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ABSTRACