691 912	1 318 985	14,7%	15,1%
Oct	6 699 422	894 878	15,8%	8 981 642	2 685 058	28,8%	22,8%
Nov	6 483 312	763 314	12,3%	8 691 912	3 146 489	34,3%	25,8%
Dec	6 699 422	544 173	7,9%	8 981 642	2 917 284	30,8%	22,1%
Total	78 880 296	11 131 150	14,1%	105 751 596	28 991 982	27,4%	**21,7%**

In the PJM RTO electricity grid, wind and solar power are part of a mix different power generation systems where demand load is delivered by balancing each of those different systems against each other. Wind and solar systems are balanced with production from gas and sometimes coal power generation and are not stand-alone self-sufficient systems.

Tables 13 to 16 are reported data. Tables 17 and 18 represent a thought experiment where the PJM RTO solar and wind networks are stand alone systems, to consistently deliver a capacity factor of 22% for solar and 24% for wind power generation.

As shown in Tables 14 and 16, solar electricity production was below 22% reported capacity factor for 6 months (182 days) in 2022 and for 7 months (212 days) in 2023. In both years, this was a continuous and persistent trend over winter for the region. In the same tables, wind electricity production was below 24% for 4 months (122 days) for both 2022 and 2023. This happened in the same months, June to September.

Table 17. Estimated size of buffer needed if the PJM RTO Solar network was self sustaining at 22% capacity.

	Solar PJM RTO	
	2022	2023
Power generated in months below specified 22% capacity	3 371 998	5 115 739
Power that would have been generated at 22% installed capacity	5 976 691	10 079 389
Shortfall	2 604 693	4 963 651
Days of solar poduction to be kept in storage	17	23
Number of days for the continuous time where solar production was below 22%	182	212

Table 18. Estimated size of buffer needed if the PJM RTO Wind Turbine network was self sustaining at 24% capacity.

	Wind PJM RTO	
	2022	2023
Power generated in months below specified 24% capacity	6 202 253	5 452 379
Power that would have been generated at 24% installed capacity	7 726 969	7 776 364
Shortfall	1 524 715	2 323 985
Days of wind poduction to be kept in storage	6	8
Number of days for the continuous time where wind production was below 24%	122	122

If these systems were self-sufficient and were to deliver on the set capacities, there would be a power buffer. Solar electricity generation systems would need approximately 23 days of capacity in storage, and that storage would need to be kept available for 212 days. Wind electricity generation systems would need approximately 8 days of capacity in storage, and that storage would need to be kept available for 122 days. What is interesting, is that solar under performed over winter, but wind underperformed in summer. While the power buffer associated with the solar generation systems was being replenished in the summer, the wind power generation systems were underperforming and would need to draw more power from the same buffer. This would complicate the efficient replenishment of that power buffer and would exacerbate the amount of extra power generation capacity required to manage this task, and still deliver on the required capacity factor. What could be interesting is to investigate the potential for excess wind power generation to be used to offset the underperformance of solar power generation in winter.

Both of these signatures were consistent for 2 years running, and if this pattern was to hold over an extended number of years, would be easily predicted. This thought experiment only examined what would be needed to account for long term seasonal variations across a year. It did not account for what would be needed to replenish that power buffer after it was depleted, in time to be ready for the next period of shortfall production. This thought experiment also did not account for multiple periods of bad weather that were within a few days of each other, that would hamper the ability for wind and solar system to generate electricity.

(Ruhnau & Qvist 2021) conducted a study of a German 100% renewable case study, examining electrical power supply from renewable energy systems, using 35 years of hourly time series data (ENTSO-E 2024), based on the years 1982–2016. The dataset includes hourly load data and hourly generation profiles for wind and solar energy. Previous studies on renewable scarcity periods mostly focused on wind power (Cannon et al. 2015, Patlakas et al. 2017, Ohlendorf & Schill 2020). These studies identified the maximum duration of low-wind events identified in these studies is 4–10 days.

Low-wind events are more pronounced when focusing on single regional locations (Leahy & McKeogh 2013). This becomes less pronounced when the data set is expanded to a continental scale (Grams et al. 2017, Handschy et al. 2017, Kaspar et al. 2019). (Raynaud et al. 2018) extended the scope of analysis of load demand against more renewable energy systems: solar, hydro, and wind. This was done to examine periods when renewables supply less than 20% of demand (termed an energy drought).

The analysis done by (Ruhnau & Qvist 2021) supported the outcomes of previous studies, where periods with persistently scarce supply last no longer than two weeks. However, (Ruhnau & Qvist 2021) also found that the maximum energy deficit occurs over a much longer period of nine weeks. This happened because it was found that there were multiple examples of more than one scarce power supply period closely follows another. The power storage buffer had not had time to replenish itself. For this reason, (Ruhnau & Qvist 2021) recommended a 12 week power storage capacity, to account for storage losses and charging limitations.

It was also observed that a single-year optimization generally underestimates the required storage volume when compared to multi-year optimization (Ruhnau & Qvist 2021, Dowling et al. 2020).

The true size of the needed power buffer for wind and solar systems is still relatively unknown, as the full scope of work to estimate this has not been done. It could be concluded though, that the conventional view that only 5 to 7 hours of power capacity buffer would be inadequate, and the practical outcome would exceed 20 days.

The size of the buffer needed for stationary power storage is contested in the literature with little agreement on what is needed (Michaux 2024).

For the purpose of this study, four capacities of power storage buffer were calculated. These four scenarios will later be used in calculations for total required metal content for just wind and solar PV power production was selected. This was done to produce a more conservative estimate. The capacities are as follows:

- 6 hours — Table 19 (Larson et al. 2021, Jenkins et al. 2021)
- 48 hours +10% — Table 20 (Steinke et al. 2012)
- 28 days — Table 21 (Droste-Franke 2015)
- 12 weeks — Table 22 (Ruhnau & Qvist 2021)

Table 19. Estimated 6 hour stationary power storage buffer needed globally to phase out fossil fuels.

Power Generation System	**Extra** required annual capacity to phase out fossil fuels (GWh)	Storage capacity for a **6 hour period** to manage winter period, with limited sun & wind (GWh)
Wind Onshore (70% share)	13 131 059,8	8 993,9
Wind Offshore (30% share)	5 627 597,0	3 854,5
Solar PV (90% share)	16 884 259,3	11 564,6
Solar Thermal (10% share)	1 874 397,5	1 283,8
	Total (GWh)	25 696,8
	Total (TWh)	**25,7**

Table 20. Estimated 48 hour + 10% stationary power storage buffer needed globally to phase out fossil fuels.

Power Generation System	**Extra** required annual capacity to phase out fossil fuels (GWh)	Storage capacity for a **48 hour + 10% period** to manage winter period, with limited sun & wind (GWh)
Wind Onshore (70% share)	13 131 059,8	79 146,1
Wind Offshore (30% share)	5 627 597,0	33 919,8
Solar PV (90% share)	16 884 259,3	101 768,1
Solar Thermal (10% share)	1 874 397,5	11 297,7
	Total (GWh)	226 131,8
	Total (TWh)	**226,1**

Table 21. Estimated 28 day stationary power storage buffer needed globally to phase out fossil fuels.

Power Generation System	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Storage capacity for a 28 day period to manage winter period, with limited sun & wind** (GWh)
Wind Onshore (70% share)	13 131 059,8	1 007 314,2
Wind Offshore (30% share)	5 627 597,0	431 706,1
Solar PV (90% share)	16 884 259,3	1 295 230,9
Solar Thermal (10% share)	1 874 397,5	143 789,4
	Total (GWh)	2 878 040,5
	Total (TWh)	**2 878,0**

Table 22. Estimated 12 week (84 day) stationary power storage buffer needed globally to phase out fossil fuels.

Power Generation System	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Storage capacity for a 12 week (84 day) period to manage winter period, with limited sun & wind** (GWh)
Wind Onshore (70% share)	13 131 059,8	3 021 942,5
Wind Offshore (30% share)	5 627 597,0	1 295 118,2
Solar PV (90% share)	16 884 259,3	3 885 692,6
Solar Thermal (10% share)	1 874 397,5	431 368,2
	Total (GWh)	8 634 121,5
	Total (TWh)	**8 634,1**

Figure 12 shows an estimate of what the stationary battery power storage market shares of the different battery chemistries might be in the year 2040 (IEA 2021a). After examining the 2040 base case in Figure 12, the assumed market share for global stationary power storage battery chemistries to be used in this study is shown in Tables 23 and 24. High home storage (high percentage of power storage done in domestic houses) and high vanadium (a higher percentage of vanadium VRB battery market share) represent are IEA scenarios. In this study, the base case scenarios are used to be more conservative.

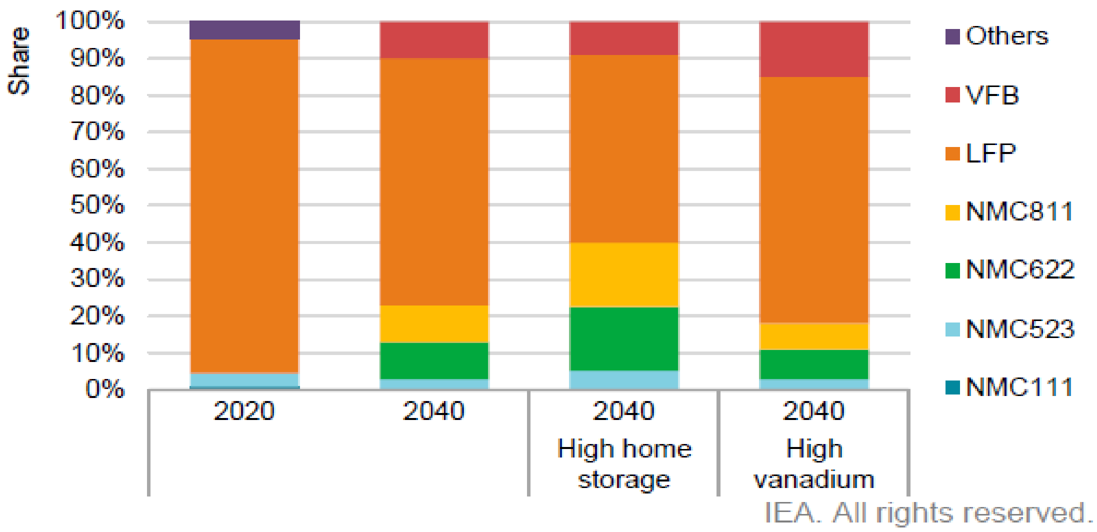

Fig. 12 Cathode chemistries for power storage estimated market share (Source: IEA 2021a) (Copyright IEA) (Copyright IEA, permission to reproduce granted).

Table 23. Global market proportions of power storage chemistries in 2040, for 6 hour buffer and 48 hour + 10% buffer calculations (Source: drawn from IEA 2021a, Diouf & Pode 2015).

Battery Chemistry	**Acronym**	**Specific Energy Density** (Wh/kg)	**Projected Market Proportion for Power Storage in 2040** (%)	**Battery capacity (6 hours) in total power storage in 2040** (TWh)	**Battery capacity (48 hours + 10%) in total power storage in 2040** (TWh)
Lithium Nickel Manganese Cobalt Oxides	NMC 532	100-135	3,3%	0,8	7,4
	NMC 622	100-135	9,9%	2,5	22,3
	NMC 811	100-135	9,9%	2,5	22,3
Lithium Iron Phosphate	LFP	90-120	73,7%	18,9	166,6
Vanadium Redox Battery	VRB	20 - 32	3,3%	0,8	7,4
Total			100,0%	25,7	226,1

Table 24. Global market proportions of power storage chemistries in 2040, for 28 day buffer and 12 week buffer calculations (Source: drawn from IEA 2021a, Diouf & Pode 2015).

Battery Chemistry	**Acronym**	**Specific Energy Density** (Wh/kg)	**Projected Market Proportion for Power Storage in 2040** (%)	**Battery capacity (28 days) in total power storage in 2040** (TWh)	**Battery capacity (12 weeks) in total power storage in 2040** (TWh)
Lithium Nickel Manganese Cobalt Oxides	NMC 532	100-135	3,3%	94,7	284,0
	NMC 622	100-135	9,9%	284,0	852,1
	NMC 811	100-135	9,9%	284,0	852,1
Lithium Iron Phosphate	LFP	90-120	73,7%	2 120,7	6 362,0
Vanadium Redox Battery	VRB	20 - 32	3,3%	94,7	284,0
Total			100,0%	2 878,0	8 634,1

The required capacity for each of the different battery chemistries shown in Figure 12, as shown in Tables 23 and 24 were then developed further. The metal content of each battery chemistry (Table 38) was projected onto the capacities shown in Tables 23 and 24 (shown in Tables 25 to 28).

Table 25. Metal required for 6 hours capacity stationary power storage batteries to phase out fossil fuels.

Battery Chemistry	**NMC 532** (tonne)	**NMC 622** (tonne)	**NMC 811** (tonne)	**LFP** (tonne)	**VRB** (tonne)	**Total** (tonnes)
Copper (Cu)	899 925	2 654 093	2 652 091	46 777 426		52 983 535
Lithium (Li)	346 125	959 991	925 148	8 971 013		11 202 277
Manganese (Mn)	674 944	1 298 812	616 765			2 590 521
Cobalt (Co)	501 881	1 411 752	616 765			2 530 398
Vanadium (V)					8 254 777	8 254 777
Nickel (Ni)	1 211 437	4 178 785	5 057 475			10 447 698
Graphite (C)	2 163 281	6 889 348	7 524 536	90 350 919		106 928 085

Table 26. Metal required for 48 hours + 10% capacity stationary power storage batteries to phase out fossil fuels.

Battery Chemistry	NMC 532 (tonne)	NMC 622 (tonne)	NMC 811 (tonne)	LFP (tonne)	VRB (tonne)	Total (tonnes)
Copper (Cu)	7 919 340	23 356 020	23 338 398	411 641 352		466 255 110
Lithium (Li)	3 045 900	8 447 922	8 141 302	78 944 917		98 580 041
Manganese (Mn)	5 939 505	11 429 542	5 427 534			22 796 581
Cobalt (Co)	4 416 555	12 423 415	5 427 534			22 267 504
Vanadium (V)					72 642 036	72 642 036
Nickel (Ni)	10 660 650	36 773 308	44 505 782			91 939 740
Graphite (C)	19 036 875	60 626 265	66 215 920	795 088 091		940 967 150

Table 27. Metal required for 28 day capacity stationary power storage batteries to phase out fossil fuels.

Battery Chemistry	NMC 532 (tonne)	NMC 622 (tonne)	NMC 811 (tonne)	LFP (tonne)	VRB (tonne)	Total (tonnes)
Copper (Cu)	100 791 598	297 258 436	297 034 158	5 239 071 753		5 934 155 945
Lithium (Li)	38 765 999	107 519 009	103 616 567	1 004 753 487		1 254 655 062
Manganese (Mn)	75 593 698	145 466 894	69 077 711			290 138 304
Cobalt (Co)	56 210 699	158 116 189	69 077 711			283 404 599
Vanadium (V)					924 535 007	924 535 007
Nickel (Ni)	135 680 997	468 023 921	566 437 231			1 170 142 149
Graphite (C)	242 287 494	771 607 005	184 895 167	10 119 302 976		11 318 092 642

Table 28. Metal required for 12 week/84 day capacity stationary power storage batteries to phase out fossil fuels.

Battery Chemistry	NMC 532 (tonne)	NMC 622 (tonne)	NMC 811 (tonne)	LFP (tonne)	VRB (tonne)	Total (tonnes)
Copper (Cu)	302 374 793	891 775 309	891 102 474	15 717 215 260		17 802 467 835
Lithium (Li)	116 297 997	322 557 027	310 849 700	3 014 260 461		3 763 965 185
Manganese (Mn)	226 781 095	436 400 683	207 233 133			870 414 911
Cobalt (Co)	168 632 096	474 348 568	207 233 133			850 213 798
Vanadium (V)					2 773 605 020	2 773 605 020
Nickel (Ni)	407 042 990	1 404 071 763	2 528 244 228			4 339 358 981
Graphite (C)	726 862 483	2 314 821 014	2 528 244 228	30 357 908 927		35 927 836 652

8 OTHER NON-FOSSIL FUEL POWER GENERATION SYSTEMS

Nuclear electrical power generation is the outcome of a sophisticated and complex value chain across the nuclear fuel cycle. In this study, nuclear power production of electricity was assumed to double from the 2018 annual production of 2 701.4 TWh (Table 4) to a new capacity of 6.4 PWh (6 371.9 TWh) a year (with the annual addition of 3 670.5 TWh), where approximately 42% of this was delivered with the existing Nuclear Power Plant (NPP) fleet. This would require the commissioning of an additional 586.7 GW of installed capacity. The estimated metal consumption of metals per MW in the construction of the extra required nuclear power plant stations was 1.28 million tonnes of chromium, 862 453 tonnes of copper and 762 713 tonnes of nickel (Table 29).

Table 29. Estimated metal consumption in construction of required extra nuclear power stations (Source: IEA 2021a, Michaux 2021a).

Metal	Element	Mass of metal	Metal Mass in 586 702 MW nuclear power generation		
		(kg/MW)	(kg)	(tonnes)	(million tonnes)
Steel *	Fe	116 552	6,84E+10	68 381 186	68,38
Concrete**	-	523 000	3,07E+11	306 845 397	306,85
Aluminium đ	Al	6 215	3,65E+09	3 646 399	3,65
Chromium	Cr	2190	1,28E+09	1 284 878	1,28
Copper	Cu	1470	8,62E+08	862 453	0,86
Nickel	Ni	1300	7,63E+08	762 713	0,76
Hafnium	Hf	0,5	2,93E+05	293	0,00029
Yttrium	Y	0,5	2,93E+05	293	0,00029

* Source: World Bank 2017

** Concrete content average between 3 technologies: PHWR (pressurized heavy-water reactor), PWR (pressurized water reactor) and BWR (boiling water reactor). (Source: Hache et al. 2020, UNEP 2016, Vidal 2017)

đ Source: U.S. Department of Energy 2020

Hydroelectric power stations require large quantities of cement and concrete. It has a relatively low mineral intensity in station construction (Ashby 2013). In this study, an extra 1.1 TW (1 111.6 GW) of installed hydropower capacity was required to phase out fossil fuels. The estimated metal consumption of metals per MW in the construction of the extra required hydro power plant stations was 1.17 million tonnes of copper, 222 327 tonnes of manganese and 33 349 tonnes of nickel (Table 30). Once again, Tables 23, 24 and 25 do not include all metals and materials to construct nuclear, hydroelectric, and geothermal power plants. For example, steel and cement would be used in vast quantities for all these types of power plant.

Geothermal power plants generate electricity by powering turbines using underground hydrothermal resources (steam or hot water) piped to the surface, which then turns an electric power generation turbine. The fluid and steam being handled is not only very hot but potentially corrosive and require the use of specialized steel alloys (high in chromium, molybdenum, nickel, and titanium) to withstand the harsh operating environment (Ashby 2013). In this study, an extra 56.8 GW of installed geothermal capacity was required to phase out fossil fuels. The estimated metal consumption of metals per MW in the construction of the extra required geothermal power plant stations was 3.67 million tonnes of chromium, 589 505 tonnes of molybdenum, and 6.81 million tonnes of nickel (Table 31).

Table 30. Estimated metal consumption in required extra hydropower plant construction based on the corresponding data in 2019 (Source IEA 2021a, Ashby 2013).

Metal	Element	Mass of metal	Metal Mass in 1 111 636 MW installed hydropower power capacity		
		(kg/MW)	(kg)	(tonnes)	(million tonnes)
Steel*	Fe	59 100	6,57E+10	65 697 713	65,70
Concrete**	-	3 000 000	3,33E+12	3 334 909 294	3 334,91
Aluminium [₫]	Al	1 900	2,11E+09	2 112 109	2,11
Copper	Cu	1050	1,17E+09	1 167 218	1,17
Manganese	Mn	200	2,22E+08	222 327	0,22
Nickel	Ni	30	3,33E+07	33 349	0,03

* Source: World Bank 2017

** The concrete content in the hydro technology was problematic to find, these values are average concrete contents for the some of the major dams in the world (Three Gorges, Hoover, Jinping I, Chevril, Gudril, Almenda). The order of magnitude is in accord with the interval presented by Vidal (2017). (Source: Hache et al. 2020, UNEP 2016, Vidal 2017)

₫ Source: U.S. Department of Energy 2020

Table 31. Estimated metal consumption in required extra geothermal plant construction based on the corresponding data in 2019 (Source IEA 2021a).

Metal	Element	Mass of metal	Metal Mass in 56 854 MW installed geothermal power capacity		
		(kg/MW)	(kg)	(tonnes)	(million tonnes)
Steel [₣]	Fe	30 000	1,71E+09	1 705 634	1,71
Concrete*	-	100 000	5,69E+09	5 685 446	5,69
Chromium	Cr	64 516,1	3,67E+09	3 668 030	3,67
Molybdenum	Mo	10 368,7	5,90E+08	589 505	0,59
Nickel	Ni	119 815,7	6,81E+09	6 812 055	6,81
Titanium	Ti	1 728,1	9,83E+07	98 251	0,098

₣ Source: U.S. Department of Energy 2020

* Ton of cement/MW, average value derived from (Yu 2017), a life cycle assessment based comparison of large & small scale geothermal electricity production systems, Thesis.

9 LIST OF RENEWABLE TECHNOLOGY UNITS TO PHASE OUT FOSSIL FUELS

Table 32 shows a list of required renewable technology (drawn from Tables 1 to 8). This is an assemblage of technology units representing a direct replacement of the current fossil fuel industrial ecosystem (using 2018 data). This would represent just one generation of technology units, each of which would have a working life of between 7 and 30 years (depending on unit and study referenced). At the end of its working life, each technology unit would need to be decommissioned, and recycled. Then a new unit would have to be manufactured. Recycling technology has been developed for some years and is now reasonably mature. The challenges the recycling industry face are more logistical than technical though. Each recycling process plant is optimized for the recovery of one or two metals from a specific residue waste stream. End of life technology waste streams are notoriously variable in character. For a recycling plant to operate effectively, a large enough and consistent enough quantity of the target residue need to be supplied over a sustained period of time. This is an issue of collection and getting the ‘right’ residue to the ‘right’ process plant. To date this has been very difficult, and as a result, the recycling of many of the more exotic metals has not been viable. This will obviously change with future demand for metals being very high and the costs of mining increasing with each passing year.

In 2021, 1.1% of the global transport fleet was an electric Vehicle (IEA 2021b). In 2021, renewable energy made up only 6.7% of primary energy

(BP Statistical Review of World Energy 2022). This means that the vast majority of the not fossil fuel system has yet to be constructed. The sourcing of this metal will have to come from mining for at least the first generation of non-fossil fuel units. Many of the metals need for the Green Transition are relatively exotic and are currently mined in relatively small quantities (Fig. 36).

Table 32. List of renewable technology units required to phase out fossil fuels.

Renewable Technology Unit or Service	Number (number)	Estimated total battery capacity (TWh)	Estimated extra total installed power generation capacity (MW)
Electric Vehicles			
Delivery Truck	9 645 529	1,99	
Bus	19 356 724	4,40	
Light Truck/Van	601 327 324	25,32	
Passenger Car	695 160 429	32,53	
Motorcycle	62 109 261	0,79	
Hydrogen Fuel Cells			
HCV Class 8 Truck	28 929 348		
Rail Freight Locomotive [*]	104 894		
Maritime Small Vessel (100 GT to 499 GT) [*]	9 155		
Maritime Medium Vessel (500 GT to 24 999 GT) [*]	7 598		
Maritime Large Vessel (25 000 GT to 59 999 GT) [*]	2 040		
Maritime Very Large Vessel (>60 000 GT) [*]	1 072		
Nuclear Power (Annual Production)			586 702
Hydroelectricity (Annual Production)			1 111 636
Geothermal Power (Annual Production)			56 854
Wind Turbines			
3MW Onshore wind turbines (70% share)	911 002		6 012 611
3MW Offshore wind turbines (30% share)	390 429		2 576 833
Solar Panels			
450 Watt commerical grade solar panels	37 587 959 078		16 914 582
Stationary power storage buffer			
6 hours capacity for wind & solar PV only		25,7	
48 hours + 10% capacity for wind & solar PV only		226,1	
28 days capacity for wind & solar PV only		2 878,0	
12 weeks (84 days) capacity for wind & solar PV only		8 634,1	

[*] Numbers drawn from Michaux 2024

9.1 Hydrogen fuel cell vehicles

Hydrogen Fuel cells (H2-Cell) are electrochemical devices that directly convert the chemical energy of the reactants, e.g., hydrogen and air, into electricity and heat (Alaswad et al. 2022). The material components are made up of comparatively exotic metals (Fig. 13).

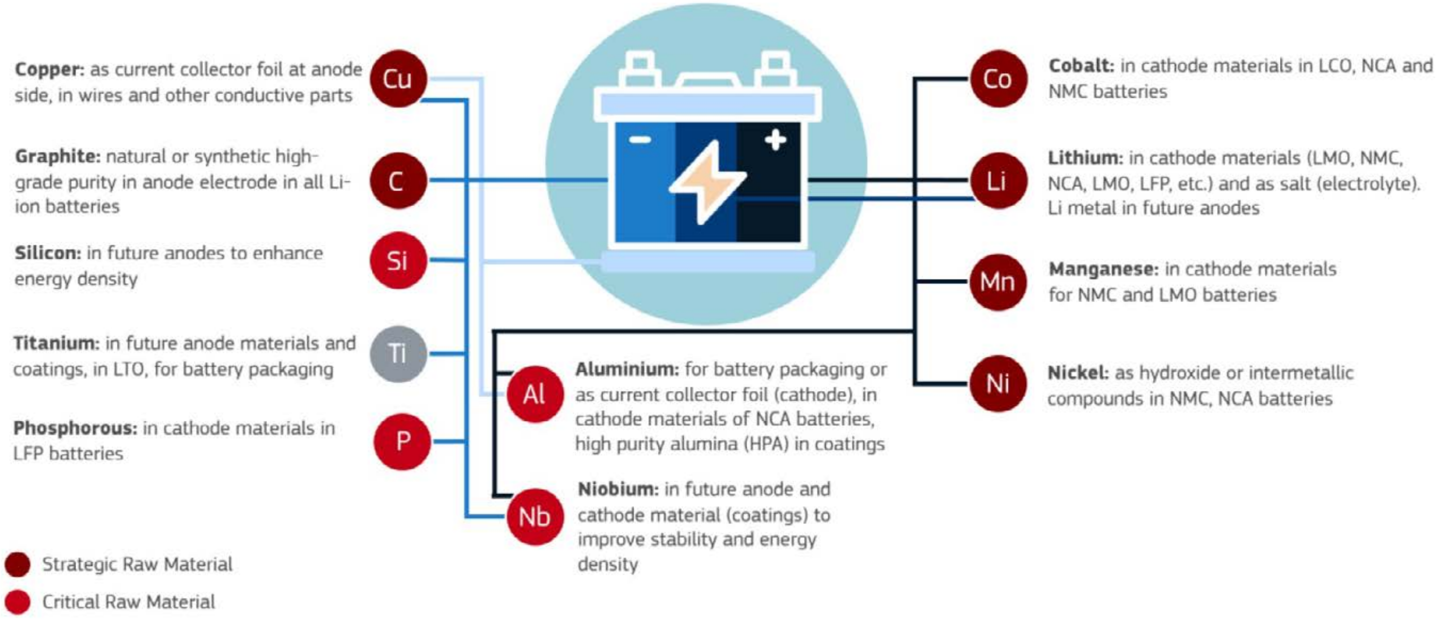

Fig. 13. Selection of raw materials used in fuel cells and their function (Source: Carrara et al. 2023) (Creative Commons Attribution 4.0 International (CC BY 4.0) license).

There are an estimated 29 million (29 054 107) (Table 2) hydrogen fuel cell units of various classes (trucks, trains, and maritime ships) required to be produced to phase out fossil fuels. Assuming each cell requires 92 g of platinum (this estimate is for a passenger car, Table 27) then 2 673 tonnes of platinum will be needed to produce one generation of H_2-cell units. Only platinum was included for this vehicle class as data, as the metal mass content data for an example fuel cell like Figure 12 was not available.

9.2 Electric vehicles and their batteries

To replace the existing fossil fuel powered Internal Combustion Engine (ICE) vehicle fleet, 1.39 billion Electric Vehicles (EV) and 29 million hydrogen fuel cell vehicles (H_2-Cell) are required to be manufactured (Michaux 2024 and Table 2). Table 33 shows an estimate of metal and materials content in an average vehicle for each type (not all metals and materials used to construct these vehicles was included).

Table 33. Metal and material content for select passenger car technologies (Source: US Department of Energy 2015, IRENA 2022, units converted to metric).

Materials (kg per vehicle lifetime)	**Passenger car (257 495 km lifetime)**		
	ICE Vehicle (kg)	Electric Vehicle (kg)	Fuel Cell Vehicle (kg)
Steel	861,8	1 179,3	997,9
Cast Iron	140,6	33,6	24,9
Wrought Aluminium	28,6	17,7	77,1
Cast Aluminium	59,0	90,7	49,9
Copper [1]	24,0	53,39	72,6
Nickel	-	39,4	1,4
Manganese [1]		24,64	
Lithium		9,03	
Cobalt [1]		13,14	
Graphite [1]		66,53	
Magnesium	0,23	0,36	0,28
Platinium	0,007	-	0,092
Neodynium		0,3	
Dysprosium		0,1	
Praseodymium		0,1	
Glass	37,2	59,0	45,4
Average Plastic	145,1	204,1	167,8
Rubber	136,1	140,6	136,1
Carbon fiber-reinforced plastic for general use	-	-	63,5
Carbon fiber-reinforced plastic for high pressure vessels	-	-	63,5
Perfluorosulfonic acid (PFSA) (Nafion 117 sheet)	-	-	5,4
Carbon paper	-	-	5,4
Polytetrafluoroethylene (PTFE)	-	-	1,4
Carbon and PFSA suspension (Nafion dry polymer)	-	-	0,5
Others	24,5	49,9	38,1
Vehicle Weight	1 315,4	1 678,3	1 587,6

[1] IEA 2021a

Table 34 shows the estimated mass of metals for just one generation of EV's that would make up the global fleet. This table assumes all EV classes, including buses and trucks have the same metal content as passenger cars. This assumption was made due to metal content of EV buses and trucks were unable to be estimated. Batteries were excluded from this calculation. This does mean though that the numbers associated with estimations for larger vehicles like buses and trucks are too conservative.

Table 34. Estimated metal content in global EV fleet (excluding batteries) for a single generation of vehicles.

Metal	**Estimated mass in a single EV** (kg)	**Estimated mass in 1.39 billion EV's** (tonnes)	**Estimated mass in 1.39 billion EV's** (million tonnes)
Steel	1 179,34	1 639 282 825	1 683,0
Cast Iron	33,57	46 656 511	1 683,0
Aluminum	108,41	150 687 921	150,4
Copper	53,39	74 209 446	74,1
Magnesium	0,36	500 400	0,50
Neodynium	0,34	472 600	0,47
Dysprosium	0,11	152 900	0,15
Praseodymium	0,11	152 900	0,15

9.3 Estimated EV battery chemistry market share

There are many available battery chemistries that could be used to manufacture a battery for an Electric Vehicle (EV). A study was published in 2021 (IEA 2021a) that developed a possible global EV battery market share for the year 2040 (Fig. 14). The EV battery chemistry market share proportions assumed in this study were developed using the prediction for 2040 in Figure 14. The assumed market proportion of Electric Vehicle batteries for this study is shown in Tables 35 to 37. Tables 38-1 and 38-2 project the battery chemistry proportions into the global vehicle fleet by vehicle class.

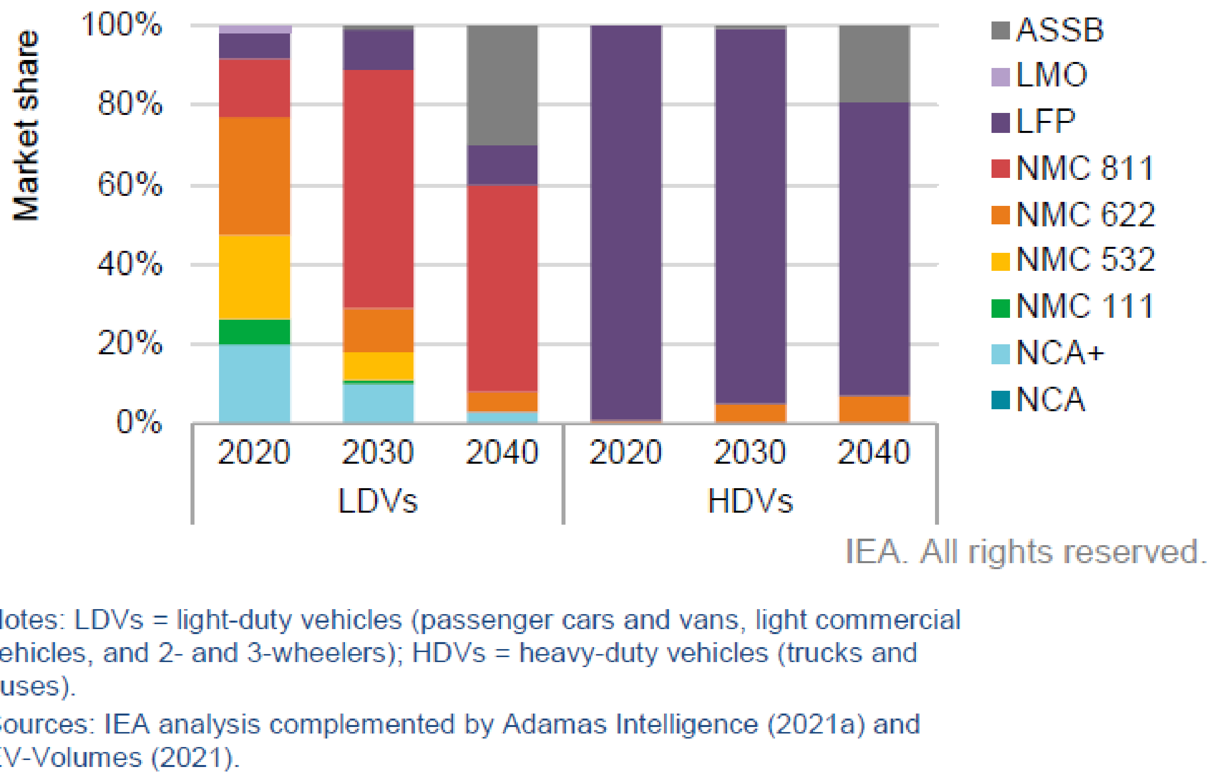

Fig. 14. Electric Vehicle (EV) cathode chemistries estimated market share (Source: IEA 2021a) (Copyright IEA) (Copyright IEA, permission to reproduce granted).

Table 35. Global market proportions of EV battery chemistries in 2040 (Source: IEA 2021a).

Battery Chemistry	Acronym	Light Duty Vehicle (LDV) (%)	Heavy Duty Vehicle (HDV) (%)
Lithium Nickel Cobalt Aluminium Oxides	NCA+	3,5%	
Nickel Manganese Cobalt	NMC 622	5,2%	7,2%
	NMC 811	52,2%	
Lithium Iron Phosphate	LFP	10,1%	73,9%
All Solid State Batteries	ASSB	29,0%	18,8%
		100,0%	100,0%

Table 36. Battery chemistry proportion in Light Duty Vehicle (LDV) EV's used in this study.

Vehicle Class	Number of Self Propelled Vehicles in 2018 Global Fleet	Number of batteries projected proportion of EV battery chemistries in EV's in 2040				
		NCA+	NMC 622	NMC 811	LFP	ASSB
	(number)	(number)	(number)	(number)	(number)	(number)
Light Trucks & Commercial Vans	601 327 324	20 915 733	31 373 600	313 735 995	61 004 221	174 297 775
Passenger Car	695 160 429	24 179 493	36 269 240	362 692 398	70 523 522	201 495 777
Motorcycle	62 109 261	2 160 322	3 240 483	32 404 832	6 300 940	18 002 684
Total	**1 358 597 014**	**47 255 548**	**70 883 322**	**708 833 225**	**137 828 683**	**393 796 236**
	1.39 billion vehicles					
Projected market proportion in 2040		3,5%	5,2%	52,2%	10,1%	29,0%

Table 37. Battery chemistry proportion in Heavy Duty Vehicle (HDV) EV's used in this study.

Vehicle Class	Number of Self Propelled Vehicles in 2018 Global Fleet	Projected proportion of EV battery chemistries in EV's in 2040		
		NMC 622	LFP	ASSB
	(number)	(number)	(number)	(number)
Delivery Trucks	9 645 529	698 951	7 129 304	1 817 274
Buses	19 356 724	1 402 661	14 307 144	3 646 919
Total	**29 002 253**	**2 101 613**	**21 436 448**	**5 464 193**
Projected market proportion in 2040		7,2%	73,9%	18,8%

Table 38-1. Estimated EV battery capacity required by chemistry.

Vehicle Class	Projected proportion of EV battery chemistries in EV's in 2040				
	Battery Capacity in EV (kWh)	NCA+ in EV's (number)	NCA+ sum total (GWh)	NMC 622 in EV's (number)	NMC 622 sum total (GWh)
Delivery Trucks	206,1			698 951	144,1
Buses	227,5			1 402 661	319,1
Light Trucks & Commercial Vans	42,1	20 915 733	881,4	31 373 600	1 322,2
Passenger Car	46,8	24 179 493	1 131,6	36 269 240	1 697,4
Motorcycle	12,7	2 160 322	27,4	3 240 483	41,2
Total			**2 040 (GWh)**		**3 524 (GWh)**

Summing the battery capacity of all chemistries from Tables 38-1 and 38-2 together, 65 TWh (65 056 GWh) of batteries need to be operational for the full EV fleet to do the same physical work as vehicles of the same class in 2018.

Table 38-2. Estimated EV battery capacity required by chemistry.

Vehicle Class	Projected proportion of EV battery chemistries in EV's in 2040						
	Battery Capacity in EV (kWh)	NMC 811 in EV's (number)	NMC 811 sum total (GWh)	LFP in EV's (number)	LFP sum total (GWh)	ASSB in EV's (number)	ASSB sum total (GWh)
Delivery Trucks	206,1			7 129 304	1 469	1 817 274	375
Buses	227,5			14 307 144	3 255	3 646 919	830
Light Trucks & Commercial Vans	42,1	313 735 995	13 222	61 004 221	2 571	174 297 775	7 345
Passenger Car	46,8	362 692 398	16 974	70 523 522	3 301	201 495 777	9 430
Motorcycle	12,7	32 404 832	412	6 300 940	80	18 002 684	229
Total			**30 607 (GWh)**		**10 676 (GWh)**		**18 208 (GWh)**

9.4 Estimated EV battery chemistry metal content

The metal content for each battery chemistry used in this study needs to be presented in the form of metal content per MW. Figure 15 shows an estimate of metal use to manufacture a typical ICE vehicle, and EV with various battery chemistries (IEA 2021a). The specifications for some battery chemistries are shown in Table 39.

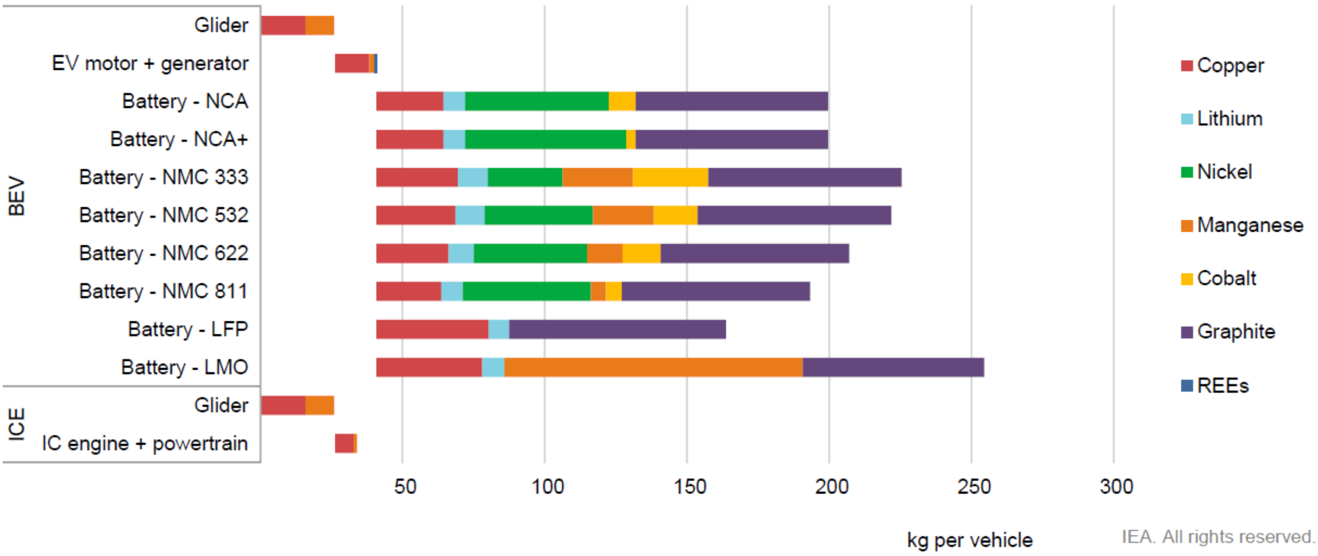

Fig. 15. Estimates of metals used to manufacture a typical ICE, EV with various battery chemistries.
(Note: the EV motor was a permanent magnet synchronous motor (neodymium iron boron [NdFeB]); the battery was a 75 kWh unit with graphite anodes). Also, not all metals used are shown, for example the amount of iron (steel) and concrete are not shown (Source: IEA 2021a) (Copyright IEA) (Copyright IEA, permission to reproduce granted).

9.4.1 Solid state battery chemistry metal content

Solid state battery's (ASSB) are projected to account for a large proportion of future battery markets. For this study, the ASSB market was to be made up of three ASSB chemistries in equal proportions. These chemistries were selected from Manthiram et al. 2017, from a range of possible options, and are assumed to be the dominant products. The element proportion mass of each chemistry was estimated using atomic mass (Lide 1991). Assuming that the specific energy density of ASSB chemistries is 600 Wh/kg (Manthiram et al. 2017), the metal content was estimated in terms of kg/MW (Tables 40 to 42).

Table 39. Specifications by Battery Chemistry (Source: Diouf & Pode 2015).

Battery Specifications	Lead Acid	NiCd	NiMH	Li-ion		
		Nickel Cadmium	Nickel Metal Hydride	Lithium Nickel Cobalt Aluminium Oxides (NCAs)	Nickel Manganese Cobalt (NMC)	Lithium Iron Phosphate (LFP)
Specific Energy Density (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal Resistance (mW)	<100 12V pack	100-200 6V pack	200-300 6V pack	150-300 7.2V	25-75 per cell	25-50 per cell
Life Cycle (80% discharge)	200-300	1000	300-500	500-1,000	500-1,000	1,000-2,000
Fast-Charge Time	8-16h	1h typical	2-4h	2-4h	1h or less	1h or less
Overcharge Tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-Discharge/ month (room temp)	0,05	0,2	0,3	<10%		
Cell Voltage (nominal)	2V	1.2V	1.2V	3.6V	3.8V	3.3V
Charge Cutoff Voltage (V/cell)	0,111111111	Full charge detection		0,180555556		0,166666667
	Float 2.25	by voltage signature				
Discharge Cutoff Voltage (V/cell, 1C)	0,09375	0,041666667		2.50-3.00		0,138888889
Peak Load Current	5C	20C	5C	>3C	>30C	>30C
Best Result	0.2C	1C	0.5C	<1C	<10C	<10C
Charge Temperature	-20 to 50°C	0 to 45°C		0 to 45°C		
	-4 to 122°F	32 to 113°F		32 to 113°F		
Discharge Temperature	-20 to 50°C	-20 to 65°C		-20 to 60°C		
	-4 to 122°F	-4 to 149°F		-4 to 140°F		
Maintenance Requirment	3-6 Months	30-60 days	60-90 days	Not required		
	(topping charge)	(discharge)	(discharge)			
Safety Requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
In Use Since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very High	Very High	Low	Low		

Table 40. Element proportions in lithium solid state battery solid-electrolyte chemistry $LiTi_2(PO_4)_3$ (Source: Manthiram et al. 2017).

Element	**Symbol**	**Atomic Mass** (amu)	**Number of atoms in $LiTi_2(PO_4)_3$** (number)	**Mass of atoms in molecule** (amu)	**Proportion of Element per unit mass** (%)	**Proportion of Element per kg** (kg)	**Metal content assuming energy density 600 Wh/kg** (kg/MW)
Lithium	Li	6,941	1	6,941	1,8%	0,0179	29,8
Titanium	Ti	47,867	2	95,734	24,7%	0,2470	411,7
Phosphorus	P	30,974	3	92,921	24,0%	0,2397	399,6
Oxygen	O	15,999	12	191,988	49,5%	0,4953	825,6
Total				387,584	100,0%	1,0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.66 x 10-27 kg

Table 41. Element proportions in lithium solid state battery solid-electrolyte chemistry $Li_{14}Zn(GeO_4)_4$ (Source: Manthiram et al. 2017).

Element	**Symbol**	**Atomic Mass** (amu)	**Number of atoms in $Li_{14}Zn(GeO_4)_4$** (number)	**Mass of atoms in molecule** (amu)	**Proportion of Element per unit mass** (%)	**Proportion of Element per kg** (kg)	**Metal content assuming energy density 600 Wh/kg** (kg/MW)
Lithium	Li	6,9	14	97,2	13,7%	0,14	228,4
Zinc	Zn	65,4	1	65,4	9,2%	0,09	153,7
Germanium	Ge	72,6	4	290,6	41,0%	0,41	682,9
Oxygen	O	16,0	16	256,0	36,1%	0,36	601,7
Total				709,1	100,0%	1,0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.66 x 10-27 kg

Table 42. Element proportions in lithium solid state battery solid-electrolyte chemistry $Li_7La_3Zr_2O_{12}$ (Source: Manthiram et al. 2017).

Element	**Symbol**	**Atomic Mass** (amu)	**Number of atoms in $Li_7La_3Zr_2O_{12}$** (number)	**Mass of atoms in molecule** (amu)	**Proportion of Element per unit mass** (%)	**Proportion of Element per kg** (kg)	**Metal content assuming energy density 600 Wh/kg** (kg/MW)
Lithium	Li	6,9	7	48,6	5,8%	0,06	96,4
Lanthanum	La	138,9	3	416,7	49,6%	0,50	827,1
Zirkonium	Zr	91,2	2	182,4	21,7%	0,22	362,1
Oxygen	O	16,0	12	192,0	22,9%	0,23	381,0
Total				839,7	100,0%	1,0	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.66 x 10-27 kg

9.4.2 Vanadium redox battery chemistry metal content

Vanadium redox battery (VRB) chemistry is projected to be part of the global battery market. It is being considered as a possible chemistry to manufacture stationary power storage in particular (IEA 2021a). The VRB is a type of rechargeable flow battery, that employs vanadium ions as charge carriers (Sangwon 2019). The battery uses vanadium's ability to exist in solution in four different oxidation states to make a battery with a single electroactive element instead of two.

The specific energy of VRB is dependent on the electrolyte, which is in the range of 15–32 Wh/kg, and the energy density is in the range of 20–33 Wh/L (Lourenssen et al. 2019). VRB electrolyte can be manufactured from multiple compounds: vanadium trichloride (VCl_3), vanadium pentoxide (V_2O_5), and vanadyl sulphate ($VOSO_4$) were each considered with hydrochloric acid (HCl), sodium hydroxide (NaOH) and sulfuric acid (H_2SO_4) (Lourenssen et al. 2019, Rychcik & Skyllas-Kazacos 1988).

For the purpose of this study, VRB electrolyte was assumed to be vanadyl sulphate ($VOSO_4$). Assuming that the specific energy density of VRB chemistries was 32 Wh/kg (Manthiram et al. 2017), the VRB metal content was estimated in terms of kg/MW (Table 43). This crude estimate does not account for metal content in electrodes or other parts of the VRB battery.

Table 43. Element proportions in VRB vanadium redox battery chemistry $VOSO_4$ (Source: Lourenssen et al. 2019).

Element	Symbol	Atomic Mass (amu)	Number of atoms in VO_5O_4 (number)	Mass of atoms in molecule (amu)	Proportion of Element per unit mass (%)	Proportion of Element per kg (kg)	Metal content assuming energy density 32 Wh/kg (kg/MW)
Vanadium	V	50,9	1	50,9	31,3%	0,31	9 766,3
Oxygen	O	16,0	5	80,0	49,1%	0,49	15 336,3
Sulfur	S	32,1	1	32,1	19,7%	0,20	6 147,4
Total				163,0	100,0%	1,00	

* Atomic Mass Unit to Kilogram Conversion 1 amu = 1.66 x 10-27 kg

9.5 Battery metal content quantity

Table 44 shows the metal content in context of kg/MW for each battery chemistry.

Table 44. Metal content kg/MW by battery chemistry (Source: Diouf & Pode 2015, Manthiram et al. 2017, Lourenssen et al. 2019).

Battery Chemistry	Units	NCA+	NMC 532	NMC 622	NMC 811	LFP	ASSB ($LiTi_2(PO_4)_3$)	ASSB ($Li_{14}Zn(GeO_4)_4$)	ASSB ($Li_7La_3Zr_2O_{12}$)	VRB
Specific Energy Density Range	(Wh/kg)	150-190	100-135	100-135	100-135	90-120	300-600	300-600	300-600	15-32
Specific energy used in this paper	(Wh/kg)	190	135	135	135	120	600	600	600	32
Mass of 1 MW battery	(kg)	5 263	7 407	7 407	7 407	8 333	1 667	1 667	1 667	31 250
Copper (Cu)	(% per kg)	13,9%	14,4%	14,1%	14,1%	29,6%				
Copper (Cu)	(kg/MW)	729,3	1 064,6	1 046,6	1 045,8	2 470,5				
Lithium (Li)	(%)	4,4%	5,5%	5,1%	4,9%	5,7%	1,8%	13,7%	6,9%	
Lithium (Li)	(kg/MW)	232,1	409,5	378,6	364,8	473,8	29,8	228,4	114,2	
Manganese (Mn)	(%)		10,8%	6,9%	3,3%					
Manganese (Mn)	(kg/MW)		798,5	512,2	243,2					
Cobalt (Co)	(%)	2,2%	8,0%	7,5%	3,3%					
Cobalt (Co)	(kg/MW)	116,0	593,7	556,7	243,2					
Germanium (Ge)	(%)							41,0%		
Germanium (Ge)	(kg/MW)							682,9		
Zirconium (Zr)	(%)								25,7%	
Zirconium (Zr)	(kg/MW)								428,8	
Lanthanum (La)	(%)								58,8%	
Lanthanum (La)	(kg/MW)								979,5	
Vanadium (V)	(%)									31,3%
Vanadium (V)	(kg/MW)									9 766
Nickel (Ni)	(%)	33,1%	19,3%	22,2%	26,9%					
Nickel (Ni)	(kg/MW)	1 740,5	1 433,2	1 647,9	1 994,4					
Graphite (C)	(% per kg)	39,1%	34,5%	36,7%	40,1%	57,3%				
Graphite (C)	(kg/MW)	2 055,4	2 559,2	2 716,8	2 967,2	4 771,8				
Zinc (Zn)	(% per kg)							9,2%		
Zinc (Zn)	(kg/MW)							153,7		

Tables 45 and 46 shows the estimated metal content for the global fleet of EV batteries, by chemistry. Tables 25 to 28 shows the estimated metal content for the four modelled global capacities for stationary power storage, by battery chemistry.

9.6 Electric vehicle battery capacity

Table 45 calculates the quantity of batteries, by chemistry from Table 36.1 & 36.2 capacities needed.

Table 45. Estimated quantity of EV batteries required to phase out fossil fuels, by chemistry and application.

Battery Chemistry	Acronym	Delivery Trucks (GWh)	Buses (GWh)	Light Trucks & Commercial Vans (GWh)	Passenger Car (GWh)	Motorcycle (GWh)	Total (GWh)
Lithium Nickel-Cobalt-Aluminum Oxide	NCA+			881	1 132	27	2 040
Lithium Nickel Manganese Cobalt Oxides	NMC 622	144,1	319,1	1 322	1 697	41	3 524
Lithium Nickel Manganese Cobalt Oxides	NMC 811			13 222	16 974	412	30 607
Lithium Iron Phosphate	LFP	1 469	3 255	2 571	3 301	80	10 676
Solid State ($LiTi_2(PO_4)_3$)	ASSB*	125	277	2 448	3 143	76	6 069
Solid State ($Li_{14}Zn(GeO_4)_4$)	ASSB*	125	277	2 448	3 143	76	6 069
Solid State ($Li_7La_3Zr_2O_{12}$)	ASSB*	125	277	2 448	3 143	76	6 069
Sum Total			4 404 (GWh)	25 342 (GWh)	32 534 (GWh)	789 (GWh)	65 056 (GWh)

* The 18 208 GWh of ASSB batteries are split evenly between three chemistries (6 069 GWh each)

9.7 Electric vehicles battery content

Table 46 calculates the metal content, by metal of the different battery chemistries (from Tables 39 and 44).

Table 46. Metal required for Electric Vehicle (EV) batteries to phase out fossil fuels.

Battery Chemistry	**NCA+** (tonne)	**NMC 622** (tonne)	**NMC 811** (tonne)	**LFP** (tonne)	**ASSB ($LiTi_2(PO_4)_3$)** (tonne)	**ASSB ($Li_{14}Zn(GeO_4)_4$)** (tonne)	**ASSB ($Li_7La_3Zr_2O_{12}$)** (tonne)	**Total** (tonne)	**Total** (million tonnes)
Copper (Cu)	1 488 200	3 688 176	32 010 062	26 374 056				63 560 494	63,6
Lithium (Li)	473 518	1 334 021	11 166 301	5 058 038	181 156	1 386 244	693 122	20 292 400	20,3
Manganese (Mn)		1 804 852	7 444 200					9 249 052	9,2
Cobalt (Co)	236 759	1 961 796	7 444 200					9 642 755	9,6
Germanium (Ge)						4 145 009		4 145 009	4,1
Zirkonium (Zr)							2 602 728	2 602 728	2,6
Lanthanum (La)							5 944 704	5 944 704	5,9
Nickel (Ni)	3 551 387	5 806 915	61 042 444					70 400 746	70,4
Graphite (C)	4 194 019	9 573 562	90 819 246	50 941 669				155 528 496	155,5
Zinc (Zn)						932 684		932 684	0,9

10 GLOBAL TOTAL METALS QUANTITY REQUIRED FOR ONE GENERATION OF RENEWABLE TECHNOLOGY UNITS

The total metal quantity required to manufacture one generation of technology units to completely phase out fossil fuels for the 2018 industrial ecosystem is shown in Tables 47-1 and 47-2 (excluding stationary power storage, which is shown in Tables 25 to 28).

Table 47-1. Total metal quantity required to manufacture one generation of technology units to phase out fossil fuels (excluding stationary power storage).

Metals and Concrete	Metal quantity required for onshore wind turbines (tonnes)	Metal quantity required for offshore wind turbines (tonnes)	Metal content in 16 903 977 MW of solar panels (tonnes)	Metal content in Nuclear power plant construction (tonnes)	Metal content in Hydro power plant construction (tonnes)
Steel	682 545 771	1 159 742 632	84 572 908	68 381 186	65 697 713
Cast Iron	85 489 033	60 924 874			
Concrete	2 531 309 377	1 674 941 732	169 145 816	306 845 397	3 334 909 294
Aluminium	9 379 674	4 019 860	202 974 979	3 646 399	2 112 109
Copper	19 482 569	23 691 198	48 054 326	862 453	1 167 218
Zinc	33 080 970	14 177 558			
Magnesium Metal	*	*			
Manganese	4 542 120	1 936 893			222 327
Chromium	2 901 924	1 347 047		1 284 878	
Nickel	2 516 340	675 150		762 713	33 349
Lithium					
Cobalt					
Graphite					
Molybdenum	634 931	272 537			
Silicon (Metallurgical)			67 387 693		
Silver			197 901		
Platinum					
Vanadium					
Zirconium					
Germanium	*	*	*		
Rare Earth Element					
Neodymium	250 841	419 830	*		
Lanthanum	*	*	*		
Praseodymium	34 641	77 841	*		
Dysprosium	20 067	39 159	*		
Terbium	8 199	14 597	*		
Hafnium	*	*	*	293	
Yttrium	*	*	*	293	

* no data available

As shown in Table 47-1 and 47-2, the metal required for the manufacture for each task of global substitution was carried out. Table 48 shows the quantity of metal to manufacture battery banks to meet power storage buffer requirements, according to the four modelled capacities.

Table 47-2. Total metal quantity required to manufacture one generation of technology units to phase out fossil fuels (excluding stationary power storage).

Metals and Concrete	Metal content in Geothermal power plant construction (tonnes)	Metal content in Electric Vehicle construction (tonnes)	Metal content in hydrogen fuel cell construction (tonnes)	Metal content in EV batteries (tonnes)
Steel	1 705 634	1 639 282 825	(only Pt data avilable)	
Cast Iron		46 656 511		
Concrete	5 685 446			
Aluminium	*	150 687 921		
Copper		74 209 446		63 560 494
Zinc				932 684
Magnesium Metal		500 400		
Manganese				9 249 052
Chromium	3 668 030			
Nickel	6 812 055			70 400 746
Lithium				20 292 400
Cobalt				9 642 755
Graphite				155 528 496
Molybdenum	589 505			
Silicon (Metallurgical)				
Silver				
Platinum			2 673,0	
Vanadium				
Zirconium				2 614 126
Germanium		*	*	4 163 162
Rare Earth Element				
Neodymium		472 600	*	*
Lanthanum		*	*	5 970 738
Praseodymium		152 900	*	*
Dysprosium		152 900	*	*
Terbium		*	*	*
Hafnium		*	*	*
Yttrium		*	*	*

* no data available

Table 48. Total metal quantity required to manufacture battery bank buffer for stationary power storage.

Metal	Metal content in 6 hours capacity stationary storage batteries (tonnes)	Metal content in 48 hours + 10% capacity stationary storage batteries (tonnes)	Metal content in 28 day capacity stationary storage batteries (tonnes)	Metal content in 12 weeks capacity stationary storage batteries (tonnes)
Copper	52 983 535	466 255 110	5 934 155 945	17 802 467 835
Manganese	2 590 521	22 796 581	290 138 304	870 414 911
Nickel	10 447 698	91 939 740	1 170 142 149	4 339 358 981
Lithium	11 202 277	98 580 041	1 254 655 062	3 763 965 185
Cobalt	2 530 398	22 267 504	283 404 599	850 213 798
Graphite	106 928 085	940 967 150	11 318 092 642	35 927 836 652
Vanadium	8 254 777	72 642 036	924 535 007	2 773 605 020

Table 49 is the sum of all metal from all parts of this study into one quantity by metal (split into the four different power buffer storage capacities). Table 43 is made up of data from the following tables:

- Table 10 & 11 metals to construct wind turbines
- Table 12 metals to construct solar panels
- Tables 25–28, 48 metals to construct stationary power storage, in the 4 modelled capacities
- Table 29 metals to construct nuclear power stations
- Table 30 metals to construct hydro–electric power stations
- Table 31 metals to construct geothermal power stations
- Table 34 metals to construct Electric Vehicles (EV), excluding their batteries
- Table 46 metals to construct EV batteries

Table 49. Total metal quantity required to phase out fossil fuels, by different buffer for stationary power storage capacity.

Metals & Minerals	**Total including 6 hours buffer stationary power storage** (million tonnes)	**Total including 48 hours + 10% buffer stationary power storage** (million tonnes)	**Total including 28 days buffer stationary power storage** (million tonnes)	**Total including 12 week / 84 day buffer stationary power storage** (million tonnes)
Steel	3 701,9	3 701,9	3 701,9	3 701,9
Cast Iron	193,1	193,1	193,1	193,1
Concrete	8 022,8	8 022,8	8 022,8	8 022,8
Cement	962,7	962,7	962,7	962,7
Aluminium	372,8	372,8	372,8	372,8
Copper	284,0	697,3	6 165	18 033
Zinc	48,19	48,19	48,19	48,19
Magnesium Metal	0,50	0,50	0,50	0,50
Manganese	18,54	38,75	306,09	886,37
Chromium	9,20	9,20	9,20	9,20
Nickel	91,65	173,14	1 251,34	4 421
Lithium	31,49	118,87	1 274,95	3 784
Cobalt	12,17	31,91	293,05	860
Graphite	262,5	1 096	11 474	36 083
Molybdenum	1,50	1,50	1,50	1,50
Silicon (Metallurgical)	67,39	67,39	67,39	67,39
Silver	0,198	0,198	0,198	0,198
Platinum	0,0027	0,0027	0,0027	0,0027
Vanadium	8,25	72,6	924,5	2 773,6
Zirconium	2,61	2,61	2,61	2,61
Germanium	4,16	4,16	4,16	4,16
Rare Earth Element				
Neodymium	1,14	1,14	1,14	1,14
Lanthanum	5,97	5,97	5,97	5,97
Praseodymium	0,27	0,27	0,27	0,27
Dysprosium	0,21	0,21	0,21	0,21
Terbium	0,0228	0,0228	0,0228	0,0228
Hafnium	0,00029	0,00029	0,00029	0,00029
Yttrium	0,00029	0,00029	0,00029	0,00029

11 RECYCLING SOURCE FOR QUANTITY OF METALS

Each of the planned renewable technology units (solar panels, wind turbines, EV's, batteries, H_2-Cell vehicles) has a working life ranging from 8 years to 25 years, after which each one is decommissioned and replaced. Even if advancements in design could extend that working life to 50 years for each unit, they would still need to be replaced. This study has assembled numbers for just the first generation of renewable technology units to phase out fossil fuels. To produce each subsequent generation of technology units, a feedstock source of metals would be needed. Recycling was the hope to be the source of this metal feedstock for the Green Transition. A fast uptake of renewable technology would mean a tsunami of end-of-life solar panels, wind turbines, EV's, batteries, and H_2-Cell vehicles in 10 to 15 years from now (assuming current work ing life for these units), all of which would have to be decommissioned, and if possible recycled.

In 2021, recycling rates of steel are approximately 89.1% (BIR 2022), and copper End-of-Life recycling rate was 40% in 2019 (ICA 2020). Current rates of recycling are very poor for some technology metals of interest in the Green Transition (for example Li, Be, Ga, Ge, Y, Hf, Ir, La, Pr, Dy, Nd, In, or Te), where rates are only a few percent globally. Figure 16 (shows this graphically) was published in 2011. In 2024, some recycling rates have improved but a similar situation still exists for most metals. Functional recycling is the recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use (UNEP 2011). Boxes colored white indicate that no data or estimates were available.

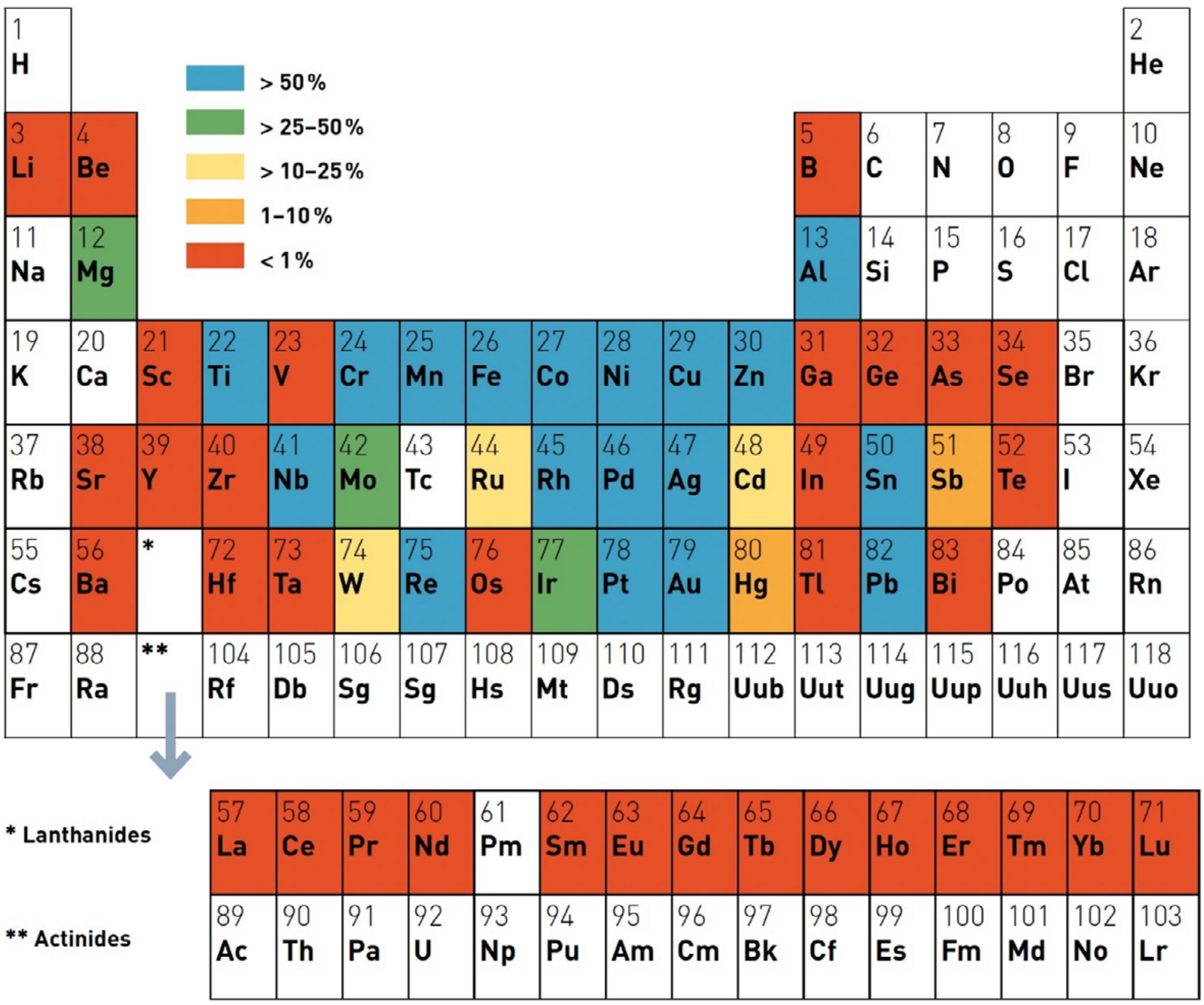

Fig. 16. The periodic table of global average End-of-Life (post consumer) functional recycling (EOL-RR) for sixty metals (Source: adapted from UNEP 2011).

The business model behind the current industrial system (at all scales) is geared to source metal and material feedstock from the mining of minerals. Recycling is often seen as a way of reducing the cost of waste disposal as opposed to being a major source of metal (this is a personal observation by the author after working in recycling research). For recycling to be the primary source of metal, a radical restructure of our industrial systems would be required. Currently the global economy and the global industrial system are only 9.1%, where only 9.1% of the waste plume is captured and reused in some form (Circle Economy 2022).

The strategic planners that developed the Circular Economy (seen by the author in many H2020 meetings in Europe) would often propose that all of societies metal resource needs would come from recycling. Mining was often seen as environmentally irresponsible and should be phased out. In those same meetings, the Green Transition (phase out of fossil fuels to be replaced by solar panels, wind turbines, EV's, batteries and hydrogen fuel cell vehicles) were all proposed in a manner that did not consider where the raw materials to produce these units would come from. It was implied on multiple occasions that recycling would be the source of metals to facilitate the Green Transition (this is a personal observation by the author). The purpose of Section 11 is to examine the question of could recycling supply the quantity of metals needed.

Most of the non-fossil fuel system has yet to be constructed (Michaux 2024) and relies on technology made from comparatively exotic materials compared to conventional fossil fuel technology. Most of the metals (and materials) needed for the Green Transition have only been mined in relatively small quantities (see Fig. 35). There may well be other sources of metals (like some forms of recycling), but they would be relatively small in quantity as most of these metals have never been consumed in such large volumes. The existing recycling infrastructure is largely insufficient to handle these waste flows. Neither does the industry appear prepared for the costs of dismantling, transportation, storage, and proper recycling, which may skyrocket in the absence of an efficient infrastructure (Duran et al. 2022).

Let us consider then a thought experiment, where the industrial system was radically reformed to recycled vast amounts of metals and materials. If all metals mined over the last few decades (now mostly in land fill dispersed across the planet) was 100% reclaimed and then recycled, with a 100% recovery rate of all metals of interest. Could that quantity of metal be sufficient feedstock to manufacture the first generation of renewable technology units in a full system replacement (based on 2018 industrial activity)?

Figures 17 to 22 show the metal globally mined over the past 34 years (1990 to 2023), compared to the total quantity of metal required for full system replacement (numbers in Table 49). If society was to fully recover all metals mined in the last 34 years, and then recycled them at 100% recovery, would the resulting outcome be enough to deliver the needed quantity of metals to rebuild a post fossil fuel system?

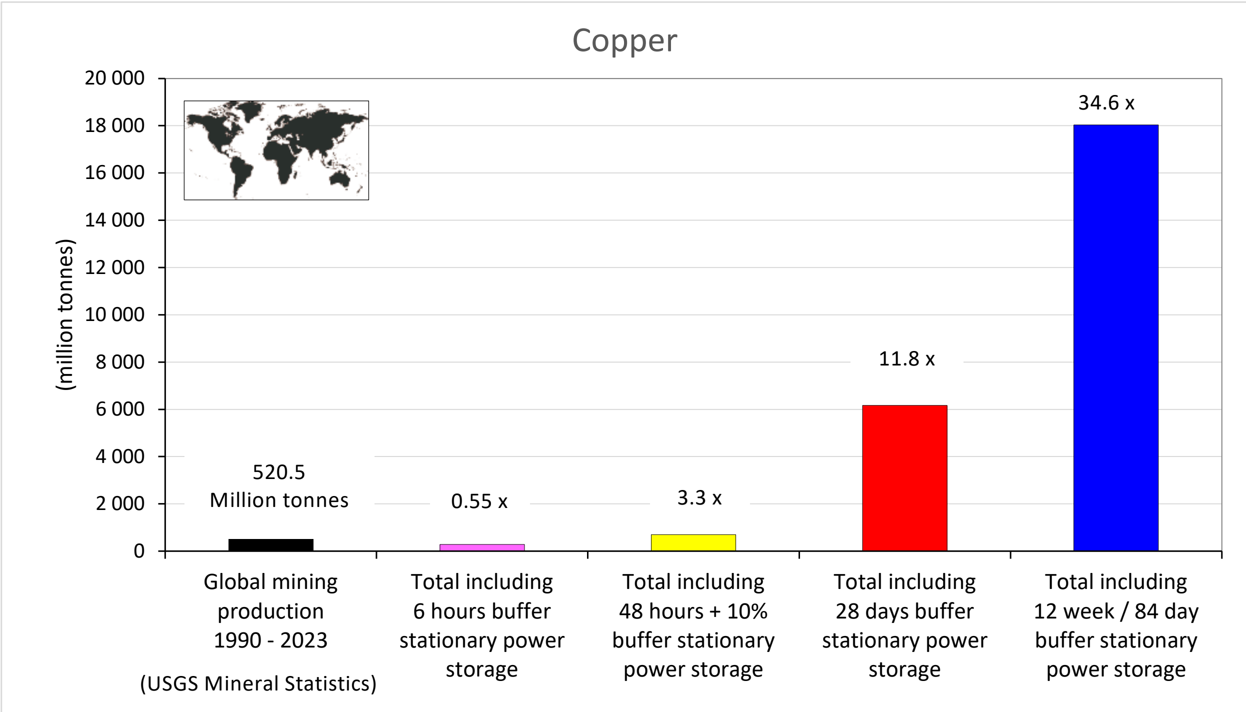

Fig. 17. Total quantity of copper mined between 1990 and 2023 (Source: USGS 2024) compared to total copper metal needed for each system replacement calculation, for all four stationary power storage capacities.

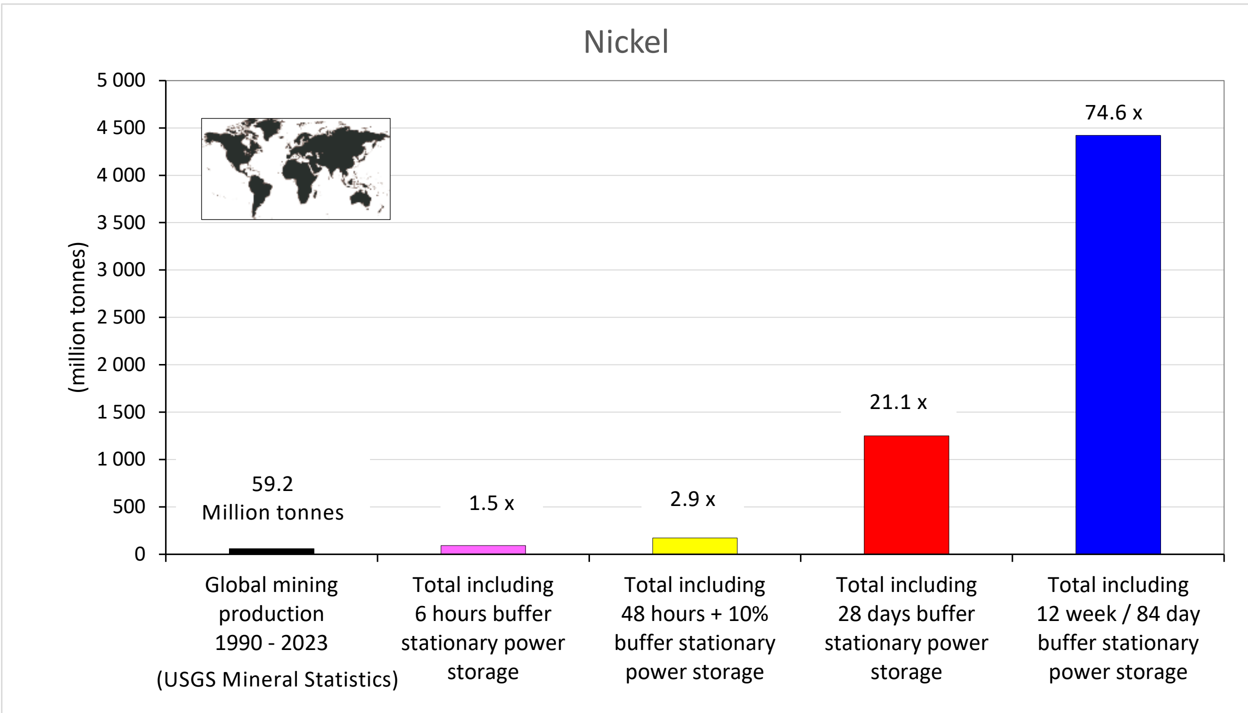

Fig. 18. Total quantity of nickel mined between 1990 and 2023 (Source: USGS 2024) compared to total copper metal needed for each system replacement calculation, for all four stationary power storage capacities.

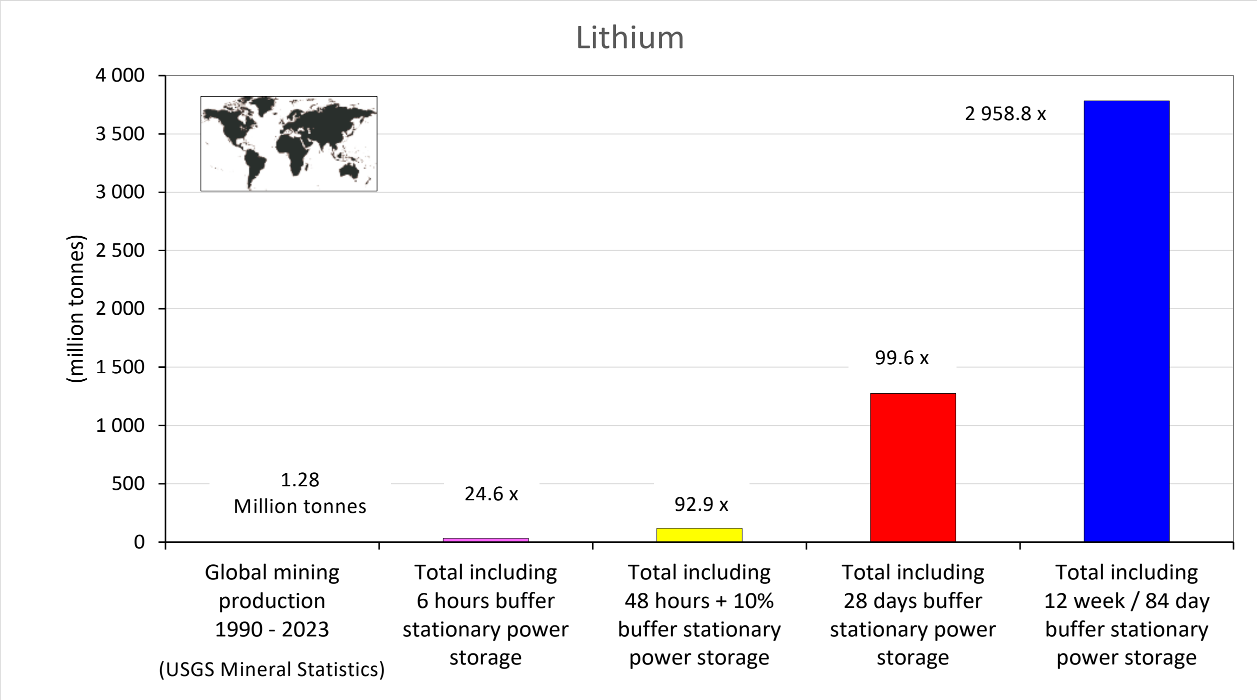

Fig. 19. Total quantity of lithium mined between 1990 and 2023 (Source: USGS 2024) compared to total copper metal needed for each system replacement calculation, for all four stationary power storage capacities.

Figure 18 shows that 59.2 million tonnes of nickel was mined between 1990 and 2023. If all 59.2 million tonnes of nickel were recovered, it would still not be even close to being enough nickel feedstock to manufacture all the needed renewable technology units. This pattern holds even for the 6 hour power buffer system calculation, let alone 12 weeks.

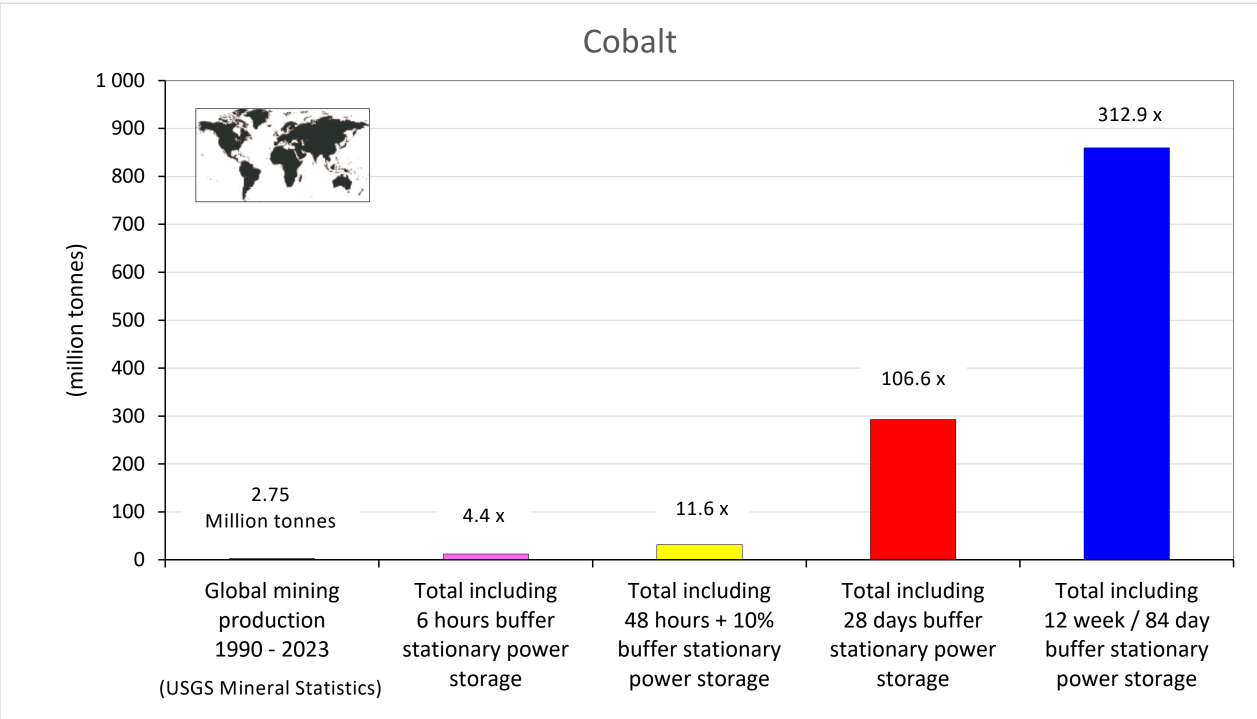

Fig. 20. Total quantity of cobalt mined between 1990 and 2023 (Source: USGS 2024) compared to total copper metal needed for each system replacement calculation, for all four stationary power storage capacities.

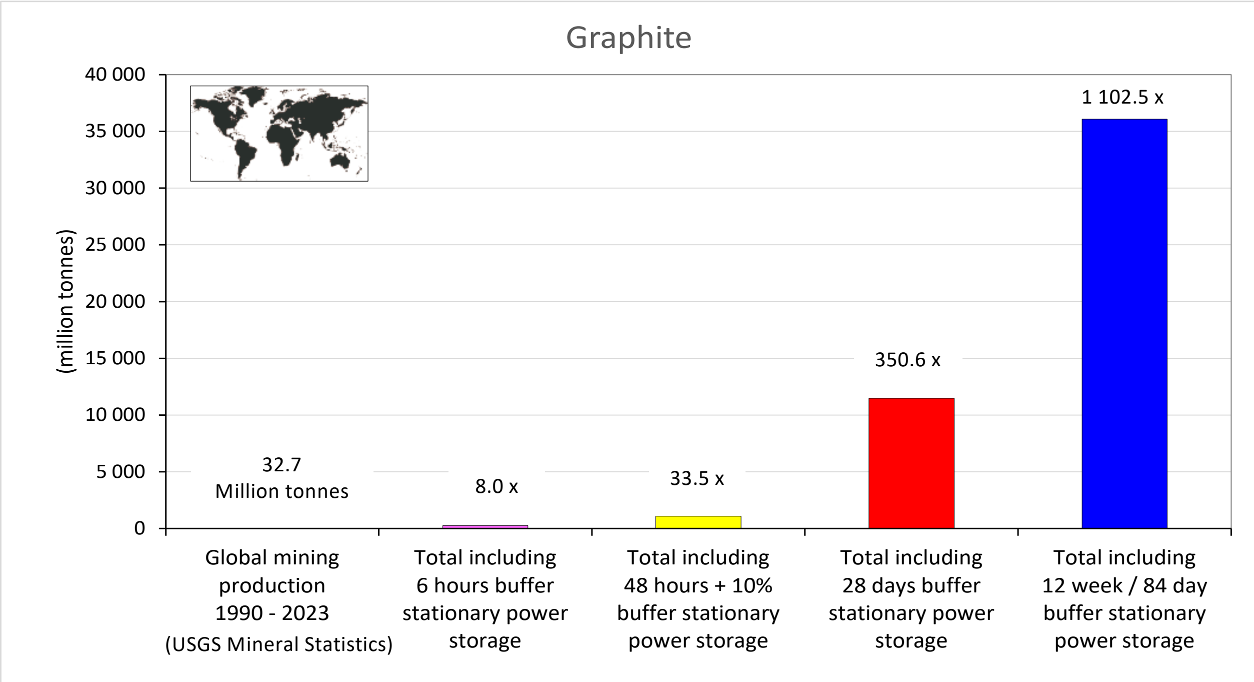

Fig. 21. Total quantity of graphite mined between 1990 and 2023 (Source: USGS 2024) compared to total copper metal needed for each system replacement calculation, for all four stationary power storage capacities.

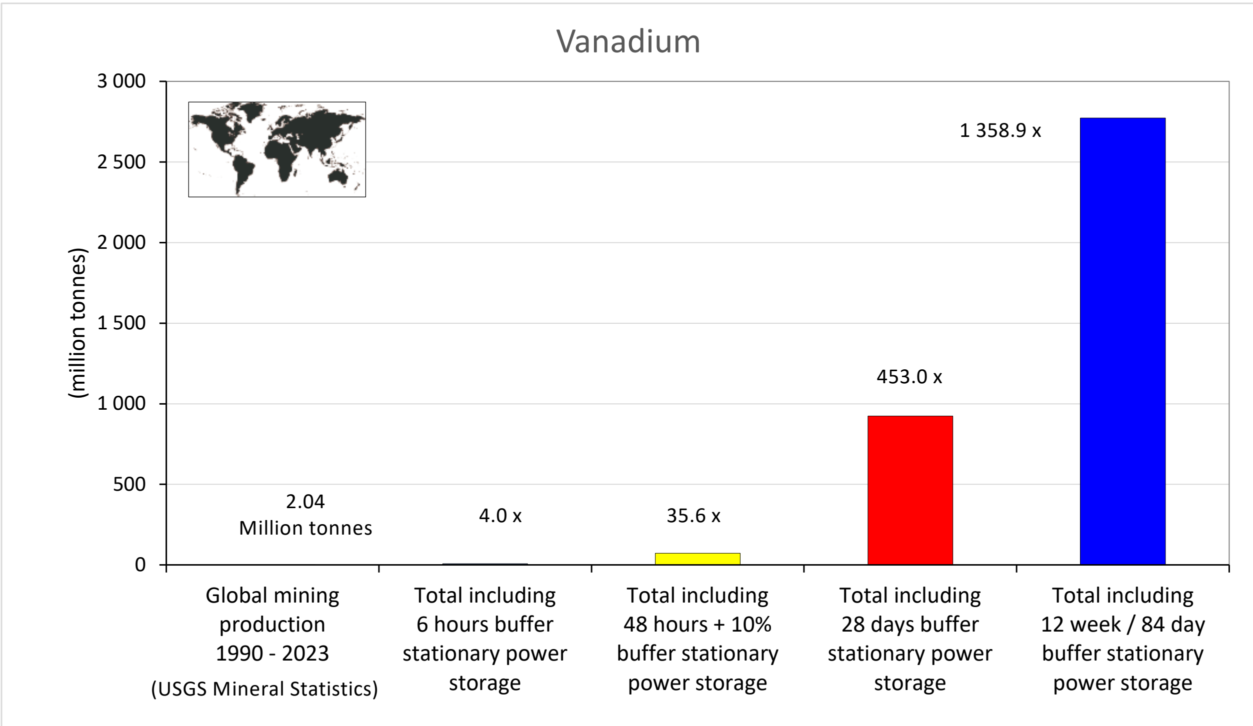

Fig. 22. Total quantity of vanadium mined between 1990 and 2023 (Source: USGS 2024) compared to total copper metal needed for each system replacement calculation, for all four stationary power storage capacities.

Lithium production over the 34 years (Fig. 19) was a global sum total of 1.28 million tonnes. Even to produce the system with the 6 hour power buffer, 24.6 times that historical quantity would have to be mined in 25.5 years to reach the target capacity in 2050. Michaux (2024) made the case that the size of the power storage buffer would have to be closer to the 12 week capacity. If this was the true answer, then lithium production in the next 25.5 years would have to be 2 958.8 times historical quantity produced over the last 34 years.

Also, each of the technology units manufactured (batteries, wind turbines, solar panels, etc.) have an operating life.

This basic pattern is seen in Figures 17 to 22. What this means is that recycling cannot be the primary source of metal for the first generation of renewable energy technology units. What has yet to be mined cannot be recycled. This then means that the sourcing of metals needed will have to be delivered from the mining of minerals at least for the next few decades.

12 MINING OF MINERALS AS A SOURCE FOR QUANTITY OF METALS

The mining of minerals has been the traditional source of metals for industrial manufacture. Table 50 shows the 2019 global mine production and refining production for the metals of interest.

For general-purpose concrete, material proportions are 1 part cement: 2 parts sand: 3 parts aggregate (by volume), with typical water-to-cement ratios range from around 0.4 to 0.6. As a general approximation, concrete is 12% cement (Rouch 2022). The quantity of concrete required to phase out fossil fuels from this simplistic study was 8 022.8 million tonnes of concrete, which would contain 962.7 million tonnes of cement (Tables 50 & 51).

Table 50 and Figure 23 show the some of the metals and minerals required to manufacture one generation of renewable technology units to completely phase out fossil fuels in the 2018 global industrial ecosystem, compared to metal production in 2019 (split into the 4 power buffer capacities). The full calculation of the numbers in Table 51 are shown in Annex A. It can be observed that time required to produce the needed quantity of copper, lithium, nickel, cobalt, graphite, vanadium, germanium, lanthanum, dysprosium, and terbium far exceeds what is practical in the required time frame to be useful in fossil fuel transition. Some of these metals require hundreds (and in some cases thousands) of years of production, at the current level, to deliver what is required to maintain the existing industrial capability. Currently, cobalt, graphite, lithium, platinum, metallurgical silicon, zirconium metal, and the REE are not used in large quantities in industrial applications. For the rest, there are no indications that other uses than energy would significantly decrease (Bobba et al. 2020, Hund et al. 2020). Clearly, this means that there are not enough producing mines, and more operations will be required to be commissioned. Any time period to produce a metal target over 25.5 years in Table 51 was colored in blue. This was done to reflect on the 2050 target (25 years 6 months away) for a complete transition proposed by strategic planners (IEA 2021a, Table 1,2 and 3).

Table 50. Metal mining production and refining in 2019 (Source: DERA 2023, Marscheider-Weidemann et al. 2021, USGS 2024, Friedrichs 2022, Mudd 2021).

Metals & Minerals	Element	Global Mine Production 2019	Units	Global Refined Production 2019	Units
Aluminium	Al	354 244	1000 metric tons (bauxite)	63 136	1000 metric tons cont. metal
Copper	Cu	20 664	1000 metric tons cont. metal	24 200	1000 metric tons cont. metal (+ recycling)
Steel and Iron	Fe	2 450	million metric tons cont. metal	1 860	million metric tons cont. metal
Cement ₣	-			4 100	million metric tons cont. cement
Zinc	Zn	12 873	1000 metric tons cont. metal	13 524	1000 metric tons cont. metal (+ recycling)
Magnesium Metal	Mg			1 120	1000 metric tons cont. metal
Manganese	Mn	56 628	1000 metric tons	20 591	1000 metric tons cont. metal
Chromium	Cr	37 498 478	metric tons		
Nickel	Ni	2 706 228	metric tons cont. metal	2 350 142	metric tons cont. metal
Lithium*	Li	95 170	metric tons cont. metal		
Cobalt*	Co	151 060	metric tons cont. metal	126 019	metric tons
Graphite (natural flake)*		1 700 000	metric tons	1 156 300	metric tons
Graphite (synthetic)*	C			1 573 000	metric tons
Molybdenum ‡	Mo	277 094	metric tons cont. metal		
Silicon (Metallurgical)**	Si	8,0	Million tonnes	3 426 641	metric tons
Silver Γ	Ag	26 282	metric tons cont. metal	31 821	metric tons cont. metal
Platinum λ	Pt	190	metric tons cont. metal	65,1	metric tons cont. metal
Vanadium ‡	V	96 021	metric tons cont. metal	102 025	metric tons cont. metal
Zirconium ‡	Zr	1 338 463	metric tons		
Germanium đđ	Ge			130	metric tons
Rare Earth Element					
Neodymium				23 900	metric tons
Lanthanum				35 800	metric tons
Praseodymium				7 500	metric tons
Dysprosium				1 000	metric tons
Terbium	Tb			280	metric tons
Hafnium °	Hf			66	metric tons
Yttrium	Y			14 000	metric tons

* 2018 production value

** This includes 310 000 t of Ferro-silicon & silicon metal from USA (Source: USGS Mineral Statistics)

° Source: CRM Alliance 2024

λ Source: Johnson Matthey 2020. PGM market report, May 2020. 43 p. Available at: https://matthey.com/documents/161599/509428/PGM-market-report-May-2022.pdf/542bcada-f4ac-a673-5f95-ad1bbfca5106?t=1655877358676

Γ This number includes by products from other mining, and recycling of jewelry. Source: Silver Institute 2020. World Silver Survey 2020. 83 p. Available at:: https://www.silverinstitute.org/wp-content/uploads/2020/04/World-Silver-Survey-2020.pdf

đđ Source: Mudd 2021

‡ Estimated from mining production. All other values are refining production values.

₣ Concrete as an approximation has 12% cement by volume. Source: Rouch 2022

Table 51. Quantity of metals required compared to global mining production in 2019 (numbers drawn from Annex A).

Metals & Minerals	**Global Metal Production 2019** (million tonnes)	**Years to produce metal at 2019 rates of production, for total quanity of metal to produce full system: EV's, batteries, wind turbines, solar panels and new power stations**			
		Assuming the 6 hour buffer for just wind & solar (years)	**Assuming the 48 hour + 10% buffer for just wind & solar** (years)	**Assuming the 28 day buffer for just wind & solar** (years)	**Assuming the 12 week buffer for just wind & solar** (years)
Iron	1 860	2,1	2,1	2,1	2,1
Cement	4 100	0,2	0,2	0,2	0,2
Aluminium	63,14	5,9	5,9	5,9	5,9
Copper	24,2	11,7	28,8	254,8	745,2
Zinc	13,5	3,56	3,6	3,6	3,6
Magnesium Metal	1,12	0,45	0,4	0,4	0,4
Manganese	20,6	0,90	1,9	14,9	43,0
Chromium	37,5	0,25	0,2	0,2	0,2
Nickel	2,35	39,0	73,7	532,5	1 881,0
Lithium	0,095	330,9	1 249,1	13 396,5	39 763,1
Cobalt	0,126	96,6	253,2	2 325,4	6 823,2
Graphite ¨	2,73	96,2	401,7	4 203,9	13 220,7
Molybdenum	0,28	5,4	5,4	5,4	5,4
Silicon (Metallurgical)	3,43	19,7	19,7	19,7	19,7
Silver	0,0263	7,5	7,5	7,5	7,5
Platinum	0,00019	14,1	14,1	14,1	14,1
Vanadium	0,096	86,0	756,5	9 628,5	28 885,4
Zirconium	1,34	1,95	2,0	2,0	2,0
Germanium	0,00013	32 024,3	32 024,3	32 024,3	32 024,3
Rare Earth Element					
Neodymium	0,0239	47,8	47,8	47,8	47,8
Lanthanum	0,0358	166,8	166,8	166,8	166,8
Praseodymium	0,0075	35,4	35,4	35,4	35,4
Dysprosium	0,0010	212,1	212,1	212,1	212,1
Terbium	0,00028	81,4	81,4	81,4	81,4
Hafnium	0,000066	4,4	4,4	4,4	4,4
Yttrium	0,014	0,021	0,021	0,021	0,021

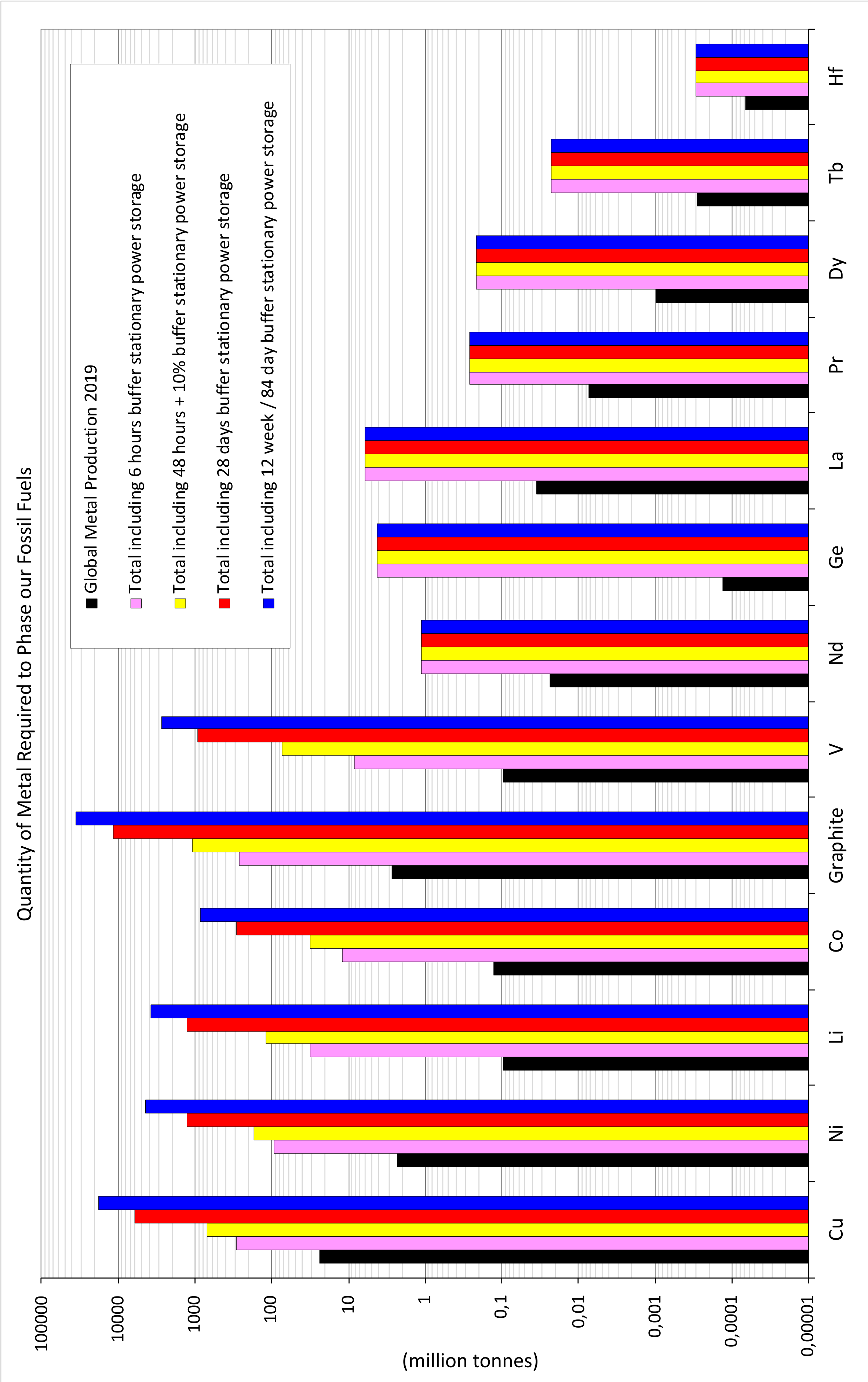

Fig. 23. Metal required to phase out fossil fuels compared to global mining production in 2019, split into the four power storage buffer capacities (USGS 2024) (Annex A).

If 2019 production rates remained static (obviously this would not happen and mining rates would change), the time required to produce the need quantity of germanium, lanthanum, dysprosium, and terbium also far exceeds what is practical in the required time frame to be useful in fossil fuel transition, which implies securing the required quantity of metals from mining may not be easy. So, more mines would need to be opened.

The purpose of this paper was to provide a snapshot reference point to estimate the mining industry's ability to deliver the raw materials needed for the Green Transition. As previously stated, the year 2019 may well be the most stable year for data mapping for the next several years due to the industrial supply disruptions associated with the Covid 19 pandemic. Yes, mining rates will increase. The basic pattern shown by this paper would probably remain unchanged.

13 RESERVES VS. RESOURCES

This study will now examine the quantities of metals required in Table 43 in comparison to reserves and resources of geological mineralized deposits. Mines are opened on the basis of a business model that depends on the metal grades reported in a mineral reserve. A Mineral Reserve is the economically mineable part of a Measured or Indicated Mineral Resource demonstrated by at least a Preliminary Feasibility Study (JORC 2012).

- **Reported Reserves, or Proven Reserves:** the economically mineable part of a measured resource for which at least a preliminary feasibility study demonstrates that, at the time of reporting, economic extraction could be reasonably justified with a high degree of confidence (JORC 2012).
- **Mineral Resource:** is the in situ natural concentration of minerals within a geologically defined envelope, that is higher grade than 'background' mineralization. The geological characteristics (quantity, grade, and continuity) are only partially known (JORC 2012). These characteristics are estimated or interpreted from broad-based evidence and regional knowledge. The presence of mineralization is inferred without comprehensive verification and cut-off concept. The main emphasis is the estimation of resource inventory at low confidence made during the early stages of exploration or around the outer periphery of known economic concentration. A mineral resource classification includes:
    - Mineralized deposits that may be too deep for existing mining technology, where the current depth limit is approximately 3 km.
    - Mineralogy that has mineral grains too small in size for practical mineral processing grind size.
    - Ore that is extremely low in grade.
- **Undersea Mineral Resource:** A mineral resource under the sea (Hein et al. 2020).

Mineral resources can be upgraded to a Mineral Reserve if the metal grade is economic and extraction technology is able to access the relevant ores. A mineral resource is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade (or quality), and quantity that there are reasonable prospects for eventual economic extraction (JORC 2012, Maier et al. 2015).

Current mining methods are heavily dependent on fossil fuel energy technology, and it is not yet clear how a fossil free mining method would operate. Mining methods, as they exist now have been developed with the use of fossil fuels. The cost of mining has been increasing, due to several persistent trends observed over time. Figures 24 and 25 shows a general decreasing in grade being mined, which has driven mining costs up, and that any future increase in production will become increasingly difficult. A case can be made that the mining industry may struggle to increase in demand capacity at all (Michaux 2021b) let alone a massive expansion as proposed in Figures 26 to 29.

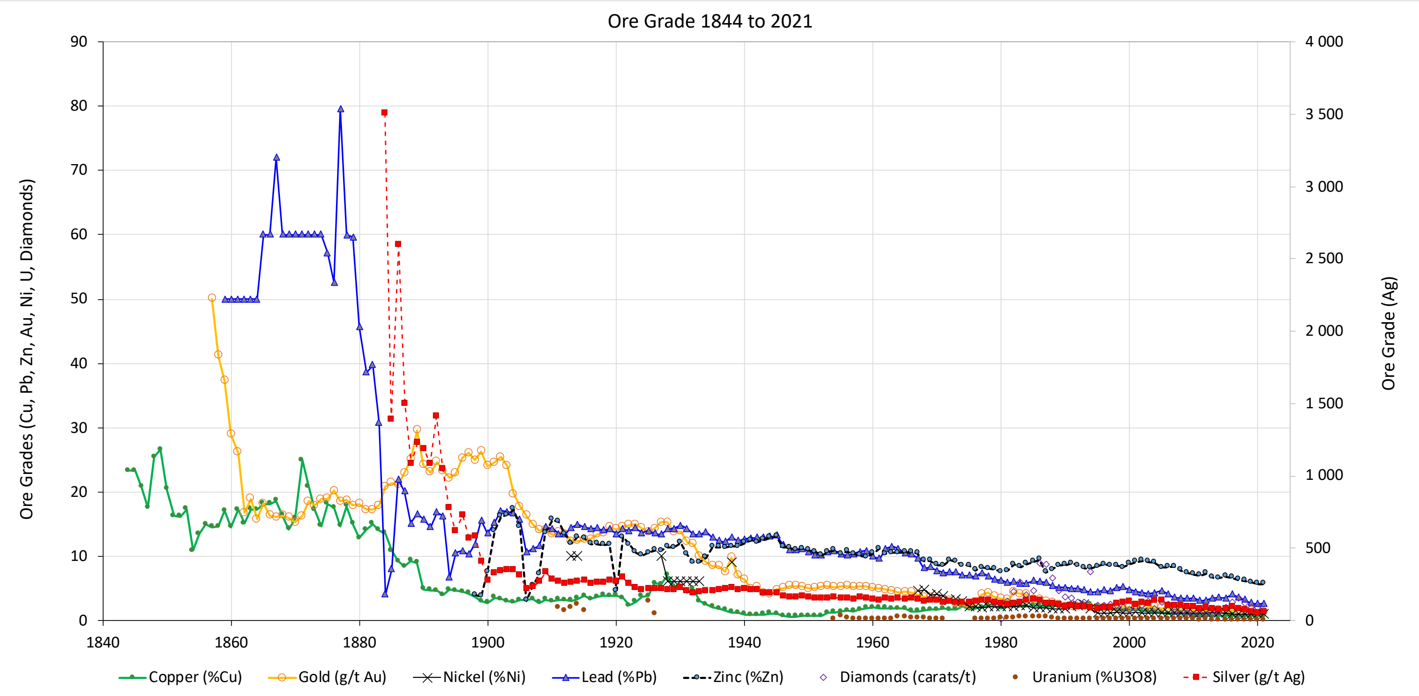

Fig. 24. Grade of mined minerals has been decreasing, 1842 to 2021 (Source: Mudd 2009 – updated in 2020 by G Mudd from Mudd 2010 and related papers) (Copyright permission granted).

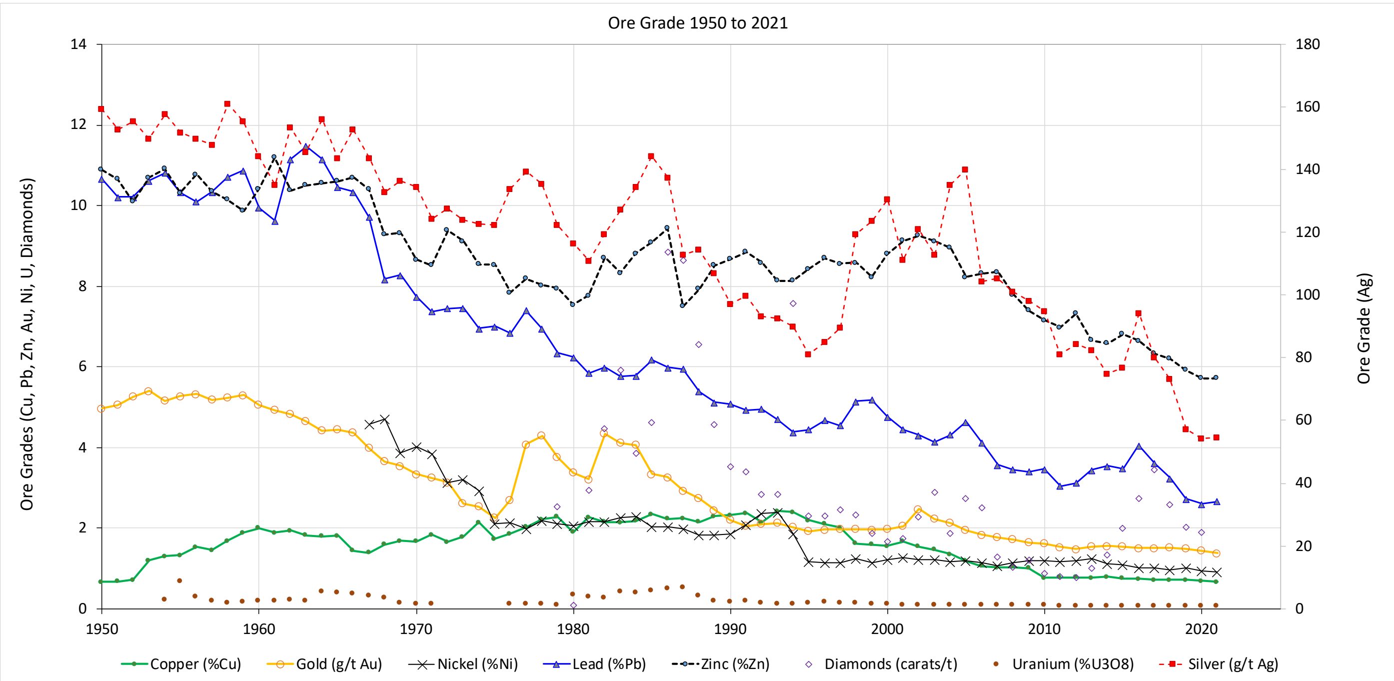

Fig. 25. Grade of mined minerals has been decreasing, 1950 to 2021 (Source: Mudd 2009– updated in 2020 by G Mudd from Mudd 2010 and related papers) (Copyright permission granted).

Another trend seen in the mining industry has been decreasing grind size (driven by the size of the target mineral grains also decreasing), which results in a significant increase in the energy needed for grinding (Michaux 2021b, Hukki 1962). In conjunction to this has been the observation that the ore being mined has been harder in impact breakage resistance (Michaux 2021b). All of this has been the result of a different style of mineralogy being mined compared to a century ago. The economics of production are quite different now.

All of the above has translated into an increase in energy required for the mining of metals. The energy system currently supporting mining are fossil fuel based. While most underground equipment units are electric, the electricity that powers them is usually generated from fossil fuel systems (natural gas being the energy source of choice). Most truck and shovel fleets are dependent on diesel fuel to run them. These fossil fuel energy systems have been in use for more than a century and are well understood.

Any currently available substitution system that would replace fossil fuel would not be as effective in context of capability or performance metrics (Michaux 2021a). So, it is not clear what capabilities for a non-fossil fuel system would have. It is probable that a non-fossil fuel mining method would be more expensive and not as capable. As any given mining operation is designed around the performance metrics of the selected equipment, this in turn would mean what is an economically viable mineral reserve would be different. Just so, how a mining operation would run on an energy system that is mostly wind and solar is not yet understood. It is possible that how mining is done will have to be retooled and redeveloped to accommodate variable power supply.

If fossil fuels were phased out and electrical power generation was then based in renewable technology, mining of minerals could become more expensive. There is a push for development of new technologies, where mining would no longer be powered by fossil fuels. One such innovation is the electric haul truck. Fortescue and Liebherr has developed a 240-tonne mining haul truck fitted with a 1.4 megawatt-hour (MWh) prototype battery system (Lewis 2023). This electric truck can be charged in 30 minutes. Technology like this is only just beginning and is to be subject to future work. What may be practical is an EV mining haul truck that draws power from overhead power lines.

Many reserves could be required to be smaller in size as they would no longer be viable. Mineral reserve/resource classification would then be subject to two opposing trends. Trend 1 would be related to the demand for metals going up in a scarcity styled market, driving market price up. This would upgrade many Mineral Resources into Mineral Reserves. Trend 2 would be the increasing cost of mining, and a change of the rate of mining as a consequence of phasing out fossil fuel supported technology. This could downgrade many Mineral Reserves back into Mineral Resources. It could well be possible that future Mineral Reserves in a post fossil fuel mining industry would be smaller in quantity than they are now, in spite of a much higher market price in a perceived scarcity supply to demand circumstance. This describes a shift of priority from the cost of mining per tonne, to the availability of energy per tonne.

Table 52 shows reported Mineral Reserves, estimated Mineral Resources on land, and estimated under sea resources.

Table 52. Reported global reserves, estimated global resources on land, estimated global under sea resources (Source: USGS 2024, Hein et al. 2020).

Metals & Minerals	Reported Global Reserves (USGS 2022) (million tonnes)	Estimated Global Resources (USGS 2022) (million tonnes)	Estimated global tonnage of metals in under sea CCZ polymetallic nodules þ (million tonnes)
Iron	180 000	800 000	*
Bauxite (Aluminium)	32 000	55 000 - 75 000	*
Cement	*	*	*
Copper	880	2 100	226
Zinc	250	1 900	*
Magnesium Metal	*	unkown Φ	*
Manganese	1 500	unknown Ω	5 992
Chromium	570 †	12 000	*
Nickel	95	300	274,0
Lithium	22	89	2,8
Cobalt	7,6	25	44,0
Graphite (natural flake)	320	800	*
Molybdenum	16	20	12,0
Silicon (Metallurgical)	*	unknown δ	*
Silver	0,53	unknown Ψ	*
Platinum	0,07	0,10	0,0030
Vanadium	24	63,0	9,4
Zirconium	70	unknown Δ	6,5
Germanium	*	*	*
Rare Earth Element			
Neodymium	*	*	*
Lanthanum	*	*	*
Praseodymium	*	*	*
Dysprosium	*	*	*
Terbium	*	*	*
Hafnium	*	*	*
Yttrium	*	*	2,0

† shipping grade

* no data available

þ CCZ, Clarion–Clipperton Zone under water mineral resources, data taken from Hein et al. 2020, Hein et al. 2013

Φ Magnesium metal is abundant, where it can be extracted out of sea water

Ω Land-based manganese resources are large but irregularly distributed

δ World and domestic resources for making silicon metal and alloys are abundant. The source of the silicon is silica in various natural forms, such as quartzite

Ψ Silver resources are unkown. Although silver was a principal product at several mines, silver was primarily obtained as a byproduct from lead-zinc, copper, and gold mines.

Δ Zirconium resources are unknown, and are associated with titanium resources in heavy-mineral-sand deposits. Phosphate rock and sand and gravel deposits could potentially yield substantial amounts of zircon as a byproduct.

To assess the potential to open more mines, the same metal quantity requirements from Table 45 was compared against reported mineral reserves, estimated conventional resources (on land) and estimated resources known to be under the sea (Table 52). The calculations this resulted in are shown in Annex A.

Global reserves for copper, lithium, nickel, cobalt, graphite, vanadium was all well below what was calculated in, assuming the each of the four power storage buffer capacities (from Tables 25 to 28) (Fig. 26). The appropriateness of the size of the power buffer was discussed in (Michaux 2024), where the appropriate size was probably between 28 days and 12 weeks. The sizes of 6 hours and 48 hours +10% were too small in capacity to be useful in balancing power production between winter and summer.

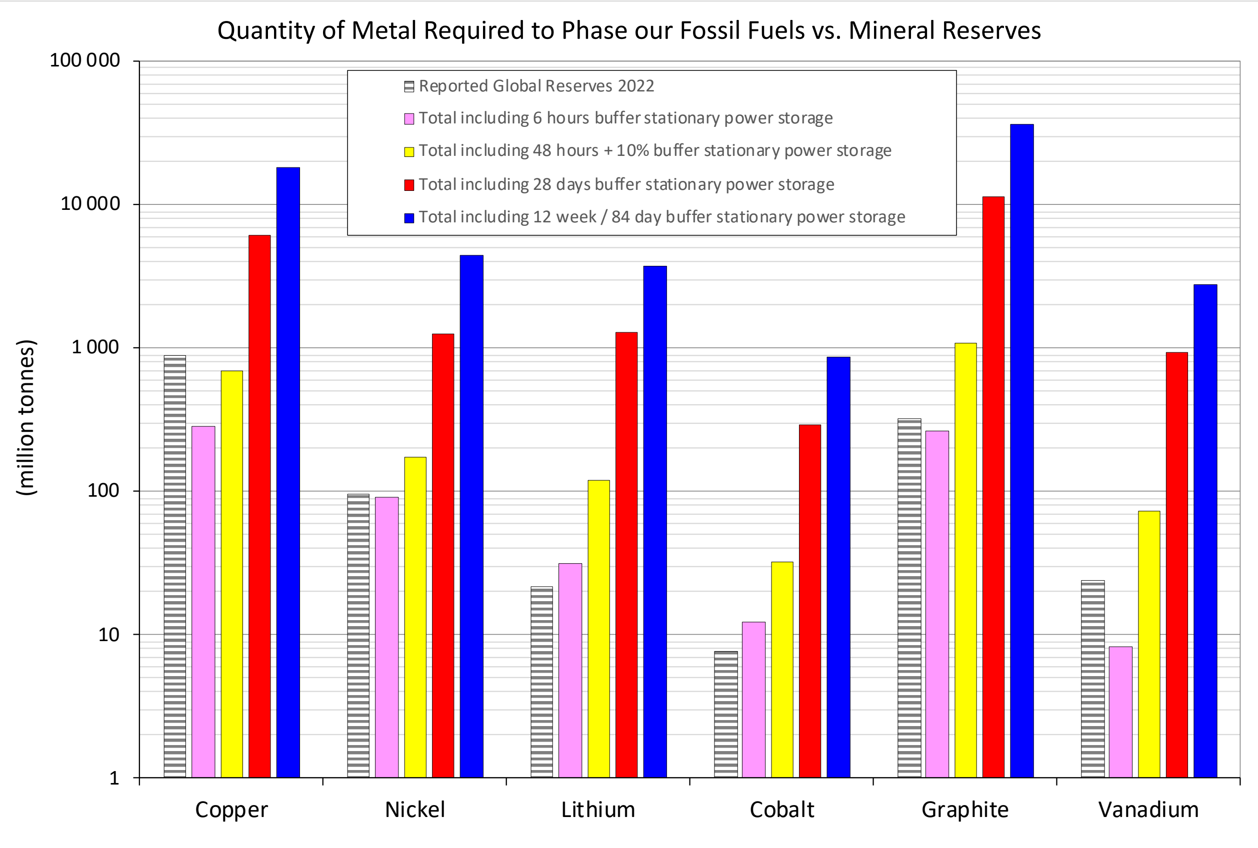

Fig. 26. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves, using four different power buffer storage capacities (USGS 2024) (Annex A).

The mineral reserves for battery metals (lithium, nickel, cobalt, graphite, and vanadium) were all less than what was needed to produce enough renewable technology units to replace the 2018 scope fossil fuel system. Remember, this quantity of metal calculated was for just the first generation of renewable technology units. These units wear out and at the end of their working life have to be decommissioned and replaced. Even if the average working life was 30 years (which is very optimistic), then every 30 years, the quantities of metals in Table 49 would have to be sourced from somewhere. Recycling technology will most certainly be a center piece of the future industrial system, but could it deliver such large quantities in such small period?

As previously discussed, mineralized reserves are a function of economic viability. Market conditions could change (with the metal price going up or down). Another way to study this problem would be remove all economic and extraction technology limitations and compared the needed metal quantity against mineral resources. Figure 27 shows the needed metal to phase out fossil fuels (Table 49) plotted against reported mineral reserves in 2022 plus estimated mineral resources in 2022 (USGS 2024, and Table 51).

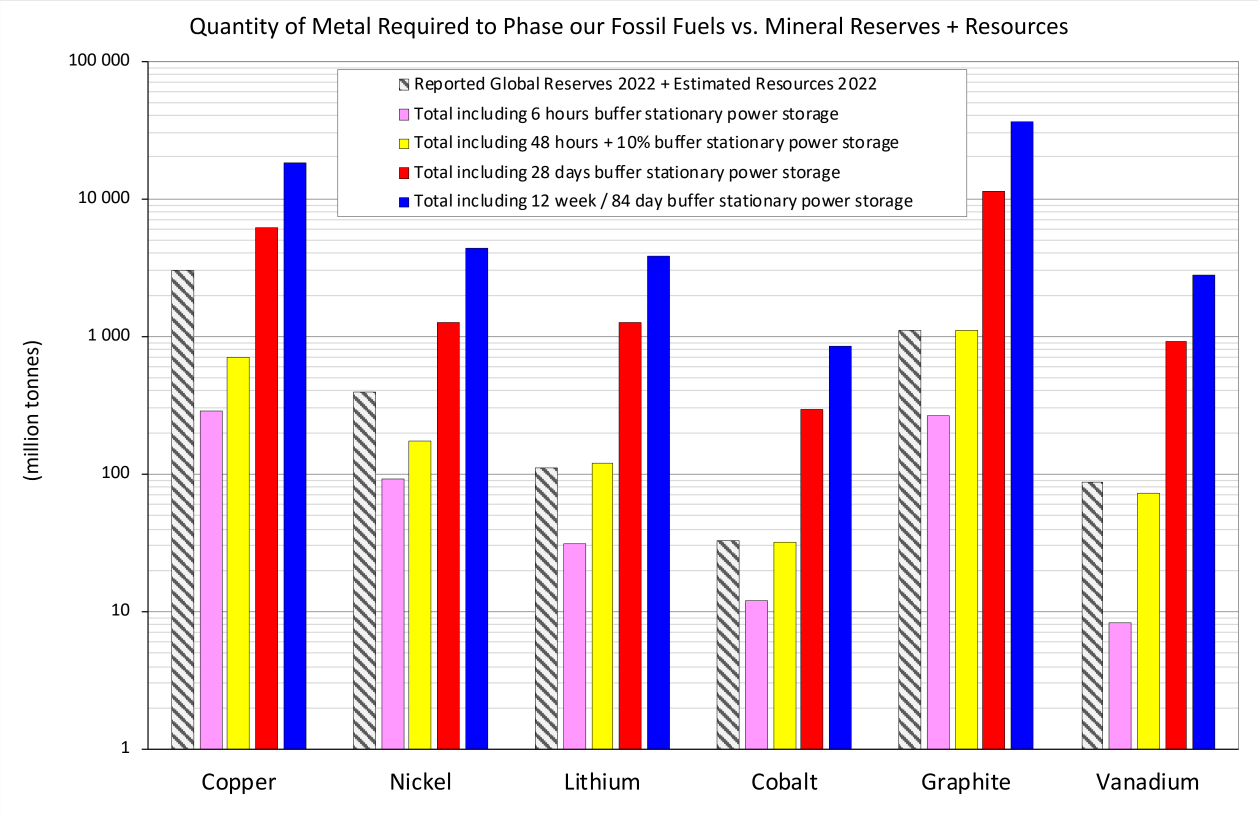

Fig. 27. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves + estimated mineral resources, using four different power buffer storage capacities (USGS 2024) (Annex A).

A solution that has been proposed to meet this resource shortfall, has been to mine under the sea. Estimated resources from mineralized zones under the sea (Hein et al. 2020, Hein et al. 2013, Ilves 2022, Table 51) were included into the tables in Annex A. These mineralized resources on the ocean seabed are termed deep- ocean polymetallic nodules, that form on or just below the vast, sediment- covered, abyssal plains of the global ocean. These polymetallic nodules contain precipitated iron oxyhydroxides and manganese oxide minerals, which in turn contain comparatively high grades of metals such as nickel, cobalt, copper, titanium, and rare earth elements. It is conservatively estimated that something like 21 billion dry tons of nodules is in the Clarion–Clipperton Zone (CCZ), which is located in the northeast equatorial Pacific Ocean (Hein et al. 2020).

These undersea resources would almost certainly be just a small proportion of potential mineralized deposits. This is the most up to date data available at the time of writing this paper. Also, the logistics and practicalities of producing large enough quantities of metal off the sea floor to be useful in expanding market supply is very much in question.

Figures 28 & 29 shows the needed quantity of metal to phase out fossil fuels (assuming all four power storage buffer capacities) is compared against the total metal content in the whole planetary environment, including the deep ocean polymetallic nodules under sea resources (Hein et al. 2020). So, Figure 28 shows reported mineral reserves plus estimated mineral resources on land plus estimated undersea mineral resources. This is the summation of mineral reserves, resources, on land and under the sea, in the planetary environment. Even with this extreme summation of conventional and unconventional sources, there was not enough copper, nickel, lithium, cobalt, or vanadium to manufacture even just the first generation of renewable technology to replace the existing fossil fuel industrial system.

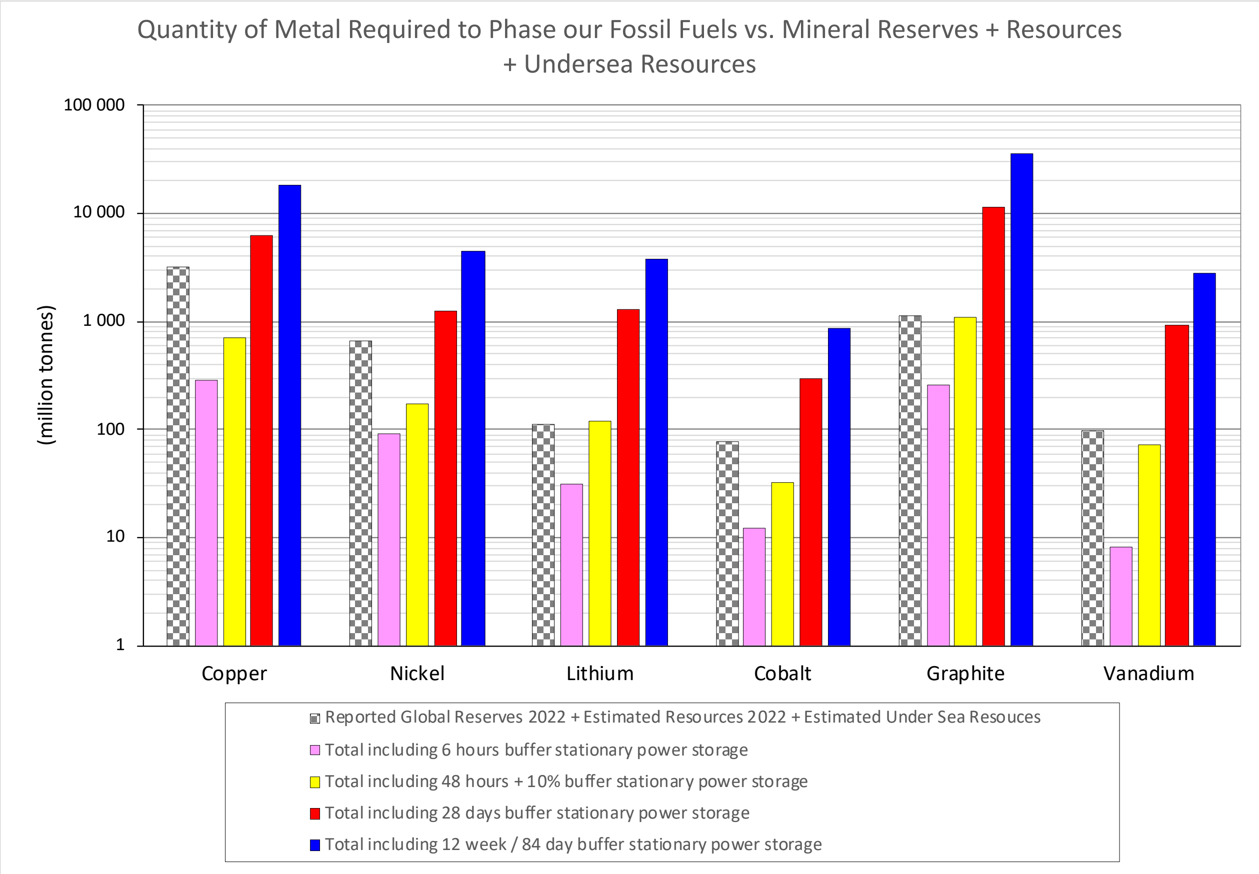

Fig. 28. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves + estimated mineral resources + undersea mineral resources, using four different power buffer storage capacities (USGS 2024, Hein et al. 2020) (Annex A).

At the time of writing, most of these under sea resources are not extractable with modern mining technology, in large enough quantities to be considered useful. As a future resource, their potential is vast as the majority of the ocean floor has not been explored at all for mineralization (Royal Society 2017). This may change. The numbers for undersea resources shown in Table 46 are most certainly a gross underestimation in context of what might be in ocean floor deposits. That being stated, even if it was possible to mine these deposits on the sea floor, the environmental impact on the ocean and the life it contains would be on a scale unlike anything seen before. Thus, at this time we should seriously consider not mining these deposits until technology evolves to the point where the environmental impact is negligible. Also, current methods of operation to access these deposits would be heavily dependent on fossil fuel energy technology. How this could be done with renewable energy technology is not clear.

Figure 29 shows the same data as Figure 28, but on a linear scale.

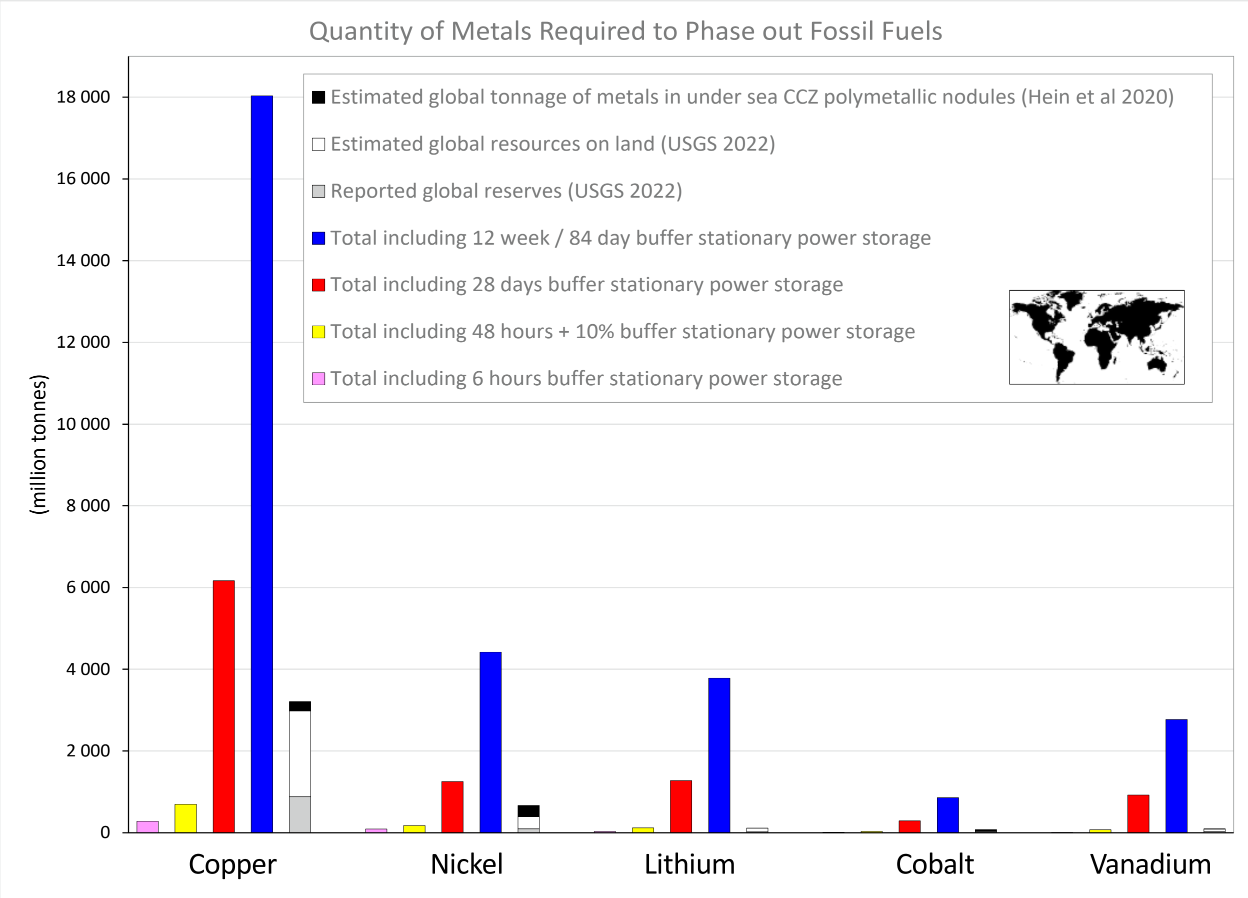

Fig. 29. Quantity of metal required to phase out fossil fuels compared to global reported mineral reserves + estimated mineral resources + undersea mineral resources, using four different power buffer storage capacities, linear scale (USGS 2022, Hein et al. 2020) (Annex A).

14 GENERATION OF MINING WASTE FOR THE GREEN TRANSITION

If the mining industry was significantly expanded in size to deliver the values in Table 49 and Figures 28 & 29, how much waste rock would be generated? Historical waste rock generated by mining of black coal, brown coal, uranium, diamonds, copper, and gold in Australia between 1871 and 2012 was 54 billion tonnes (calculated from Mudd 2021). The overburden rock generated by mining coal represents 78.3% (41.5 billion tonnes) of this (tonnage of coal was estimated from data in m^3, using a density of coal of 1.346 tonnes/m^3). Figure 30 shows the waste rock generated by copper mining in Australia between 1871 and 2012. As can be observed a different business model in Australian mining started in 1997, where much more mining waste rock was generated. In 2012, Australian production of copper accounted for 5.51% (914 000 tonnes) of global production (16.9 million tonnes).

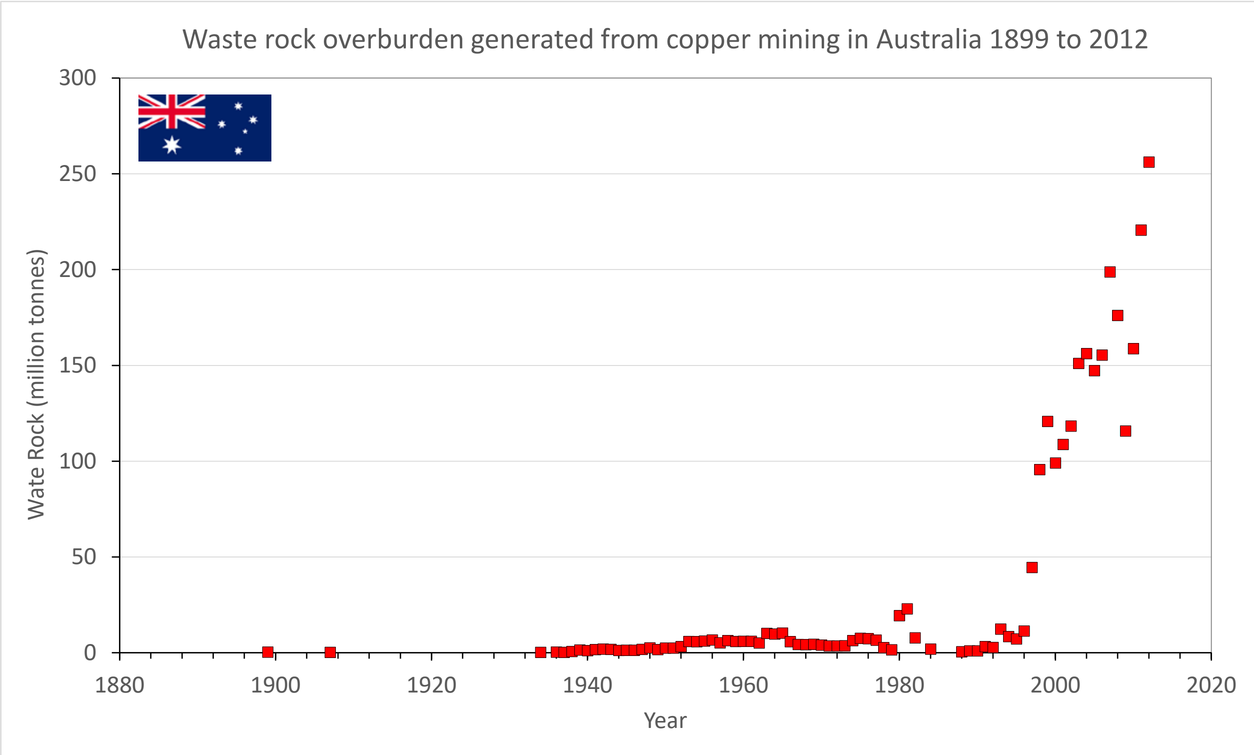

Fig. 30. Waste rock generated from copper mining in Australia between 1871 to 2012 (Source: Mudd 2021).

In 2012, Australia produced 914 000 tonnes of copper, and generated 256 million tonnes of waste rock. This represents a waste/ore ratio of 280.2. This means for each tonne of copper ore produced in 2012, 280.2 tonnes of waste rock were dumped on a mullock heap somewhere in Australia. Assuming all future global mining will have the same strip ratio as Australia copper mining in 2012 (grade will have decreased since then, Fig. 25) the mass of waste rock generated by mining copper for the Green Transition were estimated from the quantities of copper shown in Table 49. Figure 31 shows the outcome of this calculation. Waste rock generated from the mining of copper in Australia between 1934 and 2012 was 2 819 million tonnes (calculated from Mudd 2021).

The left most column in Figure 31 is the total waste rock generated by mining in Australia over 78 years (2.8 billion tonnes). If it was assumed that Australia accounted for 5% of global copper production, then it could be estimated that the global waste rock in copper mining over the same 78 years could be of the order of 55 billion tonnes. Now look at the rest of Figure 31. The 6 hour power buffer full system calculation was estimated to generate 79.6 billion tonnes, and the 12 week estimate was 5 trillion tonnes. Moreover, these large quantities would have to be produced over the next 25.5 years to achieve full phase out of fossil fuels by 2050. If this actually happened, it would be environmentally disastrous.

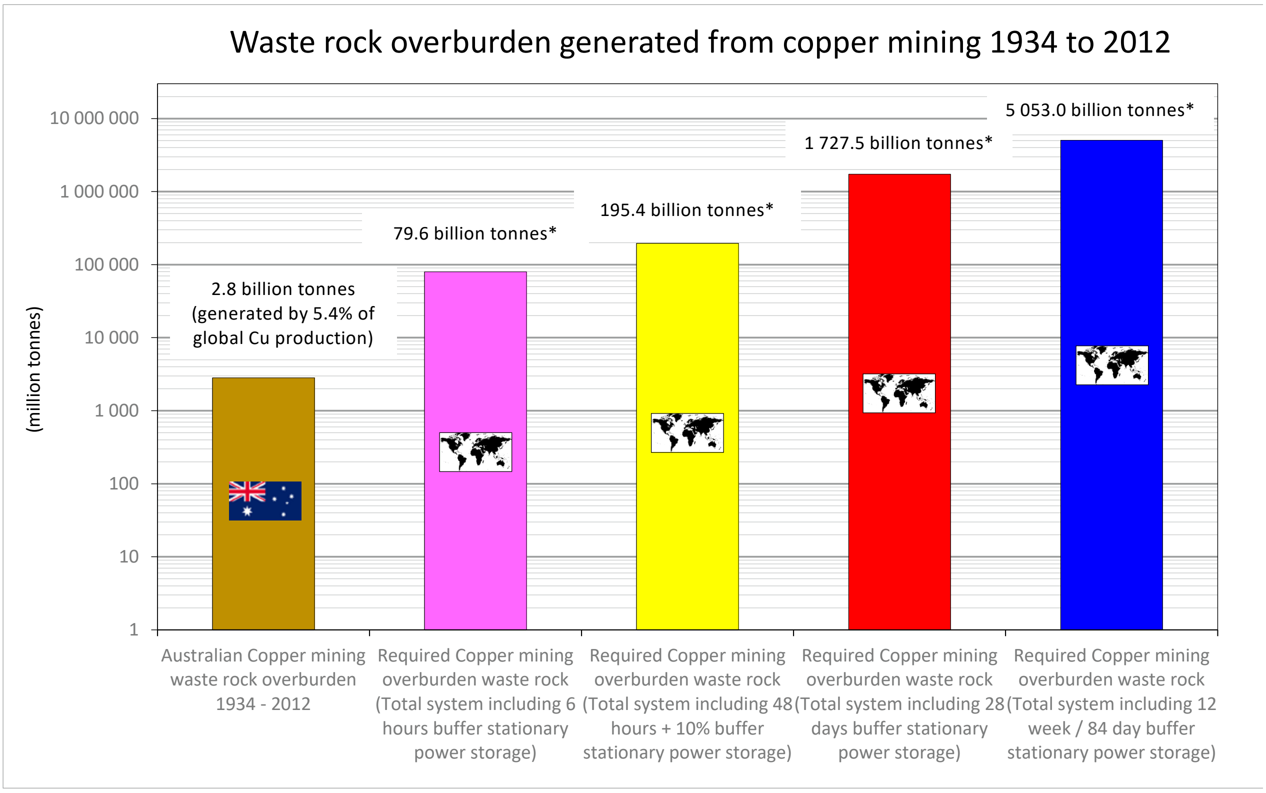

Fig. 31. Historical quantity of waste rock overburden generated from copper mining 1934 to 2012 (Source: Mudd 2021) compared to the waste rock that would be generated if enough copper was mined (assuming 280.2 strip ratio) to deliver metal feedstock for a full system replacement, for each power buffer calculation. Assuming all future global mining will have the same strip ratio as Australia copper mining in 2012.

15 SENSITIVITY ANALYSIS PART II – METAL QUANTITIES REQUIRED

A sensitivity analysis (Part II) was conducted on the data in this paper, building upon the sensitivity analysis Part I done in (Annex I from Michaux 2024). The estimated total additional electrical power outcomes previously developed were used as feed parameters to estimate the quantity of metals (focusing on copper, nickel, lithium, cobalt, graphite, and vanadium) needed to phase out fossil fuels. Annex B shows the tables of numbers of the outcomes of each scenario. The most influential parameter on the total quantity of metals needed to phase out fossil fuels is the size of the stationary power storage buffer (Figs. 26 to 29, Table 49). As previously discussed, the true size of the needed buffer is unknown as the appropriate analysis has not been done. The 6 hour buffer size is what would be needed to manage the day to day supply and demand balance. The size of the buffer may well be between 28 days and 12 weeks (Annex A, and Michaux 2024). Pumped hydro and stored hydrogen gas are not practical in a global scale up storage of such a large quantity of electrical power (Michaux 2024). Many policy makers around the world believe that their national stationary power storage needs to form a buffer (just to manage intermittent supply form wind and solar) would be delivered using a series of battery banks.

Table 53. Quantity of copper required to phase out fossil fuels, by different buffer capacity.

Size of stationary power storage to be used for buffer	Energy to be stored (TWh)	Table in this study	Reference	Total copper metal required produce one generation of technology units to phase out fossil fuels* (million tonnes)	Quanity of copper in 2022** as a proportion of what needed	
					Reported reserves (%)	Reported reserves + resources (%)
6 hours	25,7	Table 13	(Larson et al. 2021)	284	309,8%	1049,3%
48 hours +10%	226,0	Table 14	(Steinke et al. 2012)	697	126,2%	427,4%
28 days	2 876,2	Table 15	(Droste-Franke 2015)	6 165	14,3%	48,3%
12 weeks	8 628,7	Table 16	(Ruhnau & Qvist 2021)	18 033	4,9%	16,5%

* This includes EV's, H2-Cell vehicles, production of steel, ammonia and hydrogen, production of wind turbines, solar panels and batteries

** USGS 2022 stated global reserves of copper were 880 million tonnes

After the examination of power storage buffer capacity, other parameters were examined. One parameter at a time was changed, then the full calculation was done again. The quantity of metals was calculated using the 28 day power storage buffer capacity, which is considered conservative (see Fig. 11). All scenarios examined are described below.

Scenario A: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were reduced by 50% to a fleet size of 693.8 million vehicles, which would annually travel 7.13 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles.

Scenario B: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were reduced by 90% to a fleet size of 167.7 million vehicles which would annually travel 1.43 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles.

Scenario C: The entire EV fleet of passenger cars + commercial vans/light trucks + buses + motorcycles (1.39 billion vehicles annually travelling 14.25 trillion km) were increased by 200% to a fleet size of 2.78 billion vehicles annually travelling 28.50 trillion km. HCV Class 8 Trucks were not included as they were assumed to be H_2-Cell vehicles. This Scenario was developed to examine what impact a larger EV fleet might have on material demands. The size of the transport fleet is projected to grow 2.4 times between 2018 and 2050 (IEA 2021a).

Scenario D: The 28.9 million HCV Class 8 trucks were assumed to be EV, instead of H_2-Cell vehicles. The entire EV fleet now includes HCV Class 8 trucks + passenger cars + commercial vans/light trucks + buses + motorcycles (1.42 billion vehicles annually travelling 16.26 trillion km).

Scenario E: The existing fleet of 19 million buses, which annually travelled 560.8 billion km, was assumed to be expanded by 300% and were all assumed to be EV (58 million buses annually travelled 1.68 trillion km).

Scenario F: The existing fleet of 28.9 million HCV Class 8 trucks were assumed to be H_2-Cell vehicles and reduced by 50% in size (14.4 million H_2-Cell Class 8 trucks annually travelled 829 billion km).

Scenario G: The existing fleet of 28.9 million HCV Class 8 trucks were assumed to be H_2-Cell vehicles and increased by 200% in size (57.8 million H_2-Cell Class 8 trucks annually travel 3.31 trillion km). This Scenario was developed to examine the growth of the consumption of materials goods. The just-in-time supply grid would have to become large and more complex. Trucking transport would be just one input into a possible future study.

Scenario H: The existing rail transport network is expanded 300%. It was assumed that all new trains were H_2-Cell fueled electrical systems. One of the solutions to the challenge of phasing out fossil fuels is to restructure our society, where communal transport became much more important. Rail, metro, and buses would all significantly increase, and the use of personal vehicles would significantly decrease.

Scenario I: The maritime shipping fleet was reduced to by 10% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 10% fewer vessels and 10% less total distance travelled by shipping.

Scenario J: The maritime shipping fleet was reduced to by 50% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 50% fewer vessels and 50% less total distance travelled by shipping.

Scenario K: The maritime shipping fleet was reduced to by 90% in size and scope. This reduction as projected into the proposed maritime shipping fleet split of 17% hydrogen fueled, 46% ammonia fueled and 37% biofueled, where there is now 90% fewer vessels and 90% less total distance travelled by shipping.

Scenario L: If Ammonia production was reduced by 50%, where in this study, it was tasked to fertilizer production, and ammonia fuel production for 46% of the maritime shipping fleet.

Scenario M: If Ammonia production was reduced by 90%, where in this study, it was tasked to fertilizer production, and ammonia fuel production for 46% of the maritime shipping fleet.

Scenario N: If Ammonia production was increased by 200%. This scenario was to examine the impact of a larger human population, that is increasingly dependent on petrochemical supported industrial agriculture, to supply food production.

Scenario O: The quantity of steel produced annually is reduced by 50%. It was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology (HYBRIT 2024) (which is reported to be more efficient than conventional coking coal systems).

Scenario P: The quantity of steel produced annually is reduced by 90%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology (HYBRIT 2024).

Scenario Q: The quantity of steel produced annually is increased by 200%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology (HYBRIT 2024). Scenarios Q and R were assembled to examine what would happen if construction was stepped up in annual capacity. To phase out fossil fuels, a new system will have to be built around the replacement technology, using a completely different set of metrics. This would require an unprecedented demand for raw materials of all kinds, steel, and concrete in particualr (which are often used as proxies for industrialization).

Scenario R: The quantity of steel produced annually is increased by 500%. Again, it was assumed that all steel production is done in a hydrogen atmosphere, using the HYBRIT technology (HYBRIT 2024).

Scenario S: Global building heating, now delivered with heat pumps, was reduced by 50%.

Scenario T: Existing conventional electricity demand was reduced by 50%. This includes all electrical demands (domestic and industrial) in 2018, where fossil fuel systems were fueling the vast majority of the transport fleet.

Scenario U: Existing conventional electricity demand was reduced by 90%.

Scenario V: Existing conventional electricity demand was increased by 200%. This Scenario was developed to see the impact of a significant increase in electrical demand. This study was founded in the paradigm to map the industrial system as it is currently (in 2018), then substituting with non fossil fuel technology to maintain the existing society. A non fossil fuel world will be different. If it will be founded in electrical technology (where we are currently founded in fossil fuel technology), then how that society will function will be different in form and complexity. It could be possible that an electrical non fossil fuel technology system would need more electrical power to service its many networks. We may need proportionally more electricity per capita than we do now.

Scenario W: Existing conventional electricity demand was increased by 300%.

Scenario Alpha: The operating hours of Solar Photovoltaic (PV) panels increased by 200%. This Scenario was to examine what would the impact be if solar PV technology became more effective. Solar PV power stations were producing power 11.4% of the calendar year 2018 (Global Energy Observatory 2020). This was due to the day/night cycle, solar radiance between the seasons of summer and winter, and the weather in general. In this Scenario, it was assumed that operating hours availably for solar PV stations as 22.8%, producing twice as much power annually. This would mean there would be less solar panels needed to make up the target share of the energy mix.

Scenario Beta: The operating hours of wind turbines increased by 200%. Wind turbines were producing power 24.9% of the calendar year 2018 (Global Energy Observatory 2020). In this Scenario, it was assumed that this would increase to 49.8%, producing twice as much power. This would mean there would be less wind turbines needed to make up the target share of the energy mix.

Scenario Gamma: The global energy mix was 50% solar (of which 90% was solar PV and 10% was solar thermal CSP), and 50% wind (of which 70% was onshore turbines, and 30% was offshore turbines), as shown in Table 54. All other power generation systems were discarded. This Scenario was to examine a 100% renewable power grid, in line with multiple strategic plans.

Table 54. Proposed energy split for Scenario Gamma.

Power Generation System (Scenario Gamma) 	**Proposed Proportion of Energy Split on new annual capacity** (%)	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Total new annual installed capacity required** (MW)
Nuclear			
Hydroelectric			
Wind Onshore (70% share)	35,0%	17 129,0	7 843 218,6
Wind Offshore (30% share)	15,0%	7 341,0	3 361 379,4
Solar PV (90% share)	45,0%	22 022,9	22 062 497,7
Solar Thermal (10% share)	5,0%	2 447,0	2 447 947,8
Geothermal			
Biowaste to energy			
Total	100%	48 939,9	35 715 044

Scenario Delta: Nuclear power generation in the energy mix, would be increased from the 7.5% to 10%. This extra 2.5% was taken from wind and solar generation capacity (which was rebalanced to the new proportions). A nuclear power plant was estimated to run on average 71% of the time (in 2018), with expected availability to be at 92%. On average, a solar panel PV farm was reported to have an availability of 11.4% in the year 2018, and wind turbine farm had a reported availability of 24.9%. This difference between the power system availabilities would have an impact of a required lesser installed power capacity. Also, wind and solar are much more material intensive than nuclear power generation systems. Nuclear power has a much larger infrastructure support requirement than wind and solar though. Table 55 shows the proposed energy split for Scenario Delta.

Table 55. Proposed energy split for Scenario Delta.

Power Generation System (Scenario Delta) 	**Proposed Proportion of Energy Split on new annual capacity** (%)	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Total new annual installed capacity required** (MW)
Nuclear	10,0%	4 894,0	781 779,5
Hydroelectric	13,4%	6 538,0	1 110 870,3
Wind Onshore (70% share)	26,0%	12 704,0	5 813 426,1
Wind Offshore (30% share)	11,1%	5 444,6	1 963 416,0
Solar PV (90% share)	33,4%	16 333,7	16 352 814,7
Solar Thermal (10% share)	3,7%	1 814,9	1 813 722,2
Geothermal	0,7%	362,5	56 875,8
Biowaste to energy	1,7%	848,2	777 043,1
Total	100,0%	48 939,9	28 669 947,6

Scenario Epsilon: Nuclear power generation in the energy mix, would be increased from the 7.5% to 20%. This extra 12.5% was taken from wind and solar generation capacity (which was rebalanced to the new proportions).

Table 56. Proposed energy split for Scenario Epsilon.

Power Generation System (Scenario Epsilon) 	**Proposed Proportion of Energy Split on new annual capacity** (%)	**Extra required annual capacity to phase out fossil fuels** (GWh)	**Total new annual installed capacity required** (MW)
Nuclear	20,00%	9 788,0	1 563 559,1
Hydroelectric	13,36%	6 538,0	1 110 870,3
Wind Onshore (70% share)	22,46%	10 991,1	5 029 595,9
Wind Offshore (30% share)	9,63%	4 710,5	1 963 416,0
Solar PV (90% share)	28,88%	14 131,4	14 147 948,1
Solar Thermal (10% share)	3,21%	1 570,2	1 569 176,2
Geothermal	0,74%	362,5	56 875,8
Biowaste to energy	1,73%	848,2	777 043,1
Total	100,00%	48 939,9	26 218 484,4

Scenario Zeta: Nuclear power generation in the energy mix, would be increased from the 7.5% to 30%. This extra 22.5% was taken from wind and solar generation capacity (which was rebalanced to the new proportions).

Table 57. Proposed energy split for Scenario Zeta.

Power Generation System (Scenario Zeta) 	Proposed Proportion of Energy Split on new annual capacity (%)	Extra required annual capacity to phase out fossil fuels (GWh)	Total new annual installed capacity required (MW)
Nuclear	30,00%	14 682,0	2 345 339
Hydroelectric	13,36%	6 538,0	1 110 870
Wind Onshore (70% share)	18,96%	9 278,2	4 245 766
Wind Offshore (30% share)	8,13%	3 976,4	1 963 416
Solar PV (90% share)	24,38%	11 929,2	11 943 081
Solar Thermal (10% share)	2,71%	1 325,5	1 324 630
Geothermal	0,74%	362,5	56 876
Biowaste to energy	1,73%	848,2	777 043
Total	100,00%	48 939,9	23 767 021

Scenario Eta: In this study, the global battery market was assumed to be made up of a series of battery chemistries in predicted market share proportions. In Scenario Eta, it was assumed that LFP batteries made up 80% of the global market share for stationary power storage, light Electric Vehicles (EV's) and heavy EV's. The remaining battery chemistry market shares were balanced accordingly. Tables 58 and 59 shows the proposed battery chemistry market share for Scenario Eta.

Table 58. Proposed battery chemistry market for stationary power storage in Scenario Eta.

Battery Chemistry	Acronym	Specific Energy Density (Wh/kg)	Projected Market Proportion for Power Storage in 2040 (%)
Lithium Nickel Manganese Cobalt Oxides	NMC 532 NMC 622 NMC 811	100-135 100-135 100-135	3,3% 9,9% 9,9%
Lithium Iron Phosphate	LFP	90-120	80,0%
Vanadium Redox Battery	VRB	20 - 32	3,3%

Table 59. Proposed battery chemistry market for Electric Vehicles in Scenario Eta.

Battery Chemistry	Acronym	Light Duty Vehicle (LDV) (%)	Heavy Duty Vehicle (HDV) (%)
Lithium Nickel Cobalt Aluminium Oxides	NCA+	0,8%	
Nickel Manganese Cobalt	NMC 622 NMC 811	1,2% 11,6%	5,6%
Lithium Iron Phosphate	LFP	80,0%	80,0%
All Solid State Batteries	ASSB	6,5%	14,4%
		100,0%	100,0%

Scenario Theta: In Scenario Theta, it was assumed that ASSB solid state batteries made up 80% of the global market share for light Electric Vehicles (EV's) and heavy EV's. Batteries for stationary power storage remained in the same proportions as the main study. The remaining battery chemistry market shares were balanced accordingly. Table 60 shows the proposed battery chemistry market share for Scenario Theta.

Table 60. Proposed battery chemistry market for Electric Vehicles in Scenario Theta.

Battery Chemistry	Acronym	Light Duty Vehicle (LDV) (%)	Heavy Duty Vehicle (HDV) (%)
Lithium Nickel Cobalt Aluminium Oxides	NCA+	1,0%	
Nickel Manganese Cobalt	NMC 622 NMC 811	1,5% 14,7%	1,8%
Lithium Iron Phosphate	LFP	2,9%	18,2%
All Solid State Batteries	ASSB	80,0%	80,0%
		100,0%	100,0%

Scenario Mu: Scenario Mu (μ) is a hybrid of different other scenarios. This scenario was to assemble a profile of data that shows the implications of sharp degrowth of societal footprint, in conjunction of a fundamental restructure of society and the construction of the post fossil fuel industrial society. This was to map out what a sharp degrowth of the system would look like as per recommendations from The Limits to Growth study (Meadows et al. 1972), and to fully replace all fossil fuel technology systems. Electricity demand for conventional applications would contract. The number of passenger cars and the distance they travelled would contract. Communal transport would become much more prominent and important (buses would expand greatly). Rail transport would become more important in the movement of physical goods, and the manufacture sector would relocate to be directly on a train line. So, rail would have to expand greatly. Manufacture would reduce its global dependency and become more regional. This resulted in a reduction in the maritime shipping transport of physical goods. In addition to this, society would reorganize itself around a different energy and transportation system. This means the retooling, and reconstruction of the industrial system across the full value chain, of the largest, most complex and sophisticated society the world has ever known. This will require the consumption of unprecedented quantity of raw materials and metal. Vast amounts of steel and concrete will be needed in quantities never seen before. To reflect this steel manufacture would greatly increase. The parameters selected for Scenario Mu may well be too small in size, and this Scenario really is a ranging shot to develop a more appropriate study. The parameters changed for Scenario Mu were as follows:

- Class 8 HCV trucks reduced by 50%. So, the existing fleet of 28.9 million H2-Cell fueled HCV Class 8 semi-trailer trucks that traveled 1.66 trillion km (in 2018), would contract to 14.5 million H2-Cell fueled HCV Class 8 semi-trailer trucks that would annually travel 828.7 billion km.
- Delivery trucks (Rigid) reduced by 50%. So, the existing fleet of 9.6 million delivery trucks, which annually travelled 250 billion km, reduces to 4.8 million buses which would annually travel 127 billion km, and were all assumed to be EV's.
- Rail transport increased by 300%.
- Buses increased by 300%. The existing fleet of 19 million buses, which annually travelled 560 billion km, expands to 58 million buses which would annually travel 1.68 trillion km, and were all assumed to be EV's.
- Commercial vans and light trucks reduced by 40%. The existing fleet of 601.3 million commercial vans and light trucks, which annually travelled 8.07 trillion km, contracted to 360.8 million vehicles that would instead annually travel 4.84 trillion km, and were all assumed to be EV's.
- Passenger cars reduced by 70%. The existing fleet of 695.2 million passenger cars, which annually travelled 5.6 trillion km, contracted to 208.6 million vehicles that would instead annually travel 1.67 trillion km, and were all assumed to be EV's.

- Motorcycles reduced by 70%. The existing fleet of 62.1 million motorcycles, which annually travelled 163.7 billion km, contracted to 18.6 million vehicles that would instead annually travel 49.1 billion km, and were all assumed to be EV's.
- Maritime shipping reduced by 60%. The existing base line study had a maritime fleet of 116 857 vessels where 17% were fueled by hydrogen (needing 844.9 TWh annually, reduced to 338 TWh), 46% fueled by ammonia (needing 3903.1 TWh annually, reduced to 1 561.3 TWh), and 37% biofuels (needing 477.5 million tonnes of soy biomass, reduced to 191 million tonnes of soy biomass).
- Steel production increased by 300%. Existing annual production of steel (1 808.6 million tonnes for the year 2018) in a hydrogen atmosphere would require an estimated 6 939.2 TWh, where each tonne of steel requires 3 488 kWh, giving a total of 20 817.6 TWh.
- Conventional electrical power reduced by 50%, from 17 086.1 TWh to 8543.1 TWh
- Nuclear power accounts for 20% of the energy power generation mix.

Figures 32 and 33 shows the outcomes of the sensitivity study (Annex B), in context of percentage change from the base line outcome of the basic calculation.

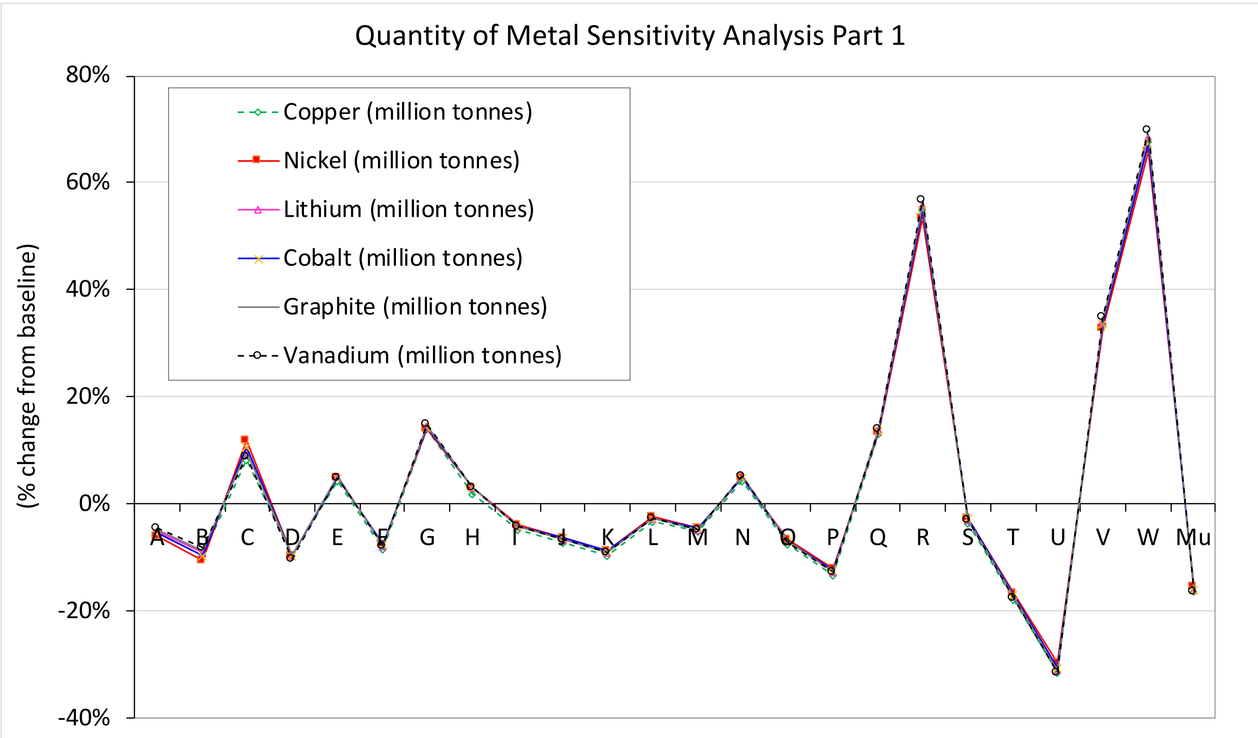

Fig. 32. Sensitivity analysis percent change from baseline study in this paper- Part 1.

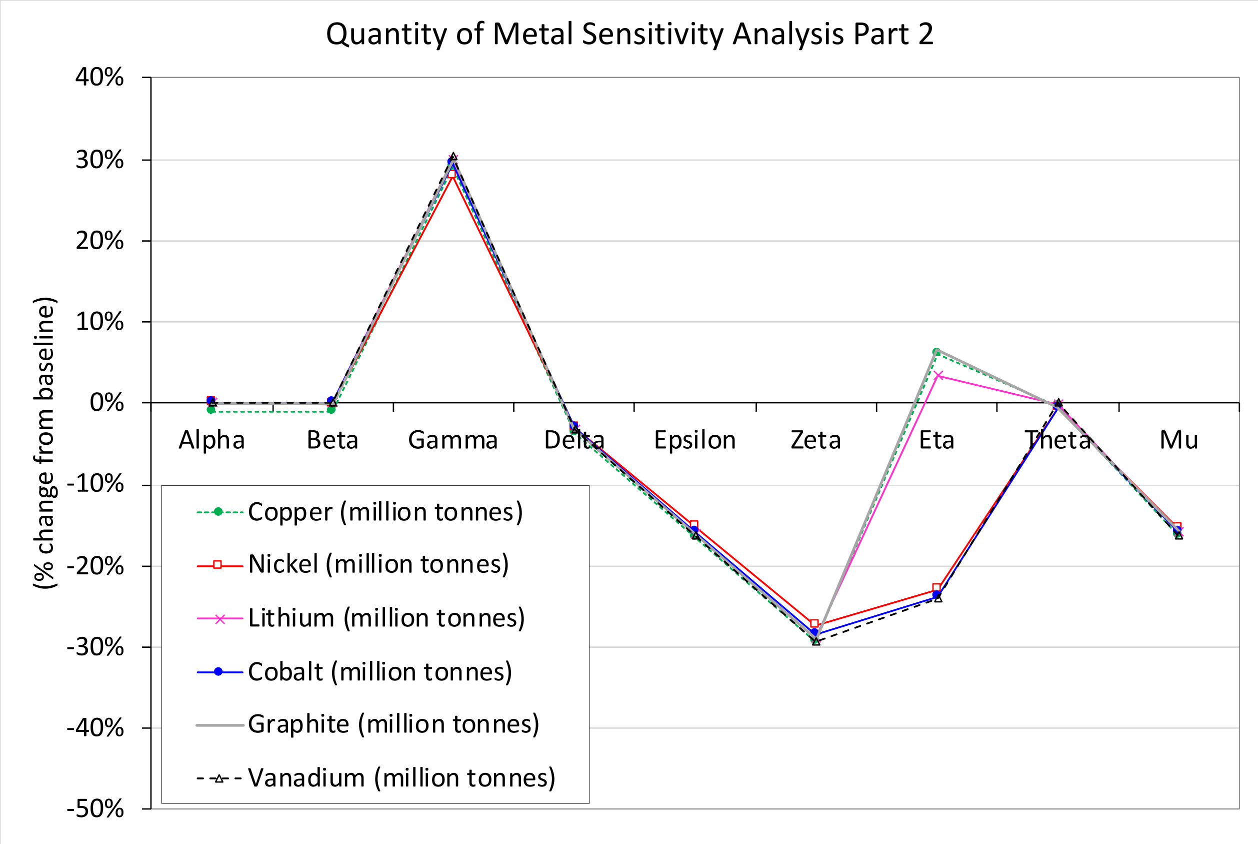

Fig. 33. Sensitivity analysis percent change from baseline study in this paper – Part 2.

16 CONCLUSIONS AND DISCUSSIONS

The estimated total quantity of metals to manufacture one generation of renewable technology units to completely phase out fossil fuels (replace the existing system) is far larger than existing strategic thinking allows for. Conventional strategic planning in the Circular Economy states that the primary source of metals for the future will become recycling (European Commission 2019a. 2019b). In 2020, there were 10 million electric passenger cars (0.7% of the global transport fleet) registered globally (IEA 2021b). In 2020, fossil fuels accounted for 82.2% of primary energy, where renewables accounted for 6.2%, hydro 7.3% and nuclear power 4.3% (BP Statistical Review of World Energy 2022). In 2020, renewable power systems accounted for 11.7% of global annual electricity production (BP Statistical Review of World Energy 2022). The majority of the global non-fossil fuel industrial ecosystem has yet to be constructed. What has yet to be constructed cannot be recycled. What is clear, is that if the mining industry and the environmental movement does not collaborate, the Green Transition will not happen.

It was shown that 2019 global production capacity (mining and/or refining) of minerals was not adequate to manufacture the non fossil fuel technology proposed by the Green Transition in a full system replacement (based on the 2018 data footprint) within the next few decades as hoped. Given that the total quantity of metal produced in the previous 34 years (1990 to 2023) is not enough to supply the needed metal feedstocks, recycling cannot be the primary source of metal for the first generation of renewable energy technology units. What has yet to be mined cannot be recycled. This then means that the sourcing of metals needed will have to be delivered from the mining of minerals.

What would then be required is the rapid expansion of mining industrial capacity on a global scale. The reported 2022 global mineral reserves, mineral resources, under sea mineral resources, or all these summed together, were nowhere near adequate for the delivery of the needed quantities of lithium, cobalt, graphite, and vanadium, to manufacture the full replacement system (using the 2018 data footprint) that has a power storage buffer larger than 48 hours in capacity. Copper and nickel resources and reserves together were inadequate to supply for a Green Transition system with a power storage buffer of 28 days (or larger). As the true size of the needed buffer is closer to 12 weeks (Michaux 2024), this indicates a resource supply shortfall. When examining just reported global mineral reserves (deposits associated with some kind of feasibility assessment in metal quantity and technological extraction feasibility), lithium, cobalt, graphite, and vanadium reserves were all inadequate to supply the construction of a Green Transition system with a 6 hour power buffer. Nickel mineral reserves would be 96.5% consumed, and copper mineral reserves would be 32.3% consumed in the construction of a Green Transition system with a 6 hour power buffer.

Comparing the calculations in this paper against reserves, resources, and mining production historically, it becomes apparent that this is a quantity step change demand problem, not a historically conventional supply problem. The types of metals that are demanded by the Green Transition are in unprecedented quantities, that may not be feasible given the types of mineralogizes involved.

The size of mineral reserves is largely due to the current economic cutoff grades and increasing energy costs for the mining of these metals. For example, most of the Andes Mountain range in South America is mineralized with very low-grade copper. Most of it is not economically viable or extractable in useful quantities with current technology. Resources are more abundant but are not as accessible as reserves. Something to consider is more mineralized deposits will be accessible through mining with the support of fossil fuel energy (with a higher Energy Return on Energy Input, ERoEI) than mining with the support of non-fossil fuel energy systems (with lower ERoEI). Thus, as we transition away from fossil fuels, less mineral deposits will be accessible, unless metal prices increase, or significant incentives to mine with negligible apparent profit comes from the society.

The question of how society delivers the quantity of power storage to buffer the intermittent supply of electricity from wind and solar power generation stations remains unresolved. While the majority of existing power storage is pumped hydro, it is not practical to expand it to the needed global capacity, due to the volume of fresh water that would be demanded from the planetary hydrological cycles (Michaux 2024). The application of hydrogen as a power storage could work in some circumstances but is not practical to expand to the needed global power storage capacity (Michaux 2024).

Battery banks will not be useful for stationary power storage in large quantities, even though policy makers believe this is the most useful option to stabilize intermittent power grids (EMA 2020). The numbers presented in this study show that there are not enough mining production or mineral reserves to deliver enough metal to manufacture enough batteries to do this, where the majority of the metals would be needed to produce battery banks for power buffer delivery. The estimated size of the required stationary power storage buffer for wind and solar power generation shown in Table 47, while large may well be still too small. To meet power grid stability requirements through season changes in solar radiance and the large swings of power production for wind power, a storage capacity of several months might be required, not just a few days. At the time of writing, there was no viable technology that could store such a large quantity of electricity for such a long time period. There may be no visible technology solution for viable long term power storage (Menton 2022), that could be constructed in the short term (the next 5 years).

This could mean that wind and solar power generation systems may not be viable in large networks with electrical engineering in their current form. This may change if the research being done in this area achieves a technology breakthrough. A useful breakthrough could be the development of an electrical engineering technology that can function with variable power supply. Variable frequency, current and voltage. If this was possible, then the requirement of a power buffer would be greatly reduced, or even removed entirely. That being stated, the outcomes of this study show that wind and solar are not viable to be the primary energy source for the next industrial era.

It could be argued that batteries could be manufactured using something other than lithium-ion chemistry, with many substitution chemistries available (Corfe & Butcher 2022). Many of these substitution chemistries use minerals and metals that are genuinely abundant and are often found in industrial waste.

Copper, however, is a different matter. Electrification of the industrial system at any scale will require vast quantities of copper. Aluminium can be used in substitution in some applications, but this may not be practical due to the energy requirements to produce this metal. So, copper will be required in unprecedented quantities. Copper traditionally has been a metal that reflects demand from development of technology. Demand has been projected to continue to grow at a compounded annual rate of 2.4% between 2020 and 2050 (S&P Global 2022). This demand would service applications such as building construction, appliances, electrical equipment, and brass hardware and cell phones, as well as expanding applications in communications, data processing, and storage. The global copper market demand was projected to grow from 25 million metric tonnes (MMt) in 2022 to approximately 50 MMt by 2050 (S&P Global 2022). Copper mining production has been struggling to grow in capacity due to capital availability. The recycling of copper has become increasingly important to meet demand, where mining production was not enough. By 2025, a copper supply gap shortfall is predicted with copper demand projected to continue increasing. This shortfall is predicted to reach 9 MMt in 2035 (based on the Rocky Road Scenario developed by S&P Global 2022, which is based on a continuation of current trends in capacity utilization of mines and recycling of recovered copper).

The copper needed to electrify the industrial system will be required in addition to this. Mining is the extraction of finite non-renewable natural resources. Society's ability to continue to do this in a useful manner will not last forever. While there are still vast resources of copper available, there are practical limitations in industrial ability to extract the desired volumes at the rate to meet demand (Michaux 2021b). A fundamental insight from work like this study is the recognition that our society and the form our industrial systems take will eventually transform into something else.

Figure 34 shows a study that mapped the historical yearly production of copper between the year 2020 back to the year 4 000 B.C., for all of humanity around the world. The same figure also shows a prediction for the future yearly quantities of copper production if copper demand continued to grow as it always has. The human species produced approximately 700 million tonnes over the 4000 years prior to 2020. For global economic demand for copper to continue its current trajectory of growth, another 700 million tonnes will be produced in the next 22 years. Current stated copper reserves were 880 million tonnes (USGS 2024), which would allow approximately 30 years of production at this growth rate.

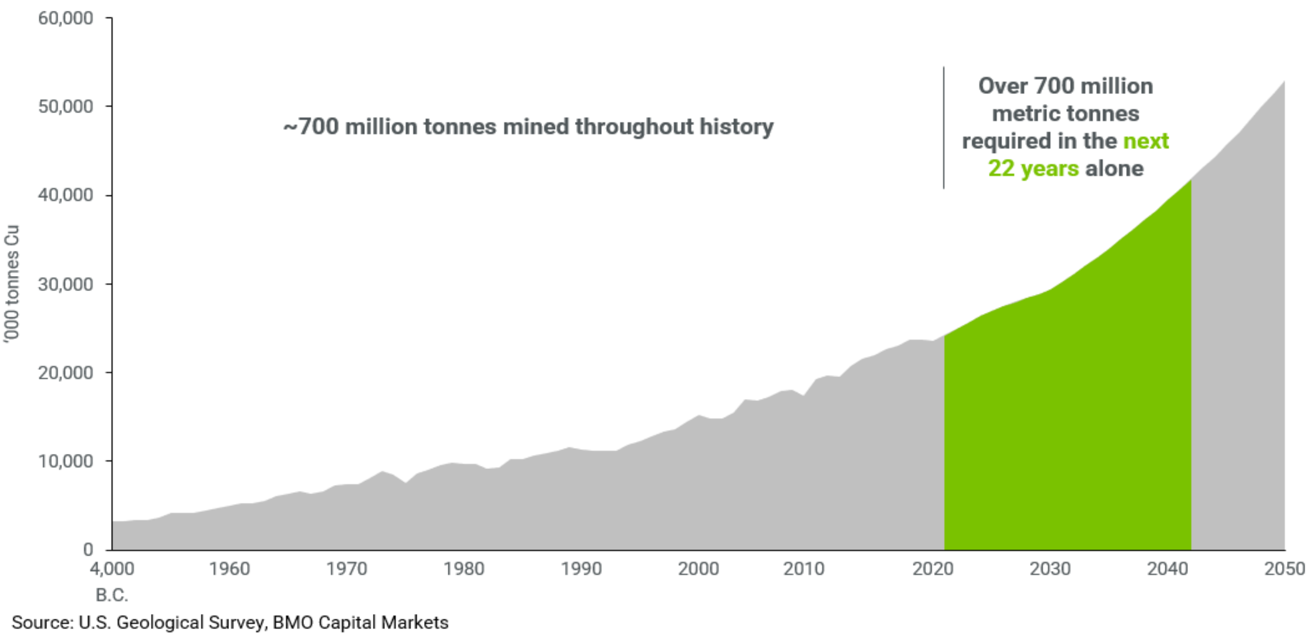

Fig. 34. Historical quantities of copper mined, from 4 000 B.C. to 2020, and projection to 2050 (Source: USGS 2024) (Copyright USGS) (Copyright permission to reproduce granted).

Now consider the implications of Tables 49, 52 and Figure 34, where the quantity of copper needed (depending on which power storage buffer is needed) ranges from 283.6 million tonnes to 18 billion tonnes to produce the first generation of renewable technology units. The 6 hour buffer is what would be needed to manage the day to day differences in the supply and demand cycles of electricity consumption. The other estimates ranging between 28 days or 12 weeks are what would be needed to manage the seasonal differences in the weather. The author is of the opinion that the needed power buffer size is closer to 12 weeks (Michaux 2024), and even 28 days would be a very conservative estimate.

If the 28 day power buffer estimate was used, the quantity of copper to produce the first generation of renewable energy technology units (to maintain the 2018 global industrial system), would be 6.1 billion tonnes (Tables 49 & 53). This would be 8.8 times the total quantity of copper mined by the human species over the last 4 000 years.

At some point, growth for natural resources like copper will not be feasible. Figures 17 and 18 show the average yearly grade of several metal ores has declined over the last 180 years. The highest quality, easy to process mineral resources were extracted and exploited first, leaving a trend of declining grade and quality. All of Tables 38 to 46 and Figure 34 suggest future demand for copper will far exceed any previous records. Consider what Figure 34 would look like if either of the copper demand calculations in the above paragraphs were added. There is a discovery pipeline to bring online new copper mining operations, but is it large enough to service this demand? (Sverdrup & Ragnarsdottir 2014) used the Hubert peak analysis tool, In conjunction with systems analysis, to examine what metals have been mined historically, what is still held in society stocks, and what might still be mined. The outcome of that study suggested that the availability of even low grade deposits for some metals is measured in decades (less than 100 years). While this analysis approach is contested in the literature, (Sverdrup & Ragnarsdottir 2014) make a strong case that we should at least consider minerals as finite resources, instead of believing their supply will never end.

A proposed solution to the perceived copper supply shortfall has been the substitution of aluminium into copper based applications (Bartoš et al. 2022). While this proposal has some merit, there are some material science limitations to overcome. Aluminium has a higher specific electrical resistivity than copper and is only about 60% as conductive as copper. This means that aluminium wire requires a 56% larger cross-section than copper for same current carrying capability. Aluminium also has a higher voltage drop over time.

Aluminium also prone to galvanic corrosion (where copper is not) and can become brittle. Aluminium, used in many copper applications could be liable to crack and break, especially where there is movement and vibration involved. It's less flexible and less suitable to be bent round tight corners (often the case in copper wiring in an electric motor for example. To avoid galvanic corrosion (which is a serious risk factor especially in damp conditions) aluminium requires a special compound at termination connector points (or an Al-Cu lug). As aluminium would also have greater thermal expansion properties compared to copper, an aluminium based circuitry could be susceptible to more maintenance failures in operation (Hofmann et al. 2014, Lide 1991, Grigsby 2006). All of these issues could be overcome but the science and engineering has not yet been done. As such, aluminium can be substituted for copper in some circumstances, but only some not all.

Reserves are not static. With each passing year some reserves are mined, and exploration adds to the global reserve inventory. Figure 35 show the most sophisticated data set available at the time of writing this paper. Supply has been able to keep up with demand thus far. So in theory, the challenges shown in Tables 44 to 53 could be addressed with more exploration. That being stated, how significant is the challenge for mining production to expand to meet the incoming demand, and how fast will it be needed?

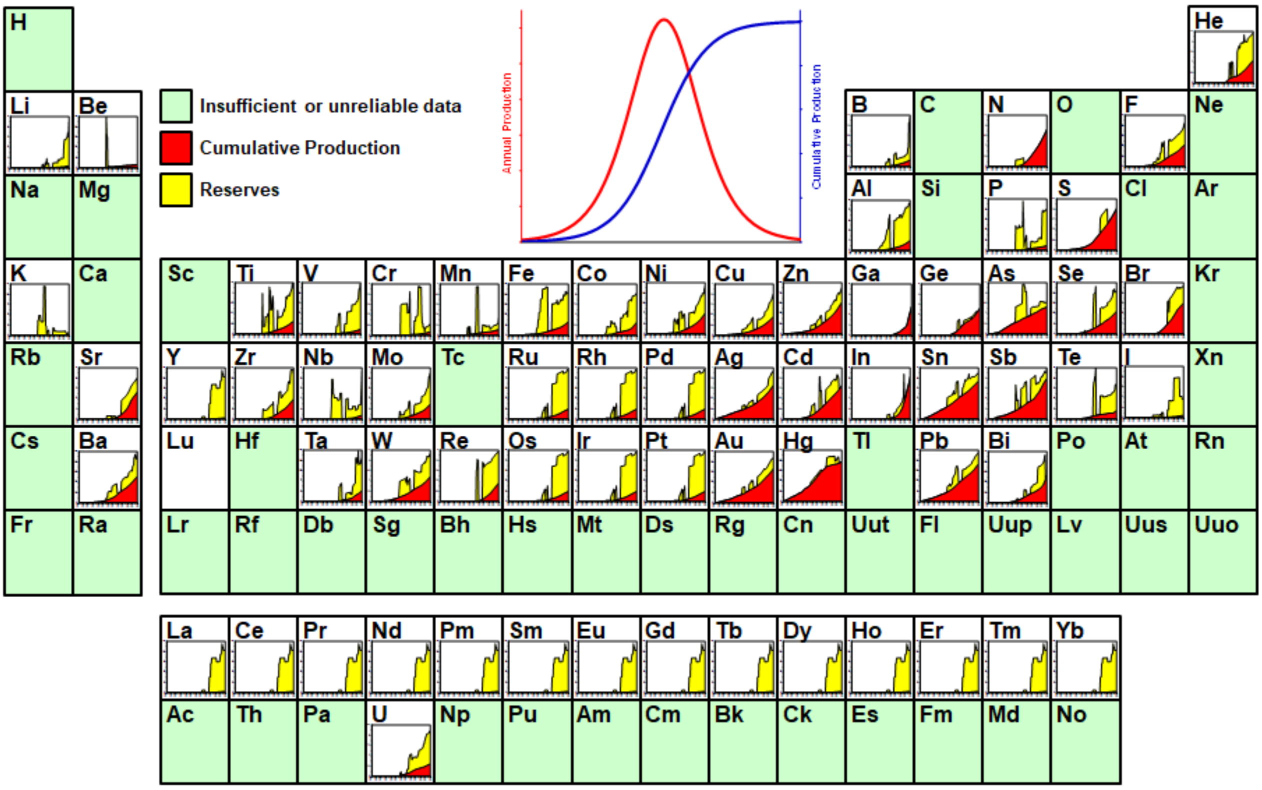

Fig. 35. Hubbert-style curves of cumulative production (red shading) and reserves (yellow shading) for numerous elements inserted within the Periodic Table of the Elements (Source: Mudd 2021) (Copyright permission granted).

Given that for every 1000 deposits discovered, only 1 or 2 become producing mines, and that it takes approximately 10–25 years to develop a discovered deposit to a producing mine (depending on the commodity), and that for every 10 producing mines, 2 or 3 mines will go out of business due to being not viable for market conditions, this task is larger than first understood (Cook 2019). It has taken an average of 16 years to progress and develop a major copper mine from discovery to production during the past 20 years (IEA 2021a). The task to explore for more of these metals far exceeds what is practical in the required time frame to be useful in fossil fuel transition. Comparing Figures 35 and 36 against Table 49, it becomes apparent that *this is a quantity step change demand problem, not a historically conventional supply problem*. The types of metals that are demanded by the Green Transition are in unprecedented quantities, that may not be feasible given the types of mineralogizes involved.

Table 51 shows the number of years required to meet the complete replacement target using 2019 global mining production rates for each metal, for each of the different power storage buffers. It may be noted that for some metals require thousands of years to produce enough product to fully replace the existing fossil fuel system, with the current mining capacity. For example, lithium, requires more than 10 000 years of mining production at current capacity rates, just to manufacture the first generation of renewable units to phase out fossil fuels. Figure 34 shows why this conclusion was drawn. The vast bulk of metals mined each year is iron ore to make steel (in this example 2 995 million tonnes), with other metals like aluminium (64.5 million tonnes) and copper (20.7 million tonnes) a small proportion in comparison. Metals like lithium (116 thousand tonnes) were considered exotic materials and were mined at much smaller volumes.

The Green Transition requires new, or different minerals that need to be mined, processed, and transported using production capacity that currently does not exist, as well as energy that is currently not available or can only be provided with conventional energy generation (Schernikau & Smith 2023).

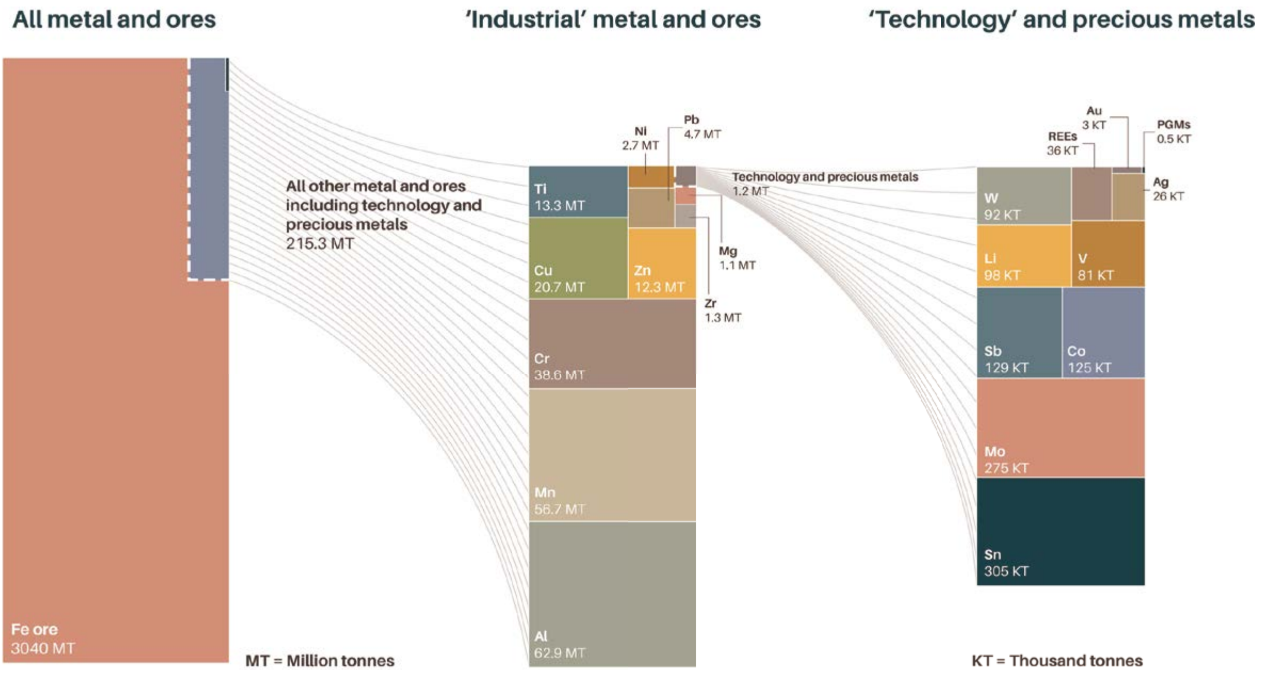

Fig. 36. Global primary metal and ore production, MT = million metric tonne. (Source: British Geological Survey 2021) (Copyright permission granted).

Table 49 shows a required quantity of 1 274 million tonnes of lithium metal (assuming the conservative 28-day buffer power storage). To achieve this in a remotely useful form, the lithium mining industry would have to expand serval thousand percent. Is this even possible? It probably does not honor the nature and form of mineral deposits available (either what is now known or might be discovered in future). There are indeed vast quantities of lithium in trace amounts in the nature (for example in seawater). Current technology is not able to extract it profitably in useful quantities, fast enough to be brought to market though. Then there would be the economic viability challenge.

Table 49 compared to Figure 36 also shows that the needed metals for the green transition (needed in such large quantities), have not been mined in large quantities in the past. This means that there is nothing to recycle yet. For example, even if all available metals were found and recycled, there is not enough copper, lithium or vanadium that has been mined in the historical past to supply future needs for just the manufacture of first-generation renewable technology units.

Each of these technology units harvest renewable energy (wind and sunlight), but they themselves have a working life of a few years (an EV working life is approximately 10-15 years, solar panels and wind turbines retain operational effectiveness for approximately 20 years, IEA 2021b). It could be argued that these technologies should not be termed renewable, but replaceable (Hagens 2021). After each unit fatigues and is no longer effective, it can be decommissioned and recycled. If all the required renewable technology units to phase out fossil fuels were constructed in 2023, it would not be until 2033 that any of these units reach the end of their working life and be available for recycling. At least the first generation of technology units will have to be manufactured, using the mining of minerals as metal feedstock.

This study has identified a series of metals that are vital for current plans to transition away from fossil fuels and may well have critical future supply issues. The Critical Raw Materials (CRM) map (European Commission 2017, Bobba et al. 2020) has not established the same profiles, due to a difference in how metal demand is calculated. The CRM map assesses what metals had the potential for economically inelastic markets over the previous 4 years (2012 to 2016). This study examines what metal quantities will be required to evolve from 2018, to a point into the future where the entire existing global industrial ecosystem is then fossil-fuel free. It is recommended in future work to develop a CRM like map but using different axes and metrics. For example, the use of exergy (Szargut 2005) as a data foundation could be one axis, the difficulty of metal extraction could be a second axis, and metal scarcity (reserves to demand ratio) could be a third. In doing so, primary, and secondary metal sources could be modelled together. It is also recomended that a method of assessing the complete value chain of each metal be developed and interfaced with LCA analysis of each class of renewable technology unit.

The calculated shortfall in copper and nickel production is of concern as both metals have no clear substitute or alternative in application. This could have difficult implications for the future viability of the industrial ecosystem in its current form. Copper in particular (often termed the metal of electrification) is a critical metal for all proposed plans to phase out fossil fuels. Copper can be substituted for aluminium in some applications but not all. Also, making aluminium metal from ore is extraordinarily energy intensive, which once fossil fuels is phased out, will be a bottleneck problem. But the potential supply demand gap is expected to be very large as the transition proceeds, with supply shortfalls seen already in the existing market, before electrification seriously gets underway. Substitution and recycling will not be enough to meet the demands of electric vehicles (EV's), power infrastructure, and renewable generation (Schernikau & Smith 2023, Hund et al. 2020, Meinert et al. 2016, Turcheniuk et al. 2018).

One strategy that could change our materials requirements short fall would be to produce batteries out of different minerals, and change how we use them. It is quite possible to develop several battery chemistry systems in parallel, and to optimize what their applications would be based on a whole industrial ecosystem-need hierarchy (Corfe & Butcher 2022). For example, lithium-ion batteries could be reserved for some applications that need high power and low mass and volume batteries. Vanadium redox batteries, on the other hand, could be reserved for industrial sized standalone battery banks that are of strategic value (with a very different working Life Cycle). The classic lead acid batteries could be used for applications that do not require weight or volume limitations.

Currently, the most investigated battery chemistries are lithium-ion batteries (LIBs), which use lightweight lithium ions as a charge carrier (Gschwind et al. 2016). These LIBs are considered the best performing systems. Additionally, systems based on H^+, OH^-, Na^+, and Mg^{2+} as shuttle ions are currently in use or being investigated (Linden & Reddy 2002, Berndt & Spahrbier 2014a, Berndt & Spahrbier 2014b, Berndt 2014). Despite these advances, it is acknowledged all of these suffer from various limitations (Tarascon & Armand 2001, Muldoon et al. 2012).

These data-based conclusions suggest that while lithium-ion battery chemistry is the preferred option to develop energy storage, it is not feasible to scale up to be available for the whole global market, due to lack of available reserves. Even if it were possible to explore for more deposits to the quantity needed, there is not the time to develop them to be useful in phasing out fossil fuels. It is recommended to develop alternative battery chemistries that use mineral/metal feedstocks that are more abundant. Battery chemistries that are based on zinc, fluoride and sodium are all viable, and should be investigated (Corfe & Butcher 2022). There are other systems that show promise (Gschwind et al. 2016). (Gschwind et al. 2016) examined all of the theoretical combinations of fluoride chemistries for anode (negative) to cathode (positive) electrode combinations, using atomic chemistry.

Figure 37 shows the grouping of battery chemistry energy footprint for several chemistries, after examining a series of combinations of gravimetric capacity for anode/cathode combinations and the volumetric energy density of fluoride chemistries for anode (negative) to cathode (positive) electrode combinations. This implies that lithium-ion battery chemistry may not be the best option to pursue for high density applications. Many of the chemistries shown in Figure 37 require metals and minerals like fluoride, sodium, or zinc, which do not have the same resource scarcity issues that lithium and cobalt do. Moreover, they could be sourced from our industrial waste.

These ideas are not really part of the conventional problem solving paradigm at this time. So, aspects may be discussed but are not developed beyond conceptual state of readiness. At the time of writing this paper, lithium-ion chemistry was still the preferred option when it came to seek research funding. The development of sodium batteries was just starting to be discussed in this context.

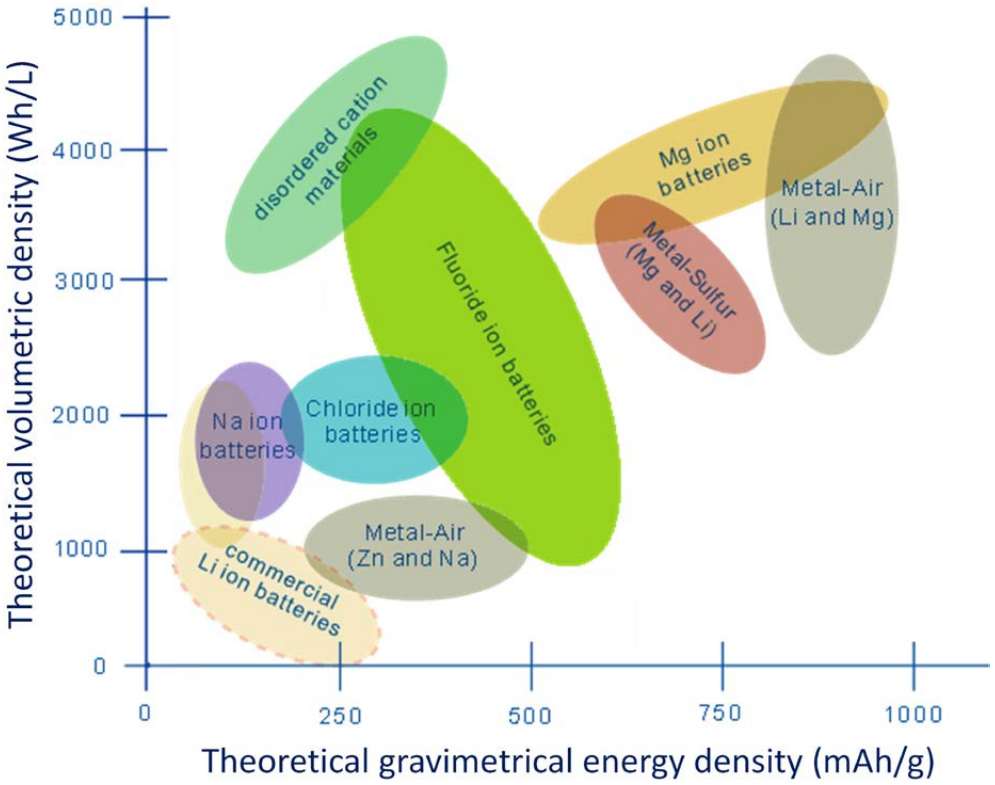

Fig. 37. Possible battery chemistries (Witter 2021).

This paper presents data the shows the existing paradigm and strategic plan to phase out fossil fuels will not be practical for 8 billion people. It faces so many macroscale challenges and logistical bottle necks in metal supply to be feasible. This in conjunction with the possibility of peak oil and/or the increasing deterioration of effectiveness of crude oil an energy source (Michaux 2019), could produce circumstances that will transform the global industrial system in an unplanned manner. The Green Transition will need to be reevaluated and a new plan is required to be developed. This plan will have to deliver a new system of resource management that merges minerals, metals, and materials across the value chain with energy, and would honor industrial thermodynamic boundary conditions (Michaux 2021c). Figure 38 shows a possible path of development for future work to be considered.

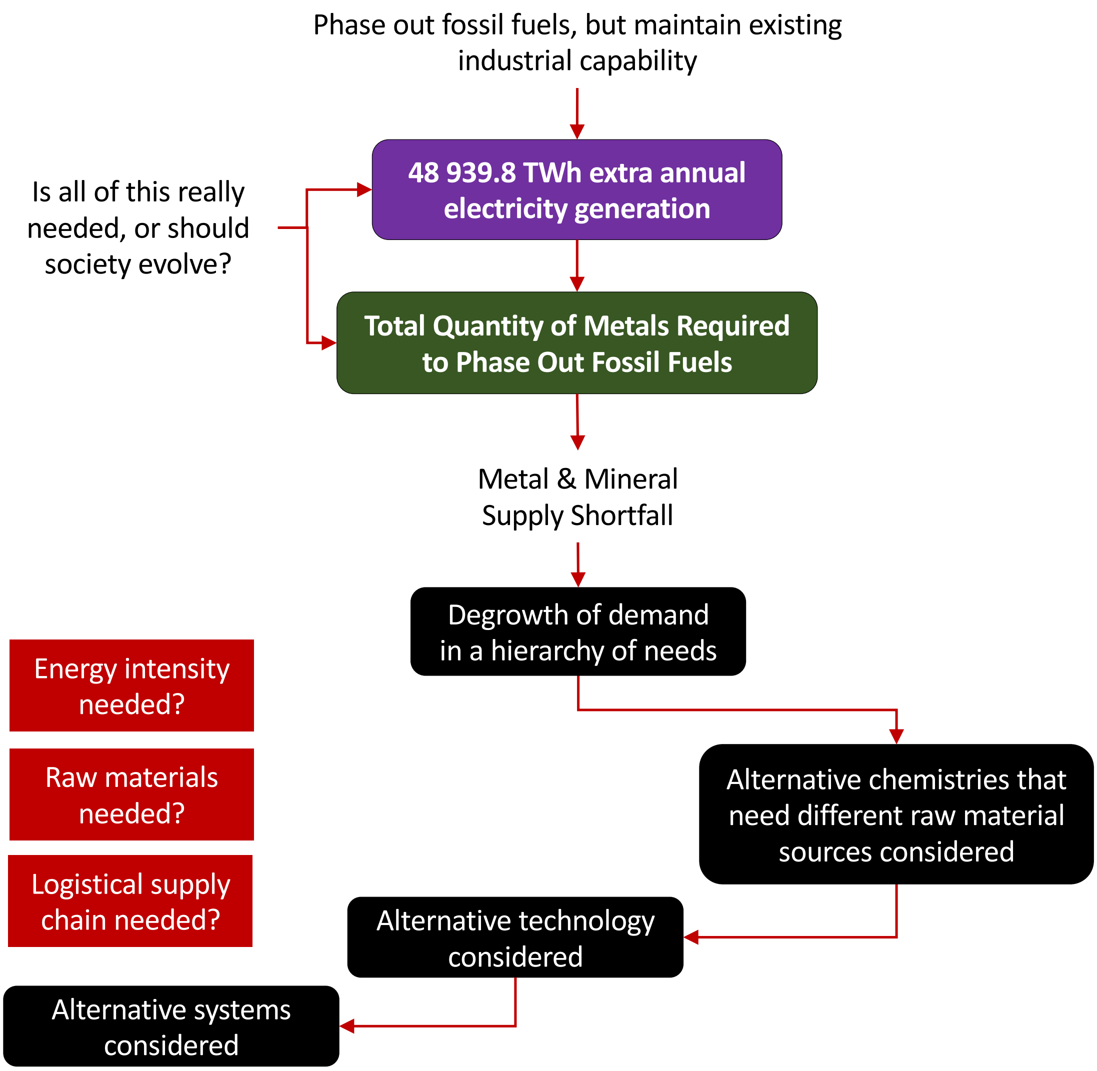

Fig. 38. A possible path of development for future work in context of the outcomes of this study.

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ANNEX A.
QUANTITY OF METAL TO PHASE OUT FOSSIL FUELS COMPARED TO MINING PRODUCTION, STATED RESERVES AND RESOURCES

The purpose of this Annex is to show the calculations for the comparison of the quantity of metals required to phase out fossil fuels, compared to mining production, stated minerals reserves, conventional resources on land, and unconventional resources under the sea. This calculation was split into four separate calculations, each based on a different power buffer to manage the intermittency of production from wind and solar stations. For the purpose of this study, four capacities of power storage buffer were calculated. These four scenarios will later be used in calculations for total required metal content for just wind and solar PV power production was selected. This was done to produce a more conservative estimate. The capacities are as follows:

- 6 hours (Larson et al. 2021)
- 48 hours +10% (Steinke et al. 2012)
- 28 days (Droste-Franke 2015)
- 12 weeks (Ruhnau & Qvist 2021)

In Tables A1 to A16, some figures are colored blue. This is to reflect an excess in time required for production, where the required target is 25 years and 6 months for full system replacement in 2050 (IEA 2021a and Table 3), or an excess of quantity over reserves or resources.

QUANTITY OF METALS REQUIRED TO PHASE OUT FOSSIL FUELS, ASSUMING A 6 HOUR POWER STORAGE BUFFER

Table A1. Total metal quantity required to manufacture one generation of technology units, with a 6 hour power buffer for wind and solar to phase out fossil fuels compared to 2019 global production.

Metals & Cement	Element	Total including 6 hours buffer stationary power storage (million tonnes)	Global Metal Production 2019 (million tonnes)	Years to produce metal at 2019 rates of production (assuming the 6 hour buffer) (years)
Steel & Iron	Fe	3 895	1 860	2,1
Aluminium	Al	372,82	63,14	5,9
Cement	-	962,74	4 100	0,2
Copper	Cu	284,01	24,2	11,7
Zinc	Zn	48,19	13,5	3,6
Magnesium Metal	Mg	0,50	1,12	0,4
Manganese	Mn	18,54	20,6	0,900
Chromium	Cr	9,20	37,5	0,25
Nickel	Ni	91,65	2,35	39,0
Lithium	Li	31,49	0,095	330,9
Cobalt	Co	12,17	0,126	96,6
Graphite ♦	C	262,46	2,73	96,2
Molybdenum	Mo	1,50	0,28	5,4
Silicon (Metallurgical)	Si	67,39	3,43	19,7
Silver	Ag	0,20	0,0263	7,5
Platinum	Pt	0,00	0,00019	14,1
Vanadium	V	8,25	0,096	86,0
Zirconium	Zr	2,61	1,34	2,0
Germanium	Ge	4,16	0,000130	32 024,3
Rare Earth Element				
Neodymium	Nd	1,143	0,0239	47,8
Lanthanum	La	5,971	0,0358	166,8
Praseodymium	Pr	0,265	0,0075	35,4
Dysprosium	Dy	0,212	0,0010	212,1
Terbium	Tb	0,023	0,0003	81,4
Hafnium	Hf	0,00029	0,000066	4,4
Yttrium	Y	0,00029	0,0140	0,021

♦ Natural flake graphite and synthetic graphite was combined to estimate total production

Table A2. Total metal quantity required to manufacture one generation of technology units (6 hour power storage buffer) to phase out fossil fuels compared to 2022 reported global reserves (Source: USGS 2024).

Metal	**Total metal required produce one generation of technology units to phase out fossil fuels (6 hour buffer)** (million tonnes)	**Reported Global Reserves 2022** (million tonnes)	**Global Reserves as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	180 000	4621%
Aluminium	372,8	32 000	8583%
Copper	284,0	880	310%
Zinc	48,2	250	519%
Magnesium Metal	0,5	*	
Manganese	18,5	1 500	8090%
Chromium	9,2	570 †	
Nickel	91,6	95	104%
Lithium	31,5	22	70%
Cobalt	12,2	7,6	62%
Graphite	262	320	122%
Molybdenum	1,5	16	1069%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	0,53	268%
Platinum	0,0027	0,070	2619%
Vanadium	8,3	24,0	291%
Zirconium	2,6	70,0	2678%
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A3. Total metal quantity required to manufacture one generation of technology units (6 hour power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land (Source: USGS 2024).

Metal	Total metal required produce one generation of technology units to phase out fossil fuels (6 hour buffer) (million tonnes)	Reported global reserves 2022 + Estimated conventional resources 2022 (million tonnes)	Global Reserves and resources as a proportion of metals required to phase out fossil fuels (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	107 000	28700%
Copper	284,0	2 980	1049%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	18,5	1 500	8090%
Chromium	9,2	12 570	136603%
Nickel	91,6	395	431%
Lithium	31,5	111	352%
Cobalt	12,2	32,6	268%
Graphite	262,5	1 120	427%
Molybdenum	1,5	36	2405%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,0027	0,170	6360%
Vanadium	8,3	87,0	1054%
Zirconium	2,6	*	
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A4. Total metal quantity required to manufacture one generation of technology units (6 hour power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land + estimated undersea resources (Source: USGS 2024).

Metal	**Total metal required produce one generation of technology units to phase out fossil fuels (6 hour buffer)** (million tonnes)	**Reported global reserves 2022 + Estimated conventional resources 2022 + estimated resources under sea** (million tonnes)	**Global Reserves and resources as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	39 500	10595%
Copper	284,0	3 206	1129%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	18,5	7 492	40408%
Chromium	9,2	12 570	136603%
Nickel	91,6	669	730%
Lithium	31,5	114	361%
Cobalt	12,2	76,6	629%
Graphite	262,5	1 120	427%
Molybdenum	1,5	48	3206%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,0027	0,173	6472%
Vanadium	8,3	96,4	1168%
Zirconium	2,6	*	
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,0228	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

QUANTITY OF METALS REQUIRED TO PHASE OUT FOSSIL FUELS, ASSUMING A 48 HOUR + 10% POWER STORAGE BUFFER

Table A5. Total metal quantity required to manufacture one generation of technology units, with a 48 hour + 10% power buffer for wind and solar to phase out fossil fuels compared to 2019 global production (Source: USGS 2024).

Metals and Cement	Element	Total including 48 hours + 10% buffer stationary power storage (million tonnes)	Global Metal Production 2019 (million tonnes)	Years to produce metal at 2019 rates of production (assuming the 48 hour + 10% buffer) (years)
Steel & Iron	Fe	3 895	1 860,00	2,1
Cement	-	963	4 100,00	0,2
Aluminium	Al	372,82	63,14	5,9
Copper	Cu	697,28	24,20	28,8
Zinc	Zn	48,19	13,52	3,6
Magnesium Metal	Mg	0,50	1,12	0,4
Manganese	Mn	38,75	20,59	1,88
Chromium	Cr	9,20	37,50	0,25
Nickel	Ni	173,14	2,35	73,67
Lithium	Li	118,87	0,095	1249,1
Cobalt	Co	31,91	0,126	253,2
Graphite ♦	C	1 096,50	2,73	401,7
Molybdenum	Mo	1,50	0,28	5,4
Silicon (Metallurgical)	Si	67,39	3,43	19,7
Silver	Ag	0,20	0,026	7,5
Platinum	Pt	0,00	0,00019	14,1
Vanadium	V	72,64	0,096	756,5
Zirconium	Zr	2,61	1,34	2,0
Germanium	Ge	4,16	0,000130	32 024,3
Rare Earth Element				
Neodymium	Nd	1,14	0,024	47,8
Lanthanum	La	5,97	0,036	166,8
Praseodymium	Pr	0,265	0,0075	35,4
Dysprosium	Dy	0,212	0,0010	212,1
Terbium	Tb	0,023	0,00028	81,4
Hafnium	Hf	0,000293	0,000066	4,4
Yttrium	Y	0,000293	0,0140	0,021

♦ Natural flake graphite and synthetic graphite was combined to estimate total production

Table A6. Total metal quantity required to manufacture one generation of technology units (48 hour +10% power storage buffer) to phase out fossil fuels compared to 2022 reported global reserves (Source: USGS 2024).

Metal	**Total including 48 hours + 10% buffer stationary power storage** (million tonnes)	**Reported Global Reserves 2022** (million tonnes)	**Global Reserves as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	180 000	4621%
Aluminium	372,8	32 000	8583%
Copper	697,3	880	126%
Zinc	48,2	250	519%
Magnesium Metal	0,5	*	
Manganese	38,7	1 500	3871%
Chromium	9,2	570	
Nickel	173,1	95,0	55%
Lithium	118,9	22,0	19%
Cobalt	31,9	7,6	24%
Graphite	1 096,5	320,0	29%
Molybdenum	1,5	16,0	1069%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	0,53	268%
Platinum	0,0027	0,070	2619%
Vanadium	72,6	24,0	33%
Zirconium	2,6	70,0	2678%
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A7. Total metal quantity required to manufacture one generation of technology units (48 hour + 10% power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land (Source: USGS 2024).

Metal	**Total including 48 hours + 10% buffer stationary power storage** (million tonnes)	**Reported global reserves 2022 + Estimated conventional resources 2022** (million tonnes)	**Global Reserves and resources as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	107 000	28700%
Copper	697,3	2 980	427%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	38,7	1 500	3871%
Chromium	9,2	12 570	136603%
Nickel	173,1	395	228%
Lithium	118,9	111	93%
Cobalt	31,9	32,6	102%
Graphite	1 096,5	1 120	102%
Molybdenum	1,5	36,0	2405%
Silicon (Metallurgical)	67,4	*	
Silver	0,20	*	
Platinum	0,0027	0,170	6360%
Vanadium	72,6	87,0	120%
Zirconium	2,6	*	
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A8. Total metal quantity required to manufacture one generation of technology units (48 hour + 10% power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land + estimated resources under the sea (Source: USGS 2024).

Metal	**Total metal required produce one generation of technology units to phase out fossil fuels (48 hour +10% buffer)** (million tonnes)	**Reported global reserves 2022 + Estimated conventional resources 2022 + estimated resources under sea** (million tonnes)	**Global Reserves and resources as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	39 500	10595%
Copper	697,3	3 206	460%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	38,7	7 492	19336%
Chromium	9,2	12 570	136603%
Nickel	173,1	669	386%
Lithium	118,9	114	96%
Cobalt	31,9	77	240%
Graphite	1 096,5	1 120	102%
Molybdenum	1,5	48	3206%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,00267	0,17	6472%
Vanadium	72,6	96	133%
Zirconium	2,61	*	
Germanium	4,16	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

QUANTITY OF METALS REQUIRED TO PHASE OUT FOSSIL FUELS, ASSUMING A 28 DAY POWER STORAGE BUFFER

Table A9. Total metal quantity required to manufacture one generation of technology units, with a 28 day power buffer for wind and solar to phase out fossil fuels compared to 2019 global production (Source: USGS 2024).

Metal	**Element**	**Total including 28 day buffer stationary power storage** (million tonnes)	**Global Metal Production 2019** (million tonnes)	**Years to produce metal at 2019 rates of production (assuming the 28 day buffer)** (years)
Steel & Iron	Fe	3 895	1 860	2,1
Cement	-	963	4 100	0,2
Aluminium	Al	372,8	63,14	5,9
Copper	Cu	6 165,2	24,20	254,8
Zinc	Zn	48,2	13,52	3,6
Magnesium Metal	Mg	0,5	1,12	0,4
Manganese	Mn	306,1	20,59	14,9
Chromium	Cr	9,2	37,50	0,2
Nickel	Ni	1 251,3	2,35	532,5
Lithium	Li	1 274,9	0,095	13 396,5
Cobalt	Co	293,0	0,126	2 325,4
Graphite ◆	C	11 473,6	2,73	4 203,9
Molybdenum	Mo	1,5	0,277	5,4
Silicon (Metallurgical)	Si	67,39	3,43	19,7
Silver	Ag	0,198	0,03	7,5
Platinum	Pt	0,0027	0,000190	14,1
Vanadium	V	924,54	0,096	9 628,5
Zirconium	Zr	2,61	1,34	2,0
Germanium	Ge	4,16	0,000130	32 024,3
Rare Earth Element				
Neodymium	Nd	1,14	0,024	47,8
Lanthanum	La	5,97	0,036	166,8
Praseodymium	Pr	0,265	0,0075	35,4
Dysprosium	Dy	0,212	0,0010	212,1
Terbium	Tb	0,023	0,00028	81,4
Hafnium	Hf	0,000293	0,000066	4,4
Yttrium	Y	0,000293	0,014	0,021

◆ Natural flake graphite and synthetic graphite was combined to estimate total production

Table A10. Total metal quantity required to manufacture one generation of technology units (28 day power storage buffer) to phase out fossil fuels compared to 2022 global reserves (Source: USGS 2024).

Metal	Total including 28 day buffer stationary power storage (million tonnes)	Reported Global Reserves 2022 (million tonnes)	Global Reserves and resources as a proportion of metals required to phase out fossil fuels (%)
Steel & Iron	3 895	180 000	4621,31%
Aluminium	372,8	32 000	8583,21%
Copper	6 165,2	880	14,27%
Zinc	48,2	250	518,77%
Magnesium Metal	0,5	*	
Manganese	306,1	1 500	490,05%
Chromium	9,2	570	6194,39%
Nickel	1 251,3	95,0	7,59%
Lithium	1 274,9	22,0	1,73%
Cobalt	293,0	7,6	2,59%
Graphite	11 473,6	320	2,79%
Molybdenum	1,5	16,0	1068,82%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	0,53	267,81%
Platinum	0,0027	0,070	2618,80%
Vanadium	924,5	24,0	2,60%
Zirconium	2,6	70,0	2677,76%
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A11. Total metal quantity required to manufacture one generation of technology units (28 day power storage buffer) to phase out fossil fuels compared to 2022 global reserves + resources on land (Source: USGS 2024).

Metal	**Total including 28 days buffer stationary power storage** (million tonnes)	**Reported global reserves 2022 + Estimated conventional resources 2022** (million tonnes)	**Global Reserves and resources as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	980 000	25160,5%
Aluminium	372,8	107 000	28700,1%
Copper	6 165,2	2 980	48,3%
Zinc	48,2	2 150	4461,4%
Magnesium Metal	0,5	*	
Manganese	306,1	7 492	2447,7%
Chromium	9,2	12 570	136602,5%
Nickel	1 251,3	395	31,6%
Lithium	1 274,9	111	8,7%
Cobalt	293,0	33	11,1%
Graphite	11 473,6	1 120	9,8%
Molybdenum	1,5	36	2404,9%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,00267	0,170	6359,9%
Vanadium	924,5	87	9,4%
Zirconium	2,61	*	
Germanium	4,16	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A12. Total metal quantity required to manufacture one generation of technology units (28 day power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land + estimated resources under the sea (Source: USGS 2024).

Metal	**Total metal required produce one generation of technology units to phase out fossil fuels (28 day buffer)** (million tonnes)	**Reported global reserves 2022 + Estimated conventional resources 2022 + estimated resources under sea** (million tonnes)	**Global Reserves and resources as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	39 500	10595%
Copper	6 165,2	3 206	52%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	306,1	7 492	
Chromium	9,2	12 570	136603%
Nickel	1 251,3	669	53%
Lithium	1 274,9	114	9%
Cobalt	293,0	76,6	26%
Graphite	11 473,6	1 120	10%
Molybdenum	1,5	48,0	3206%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,00267	0,173	6472%
Vanadium	924,5	96,4	10%
Zirconium	2,61	*	
Germanium	4,16	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

QUANTITY OF METALS REQUIRED TO PHASE OUT FOSSIL FUELS, ASSUMING A 12 WEEK POWER STORAGE BUFFER

Table A13. Total metal quantity required to manufacture one generation of technology units, with a 12 week power buffer for wind and solar to phase out fossil fuels compared to 2019 global production (Source: USGS 2024).

Metal	Element	Total including 12 week buffer stationary power storage (million tonnes)	Global Metal Production 2019 (million tonnes)	Years to produce metal at 2019 rates of production (assuming the 12 week buffer) (years)
Steel & Iron	Fe	3 895	1 860	2,1
Cement	-	963	4 100	0,2
Aluminium	Al	372,82	63,14	5,9
Copper	Cu	18 033,50	24,20	745,2
Zinc	Zn	48,19	13,52	3,6
Magnesium Metal	Mg	0,50	1,12	0,4
Manganese	Mn	886,37	20,59	43,0
Chromium	Cr	9,20	37,50	0,2
Nickel	Ni	4 420,56	2,35	1 881,0
Lithium	Li	3 784,26	0,10	39 763,1
Cobalt	Co	859,86	0,13	6 823,2
Graphite ♦	C	36 083,37	2,73	13 220,7
Molybdenum	Mo	1,50	0,28	5,4
Silicon (Metallurgical)	Si	67,39	3,43	19,7
Silver	Ag	0,198	0,0263	7,5
Platinum	Pt	0,0027	0,00019	14,1
Vanadium	V	2 773,61	0,10	28 885,4
Zirconium	Zr	2,61	1,34	2,0
Germanium	Ge	4,16	0,000130	32 024,3
Rare Earth Element				
Neodymium	Nd	1,14	0,024	47,8
Lanthanum	La	5,97	0,036	166,8
Praseodymium	Pr	0,265	0,0075	35,4
Dysprosium	Dy	0,212	0,0010	212,1
Terbium	Tb	0,0228	0,000280	81,4
Hafnium	Hf	0,000293	0,000066	4,4
Yttrium	Y	0,000293	0,014	0,021

♦ Natural flake graphite and synthetic graphite was combined to estimate total production

Table A14. Total metal quantity required to manufacture one generation of technology units (12 week power storage buffer) to phase out fossil fuels compared to 2022 reported global reserves (Source: USGS 2024).

Metal	**Total including 12 week buffer stationary power storage** (million tonnes)	**Reported Global Reserves 2022** (million tonnes)	**Global Reserves as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	180 000	4621,3%
Aluminium	372,8	32 000	8583,2%
Copper	18 033,5	880	4,9%
Zinc	48,2	250	518,8%
Magnesium Metal	0,5	*	
Manganese	886,4	1 500	169,2%
Chromium	9,2	570 †	
Nickel	4 420,6	95,0	2,1%
Lithium	3 784,3	22,0	0,6%
Cobalt	859,9	7,6	0,9%
Graphite	36 083,4	320	0,9%
Molybdenum	1,5	16,0	1068,8%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	0,530	267,8%
Platinum	0,00267	0,070	2618,8%
Vanadium	2 773,6	24,0	0,9%
Zirconium	2,61	70,0	2677,8%
Germanium	4,16	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,0228	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A15. Total metal quantity required to manufacture one generation of technology units (12 week power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land (Source: USGS 2024).

Metal	**Total metal required produce one generation of technology units to phase out fossil fuels (12 week buffer)** (million tonnes)	**Reported global reserves 2022 + Estimated conventional resources 2022** (million tonnes)	**Global Reserves and resources as a proportion of metals required to phase out fossil fuels** (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	107 000	28700%
Copper	18 033	2 980	16,5%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	886,4	1 500	169%
Chromium	9,2	12 570	136603%
Nickel	4 420,6	395	8,9%
Lithium	3 784,3	111	2,9%
Cobalt	859,9	32,6	3,8%
Graphite	36 083,4	1 120	3,1%
Molybdenum	1,5	36,0	2405%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,00267	0,170	6360%
Vanadium	2 773,6	87,0	3,1%
Zirconium	2,6	*	
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,023	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

Table A16. Total metal quantity required to manufacture one generation of technology units (12 weeks power storage buffer) to phase out fossil fuels compared to 2022 global reserves + estimated resources on land + estimated undersea resources (Source: USGS 2024).

Metal	Total metal required produce one generation of technology units to phase out fossil fuels (12 week buffer) (million tonnes)	Reported global reserves 2022 + Estimated conventional resources 2022 + estimated resources under sea (million tonnes)	Global Reserves and resources as a proportion of metals required to phase out fossil fuels (%)
Steel & Iron	3 895	980 000	25160%
Aluminium	372,8	39 500	10595%
Copper	18 033,5	3 206	17,8%
Zinc	48,2	2 150	4461%
Magnesium Metal	0,5	*	
Manganese	886,4	7 492	845%
Chromium	9,2	12 570	136603%
Nickel	4 420,6	669	15,1%
Lithium	3 784,3	114	3,0%
Cobalt	859,9	76,6	8,9%
Graphite	36 083,4	1 120	3,1%
Molybdenum	1,5	48,0	3206%
Silicon (Metallurgical)	67,4	*	
Silver	0,198	*	
Platinum	0,0027	0,173	6472%
Vanadium	2 773,6	96,4	3,5%
Zirconium	2,6	*	
Germanium	4,2	*	
Rare Earth Element			
Neodymium	1,14	*	
Lanthanum	5,97	*	
Praseodymium	0,265	*	
Dysprosium	0,212	*	
Terbium	0,0228	*	
Hafnium	0,000293	*	
Yttrium	0,000293	*	

ANNEX B.
SENSITIVITY ANALYSIS PART II

Annex B shows the tables and charts of the outcomes of each of the scenarios examined in the sensitivity study. This is the second part of the sensitivity study, where part one was shown at the end of (Michaux 2024).

Table B1. Sensitivity analysis, Scenarios A to E.

Application task, assuming the 28 day power storage buffer Sensitivity Scenario	Base Case	If EV's were reduced by 50% A	If EV's were reduced by 90% B	If EV's increased by 200% C	If Class 8 trucks were also EV D	If buses were increased 300% E
Total additional power required (TWh)	48 939,8	46 762,8	45 021,2	53 293,9	43 925,5	51 413,7
Copper (million tonnes)	6 165,2	5 835,8	5 572,3	6 682,9	5 573,4	6 425,8
Nickel (million tonnes)	1 251,3	1 177,9	1 118,7	1 400,1	1 132,6	1 313,1
Lithium (million tonnes)	1 274,9	1 211,7	1 161,0	1 401,7	1 151,7	1 343,2
Cobalt (million tonnes)	293,0	277,4	264,8	324,6	264,6	307,9
Graphite (million tonnes)	11 473,6	10 913,8	10 465,8	12 593,8	10 362,6	12 090,5
Vanadium (million tonnes)	924,5	883,4	850,5	1 006,8	829,8	971,3

Table B2. Sensitivity analysis, Scenarios F to K.

Application task, assuming the 28 day power storage buffer Sensitivity Scenario	If trucks were reduced by 50% F	If trucks were increased by 200% G	If the rail network increased by 300% H	If maritime shipping was reduced by 10% I	If maritime shipping was reduced by 50% J	If maritime shipping was reduced by 90% K
Total additional power required (TWh)	45 101,8	56 271,3	50 526,0	46 887,7	45 689,5	44 491,4
Copper (million tonnes)	5 655,3	7 031,0	6 293,7	5 875,3	5 727,7	5 580,1
Nickel (million tonnes)	1 159,4	1 428,9	1 290,3	1 202,5	1 173,6	1 144,7
Lithium (million tonnes)	1 176,6	1 463,0	1 315,7	1 222,4	1 191,7	1 161,0
Cobalt (million tonnes)	270,9	335,6	302,3	281,2	274,3	267,4
Graphite (million tonnes)	10 586,2	13 169,4	11 840,7	10 999,2	10 722,1	10 445,0
Vanadium (million tonnes)	852,1	1 063,1	954,5	885,8	863,2	840,5

Table B3. Sensitivity analysis, Scenarios L to R.

Application task, assuming the 28 day power storage buffer	If Ammonia production reduced by 50%	If Ammonia production reduced by 90%	If Ammonia production increased by 200%	If Steel production reduced by 50%	If Steel production reduced by 90%	If Steel production increased by 200%	If Steel production increased by 300%
Sensitivity Scenario	L	M	N	O	P	Q	R
Total additional power required (TWh)	47 666,9	46 648,6	51 485,7	45 470,2	42 694,5	55 879,0	76 696,6
Copper (million tonnes)	5 971,3	5 845,8	6 441,6	5 700,7	5 358,8	6 982,7	9 546,7
Nickel (million tonnes)	1 221,3	1 196,7	1 313,4	1 168,3	1 101,3	1 419,5	1 921,8
Lithium (million tonnes)	1 242,4	1 216,3	1 340,3	1 186,0	1 114,9	1 452,9	1 986,6
Cobalt (million tonnes)	285,8	279,9	307,9	273,0	257,0	333,3	453,9
Graphite (million tonnes)	11 179,4	10 943,9	12 062,6	10 671,4	10 029,4	13 078,7	17 893,3
Vanadium (million tonnes)	900,5	881,3	972,7	859,0	806,6	1 055,7	1 449,0

Table B4. Sensitivity analysis, Scenarios S to W.

Application task, assuming the 28 day power storage buffer	If building heating reduced by 50%	If conventional electrical power reduced by 50%	If conventional electrical power reduced by 90%	If conventional electrical power increased by 200%	If conventional electrical power increased by 300%
Sensitivity Scenario	S	T	U	V	W
Total additional power required (TWh)	47 531,8	40 396,8	33 562,3	66 025,9	83 112,0
Copper (million tonnes)	5 954,6	5 075,8	4 234,1	8 232,4	10 336,9
Nickel (million tonnes)	1 218,0	1 045,8	880,9	1 664,3	2 076,6
Lithium (million tonnes)	1 238,9	1 056,0	880,8	1 713,1	2 151,1
Cobalt (million tonnes)	285,0	243,7	204,1	392,1	491,0
Graphite (million tonnes)	11 148,2	9 498,0	7 917,4	15 425,4	19 377,0
Vanadium (million tonnes)	898,0	763,2	634,1	1 247,4	1 570,2

Table B5. Sensitivity analysis, Scenarios Alpha to Gamma.

Application task, assuming the 28 day power storage buffer **Sensitivity Scenario**	**If solar panels increased their operating hours by 200%** Alpha	**If wind turbines increased their operating hours by 200%** Beta	**If the energy mix was altered to 50% solar PV and 50% wind (Table B1)** Gamma
Total additional power required (TWh)	48 939,8	48 939,8	48 939,8
Copper (million tonnes)	6 104,0	6 106,4	7 960,2
Nickel (million tonnes)	1 252,0	1 250,4	1 601,6
Lithium (million tonnes)	1 275,0	1 275,0	1 656,9
Cobalt (million tonnes)	293,1	293,1	379,4
Graphite (million tonnes)	11 473,8	11 473,8	14 919,2
Vanadium (million tonnes)	924,6	924,6	1 206,0

Table B6. Sensitivity analysis, Scenarios Delta to Zeta.

Application task, assuming the 28 day power storage buffer **Sensitivity Scenario**	**If the energy mix was altered to nuclear power increasing to 10%, reducing wind and solar** Delta	**If the energy mix was altered to nuclear power increasing to 20%, reducing wind and solar** Epsilon	**If the energy mix was altered to nuclear power increasing to 30%, reducing wind and solar** Zeta
Total additional power required (TWh)	48 939,8	48 939,8	48 939,8
Copper (million tonnes)	5 932,1	5 147,3	4 362,4
Nickel (million tonnes)	1 214,0	1 062,0	910,0
Lithium (million tonnes)	1 234,1	1 070,5	906,8
Cobalt (million tonnes)	283,9	246,9	210,0
Graphite (million tonnes)	11 105,2	9 628,8	8 152,4
Vanadium (million tonnes)	894,5	773,9	653,3

Table B7. Sensitivity analysis, Scenarios Eta to Mu.

Application task, assuming the 28 day power storage buffer **Sensitivity Scenario**	**80% of the batteries needed are LFP** Eta	**80% of EV batteries needed are ASSB solid state** Theta	**Hybrid Scenario Mu** Mu
Total additional power required (TWh)	48 939,8	48 939,8	48 988,5
Copper (million tonnes)	6 544,5	6 142,8	5 163,1
Nickel (million tonnes)	964,4	1 245,4	1 059,6
Lithium (million tonnes)	1 317,5	1 274,3	1 072,6
Cobalt (million tonnes)	223,6	291,6	246,6
Graphite (million tonnes)	12 238,3	11 428,0	9 659,8
Vanadium (million tonnes)	702,7	924,6	774,6

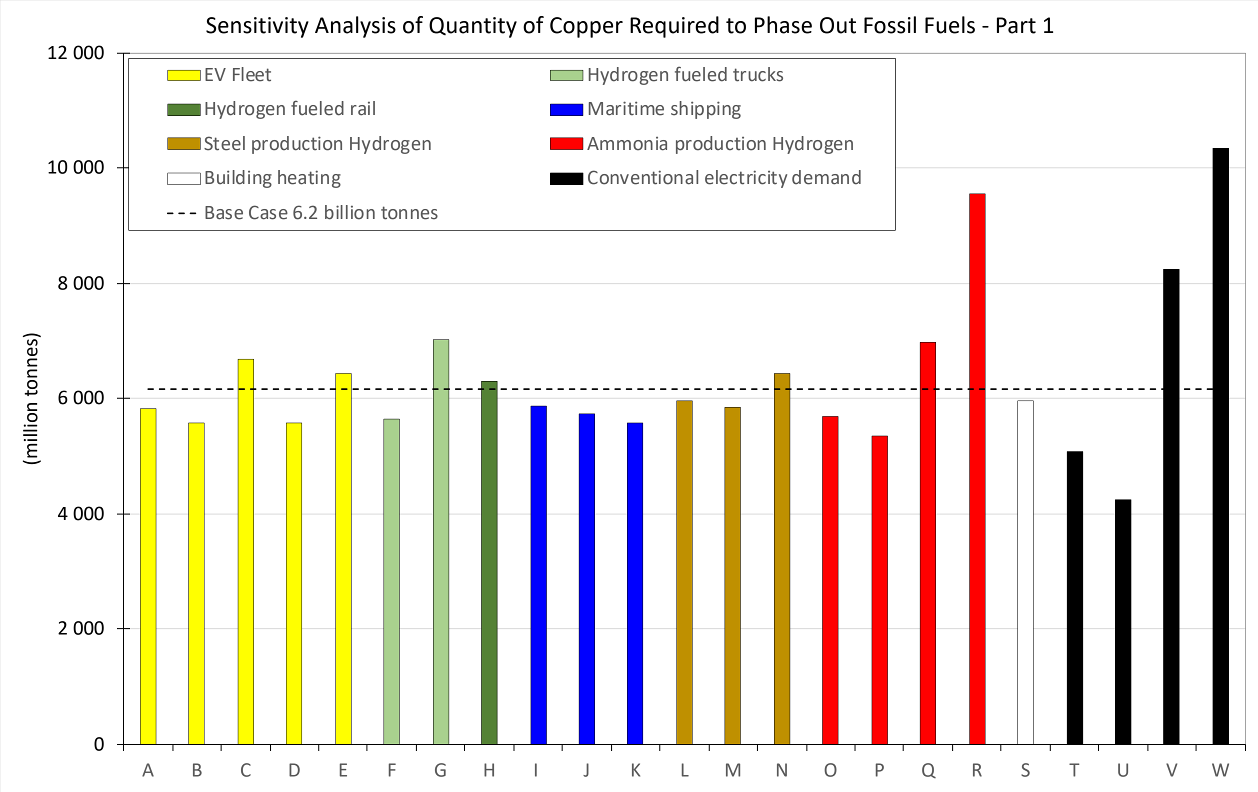

Fig. B1. Sensitivity Analysis of Quantity of Copper Required to Phase Out Fossil Fuels – Part 1.

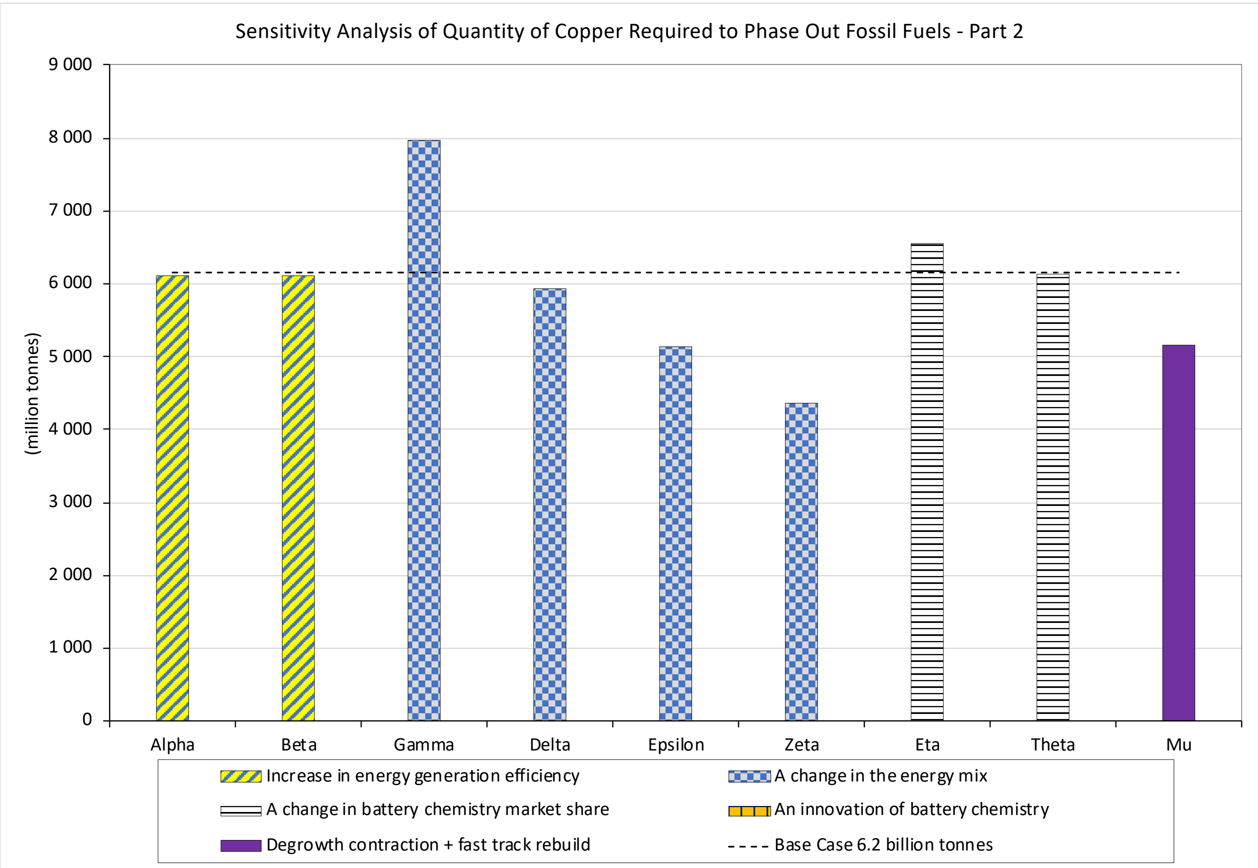

Fig. B2. Sensitivity Analysis of Quantity of Copper Required to Phase Out Fossil Fuels – Part 2.

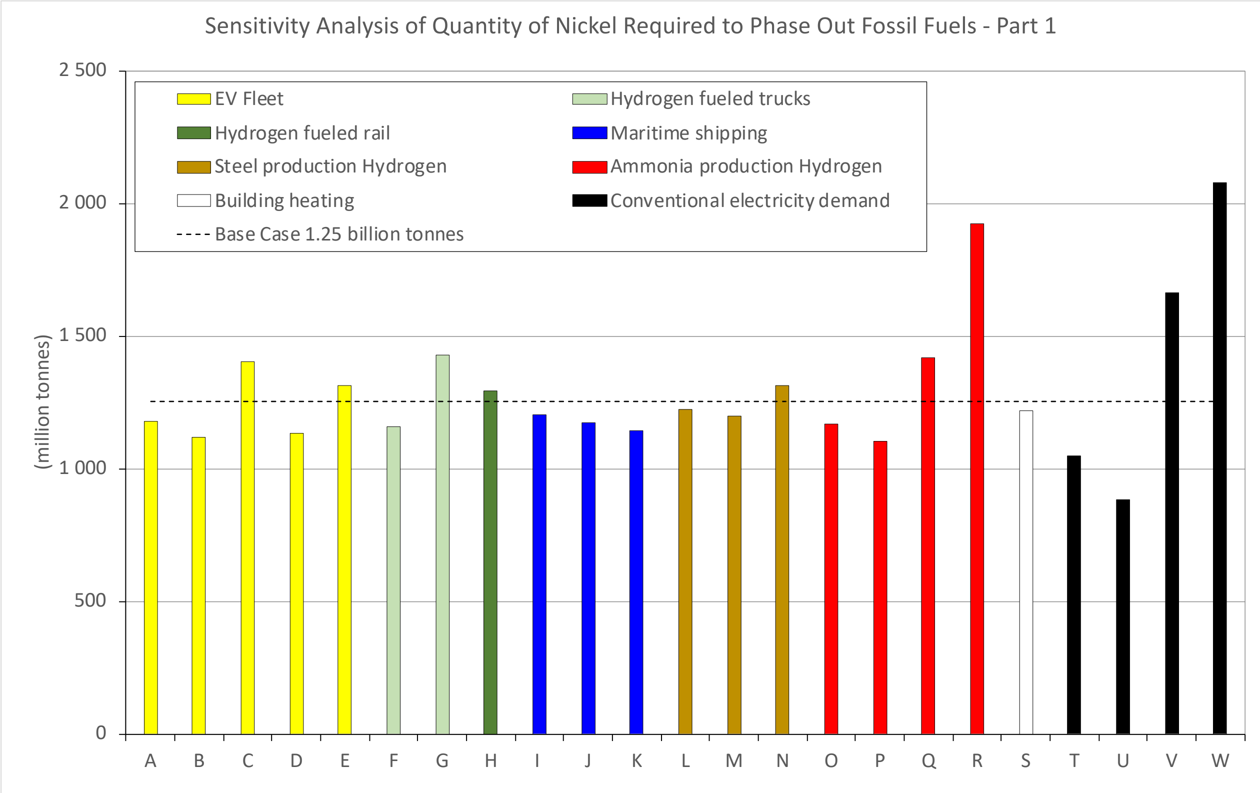

Fig. B3. Sensitivity Analysis of Quantity of Nickel Required to Phase Out Fossil Fuels – Part 1.

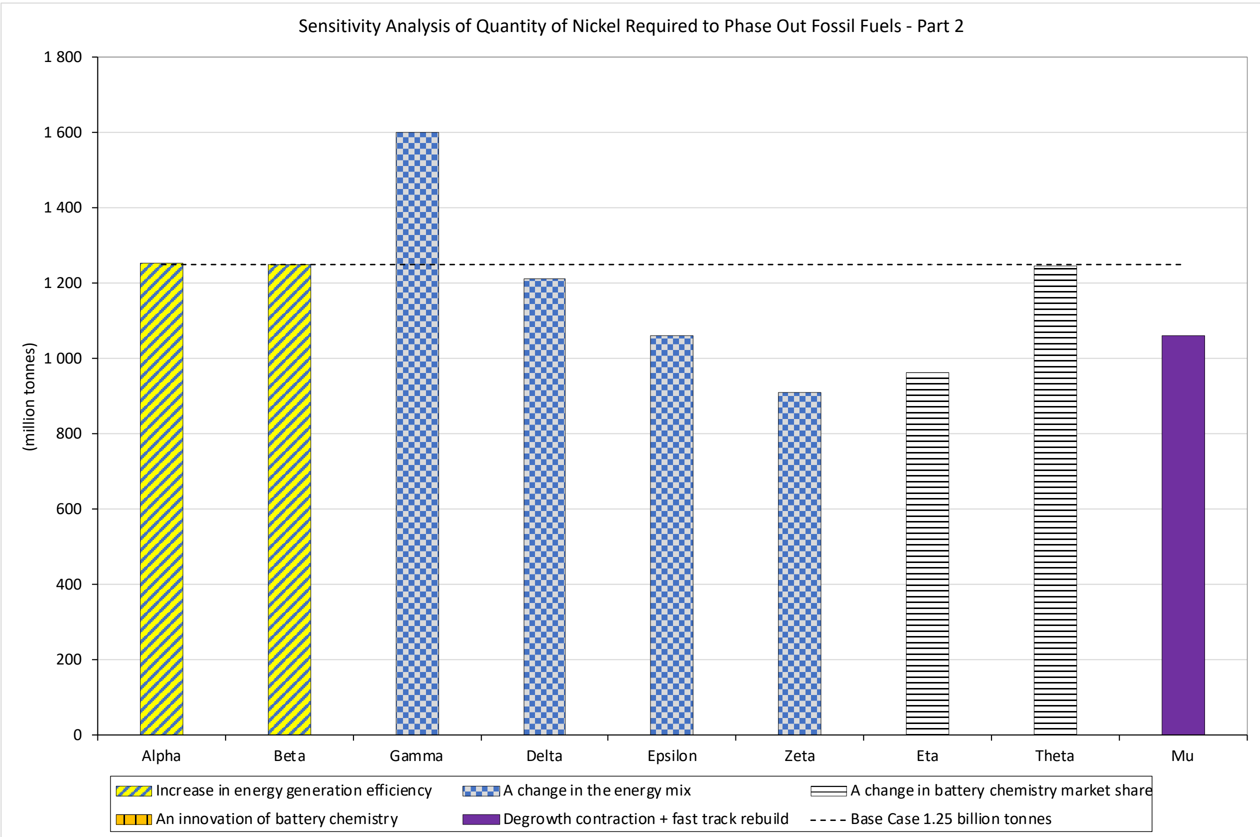

Fig. B4. Sensitivity Analysis of Quantity of Nickel Required to Phase Out Fossil Fuels – Part 2.

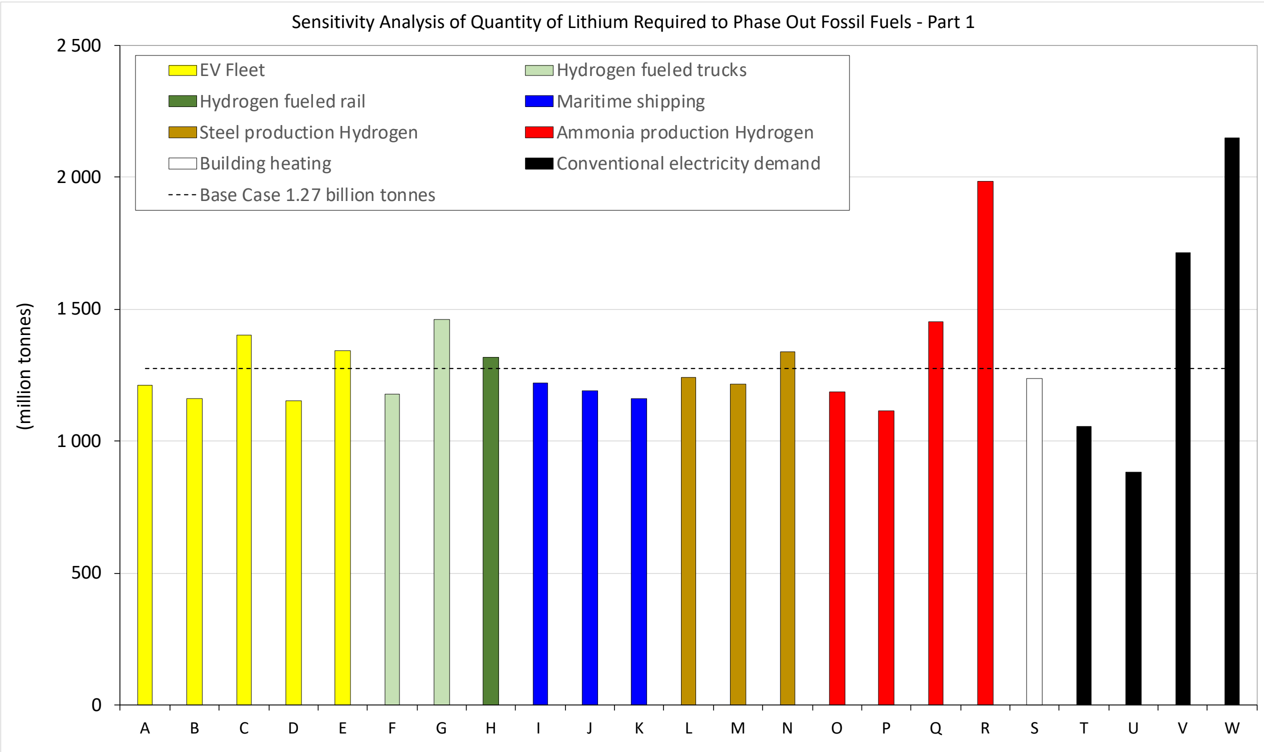

Fig. B5. Sensitivity Analysis of Quantity of Lithium Required to Phase Out Fossil Fuels – Part 1.

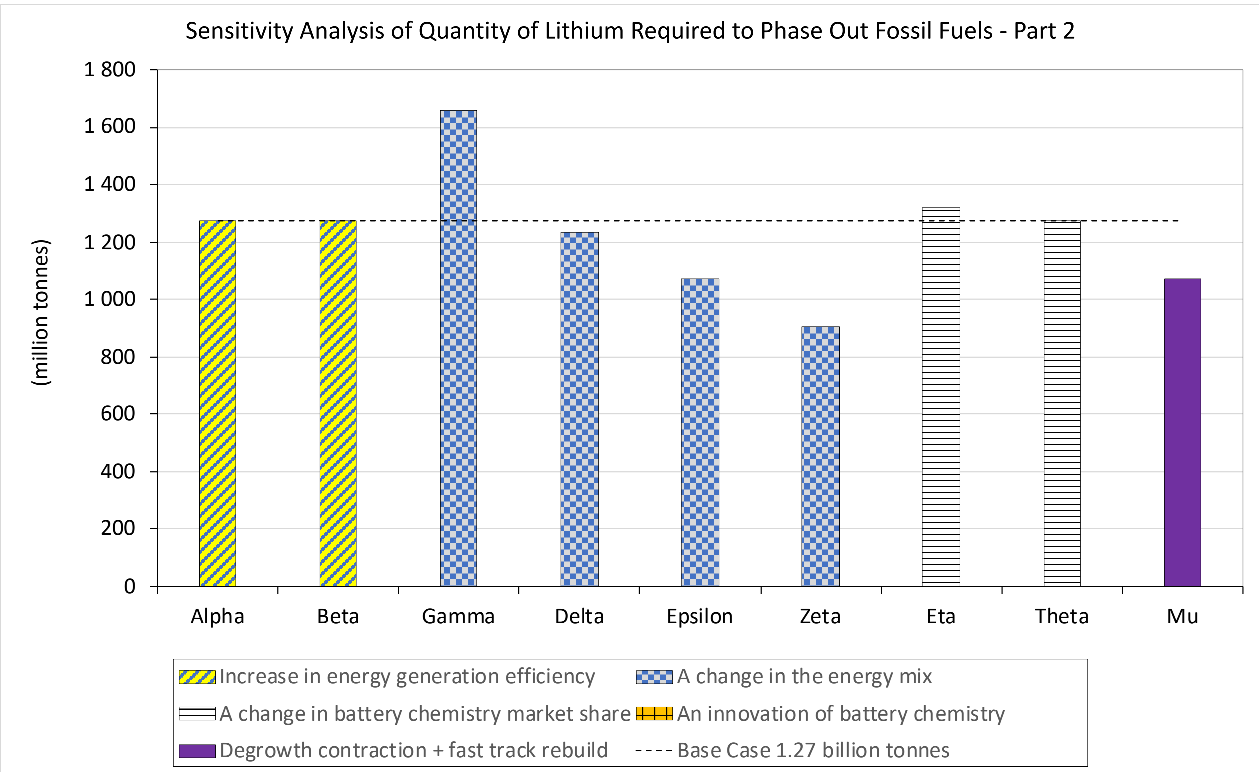

Fig. B6. Sensitivity Analysis of Quantity of Lithium Required to Phase Out Fossil Fuels – Part 2.

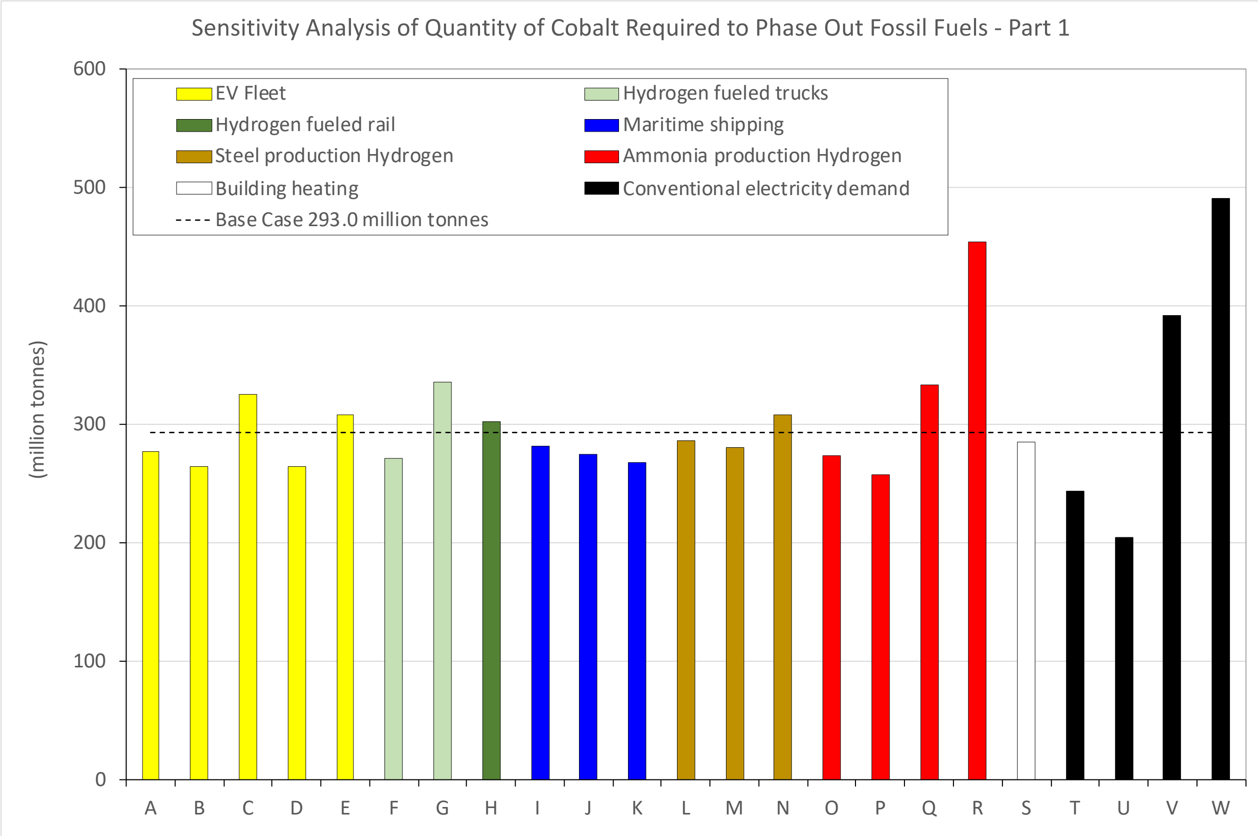

Fig. B7. Sensitivity Analysis of Quantity of Cobalt Required to Phase Out Fossil Fuels – Part 1.

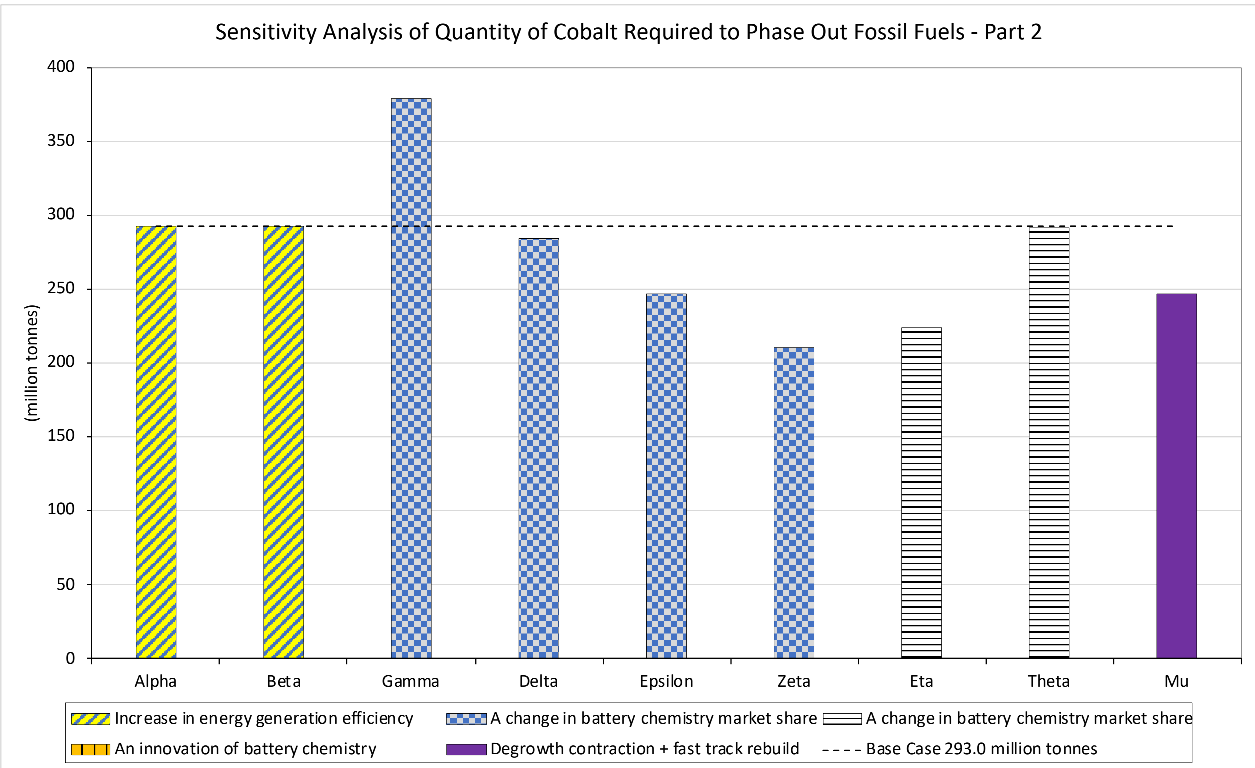

Fig. B8. Sensitivity Analysis of Quantity of Cobalt Required to Phase Out Fossil Fuels – Part 2.

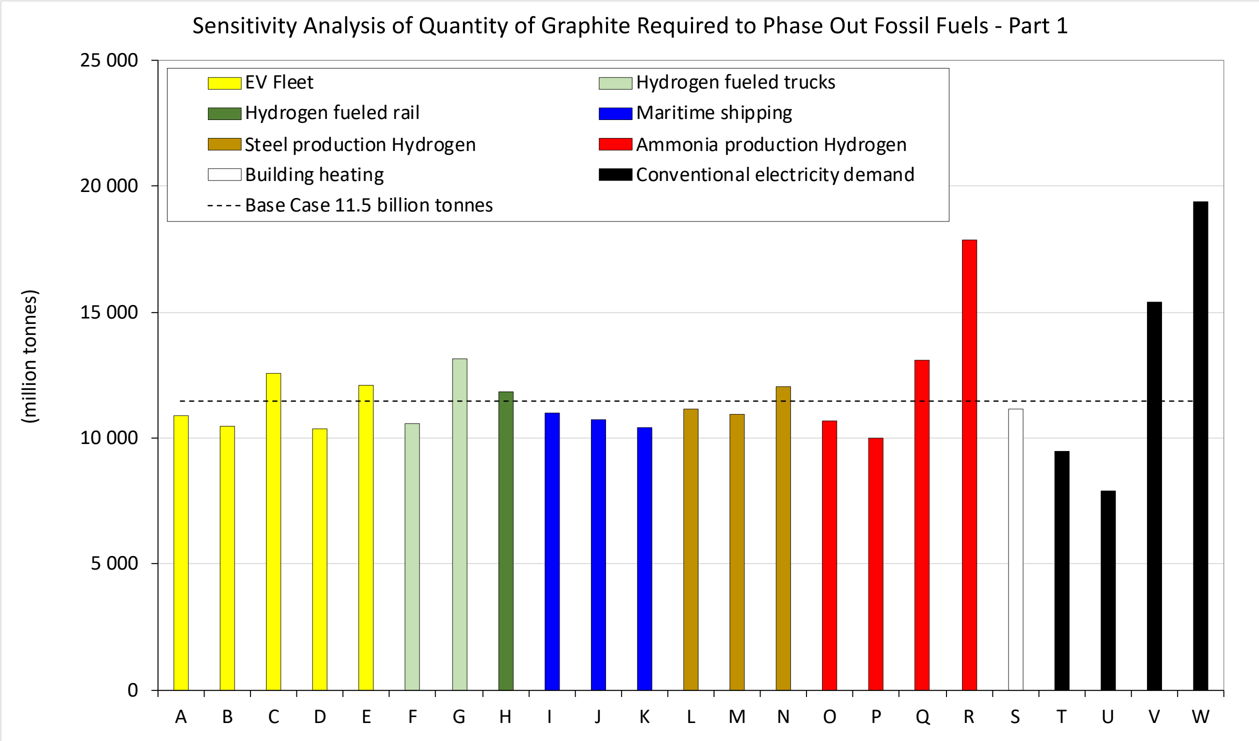

Fig. B9. Sensitivity Analysis of Quantity of Graphite Required to Phase Out Fossil Fuels – Part 1.

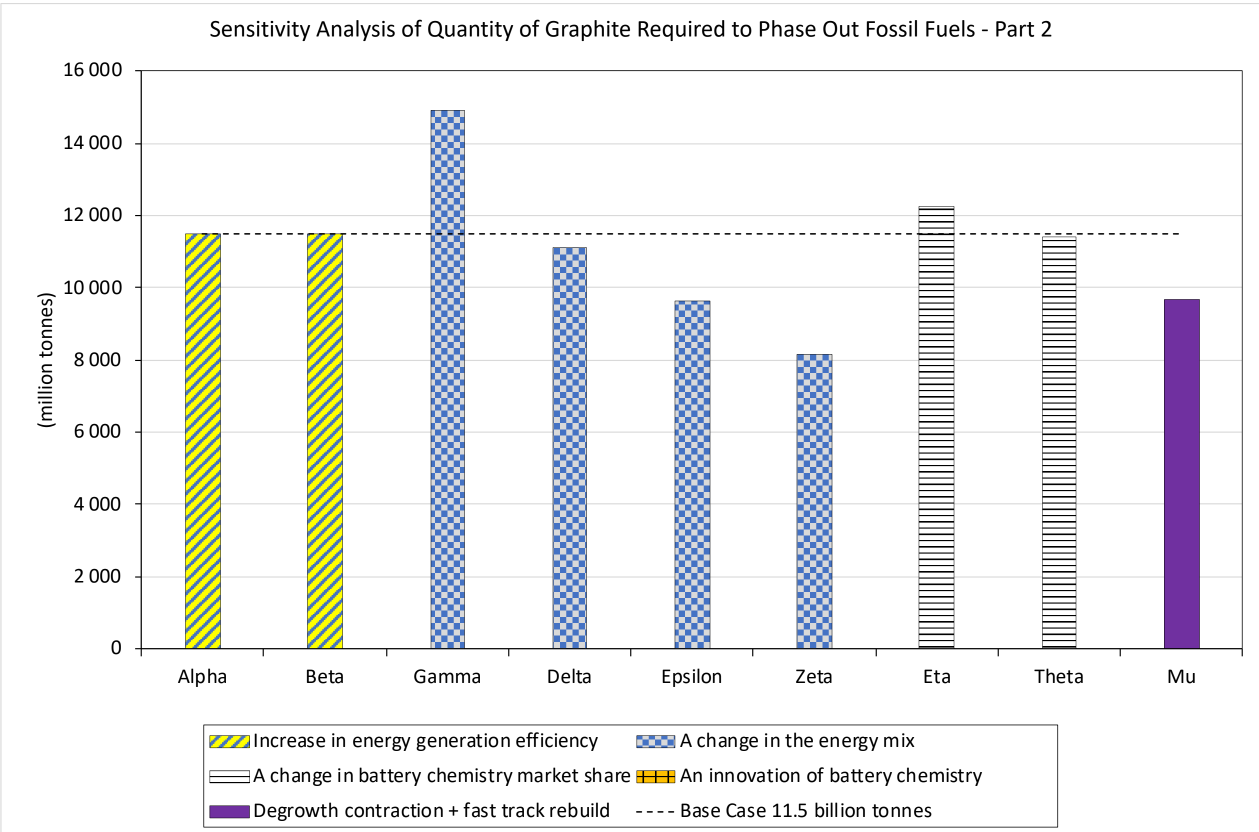

Fig. B10. Sensitivity Analysis of Quantity of Graphite Required to Phase Out Fossil Fuels – Part 2.

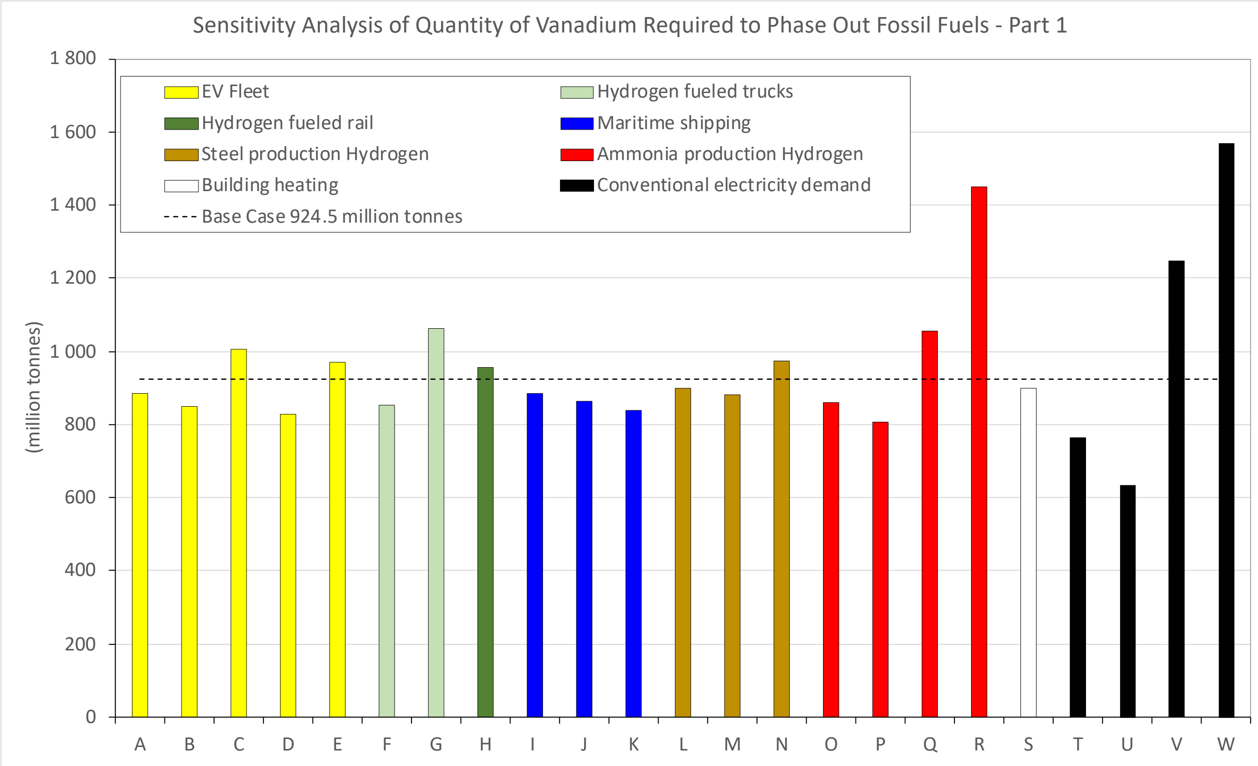

Fig. B11. Sensitivity Analysis of Quantity of Vanadium Required to Phase Out Fossil Fuels – Part 1.

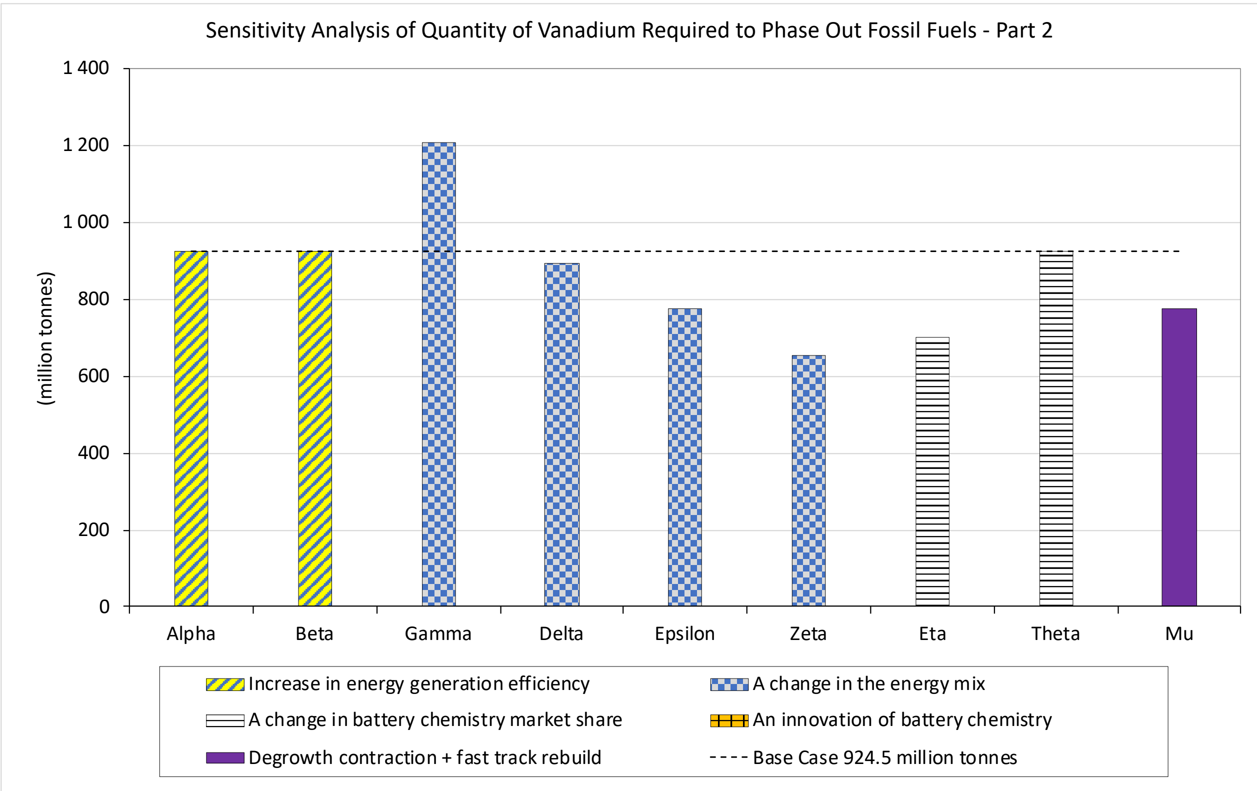

Fig. B12. Sensitivity Analysis of Quantity of Vanadium Required to Phase Out Fossil Fuels – Part 2.

Table B8. Sensitivity analysis percent change from baseline study in this paper – Scenarios A to E.

Metal (million tonnes)	**If EV's were reduced by 50%**	**If EV's were reduced by 90%**	**If EV's increased by 200%**	**If Class 8 trucks were also EV**	**If buses were increased 300%**
	A	B	C	D	E
Copper	-5,34%	-9,62%	8,40%	-9,60%	4,23%
Nickel	-5,87%	-10,60%	11,89%	-9,49%	4,94%
Lithium	-4,96%	-8,94%	9,94%	-9,67%	5,36%
Cobalt	-5,35%	-9,65%	10,78%	-9,70%	5,08%
Graphite	-4,88%	-8,78%	9,76%	-9,68%	5,38%
Vanadium	-4,44%	-8,00%	8,90%	-10,24%	5,06%

Table B9. Sensitivity analysis percent change from baseline study in this paper – Scenarios F to K.

Metal (million tonnes)	**If trucks were reduced by 50%**	**If trucks were increased by 200%**	**If the rail network increased by 300%**	**If maritime shipping was reduced by 10%**	**If maritime shipping was reduced by 50%**	**If maritime shipping was reduced by 90%**
	F	G	H	I	J	K
Copper	-8,27%	14,04%	2,08%	-4,70%	-7,10%	-9,49%
Nickel	-7,35%	14,19%	3,11%	-3,90%	-6,22%	-8,53%
Lithium	-7,71%	14,75%	3,19%	3,19%	-4,12%	-6,53%
Cobalt	-7,56%	14,52%	3,16%	-4,03%	-6,39%	-8,76%
Graphite	-7,73%	14,78%	3,20%	-4,13%	-6,55%	-8,97%
Vanadium	-7,84%	14,99%	3,25%	-4,19%	-6,64%	-9,09%

Table B10. Sensitivity analysis percent change from baseline study in this paper – Scenarios L to R.

Metal (million tonnes)	**If Ammonia production reduced by 50%**	**If Ammonia production reduced by 90%**	**If Ammonia production increased by 200%**	**If Steel production reduced by 50%**	**If Steel production reduced by 90%**	**If Steel production increased by 200%**	**If Steel production increased by 500%**
	L	M	N	O	P	Q	R
Copper	-3,15%	-5,18%	4,48%	-7,53%	-13,08%	13,26%	54,85%
Nickel	-2,40%	-4,37%	4,96%	-6,64%	-11,99%	13,43%	53,58%
Lithium	-2,56%	-4,60%	5,12%	-6,97%	-12,55%	13,96%	55,82%
Cobalt	-2,49%	-4,50%	5,06%	-6,83%	-12,31%	13,74%	54,88%
Graphite	-2,56%	-4,62%	5,13%	-6,99%	-12,59%	13,99%	55,95%
Vanadium	-2,60%	-4,68%	5,21%	-7,09%	-12,76%	14,18%	56,72%

Table B11. Sensitivity analysis percent change from baseline study in this paper – Scenarios S to W.

Metal (million tonnes)	**If building heating reduced by 50%**	**If conventional electrical power reduced by 50%**	**If conventional electrical power reduced by 90%**	**If conventional electrical power increased by 200%**	**If conventional electrical power increased by 300%**
	S	T	U	V	W
Copper	-3,42%	-17,67%	-31,32%	33,53%	67,67%
Nickel	-2,66%	-16,42%	-29,60%	33,00%	65,95%
Lithium	-2,83%	-17,17%	-30,92%	34,36%	68,72%
Cobalt	-2,75%	-16,85%	-30,36%	33,79%	67,56%
Graphite	-2,84%	-17,22%	-31,00%	34,44%	68,88%
Vanadium	-2,87%	-17,45%	-31,42%	34,92%	69,83%

Table B12. Sensitivity analysis percent change from baseline study in this paper – Scenarios Alpha to Gamma.

Metal (million tonnes)	**If solar panels increased their operating hours by 200%** Alpha	**If wind turbines increased their operating hours by 200%** Beta	**If the energy mix was altered to 50% solar PV and 50% wind** Gamma
Copper	-0,99%	-0,95%	29,12%
Nickel	0,0526%	-0,07%	27,99%
Lithium	0,00%	0,000%	29,96%
Cobalt	0,0285%	0,028%	29,47%
Graphite	0,0017%	0,002%	30,03%
Vanadium	0,0045%	0,004%	30,45%

Table B13. Sensitivity analysis percent change from baseline study in this paper – Scenarios Delta to Zeta.

Metal (million tonnes)	**If the energy mix was altered to nuclear power increasing to 10%, reducing wind and solar** Delta	**If the energy mix was altered to nuclear power increasing to 20%, reducing wind and solar** Epsilon	**If the energy mix was altered to nuclear power increasing to 30%, reducing wind and solar** Zeta
Copper	-3,78%	-16,51%	-29,24%
Nickel	-2,98%	-15,13%	-27,28%
Lithium	-3,20%	-16,04%	-28,88%
Cobalt	-3,12%	-15,74%	-28,35%
Graphite	-3,21%	-16,08%	-28,95%
Vanadium	-3,25%	-16,30%	-29,34%

Table B14. Sensitivity analysis percent change from baseline study in this paper – Scenarios Eta to Mu.

Metal (million tonnes)	**80% of the batteries needed are LFP** Eta	**80% of EV batteries needed are ASSB solid state** Theta	**Hybrid Scenario Mu** Mu
Copper	6,15%	-0,36%	-16,25%
Nickel	-22,93%	-0,48%	-15,32%
Lithium	3,34%	-0,06%	-15,87%
Cobalt	-23,71%	-0,50%	-15,86%
Graphite	6,66%	-0,40%	-15,81%
Vanadium	-24,00%	0,00%	-16,21%

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This study examines the task of phasing out fossil fuels, at a global-scale, using a bottom-up approach. The number of vehicles, their activity, and the annual extra electricity required if 100% of the system was non-fossil fuel, was investigated. The number of new power stations needed, if all were non-fossil, was estimated. The results show an annual extra 48 939.8 TWh are needed; and 796 709 new average sized non-fossil fuel power plants are required to be commissioned. The quantity of raw materials required, compared to global mining production, recycling potential, mineral reserves, and mineral resources are also presented.

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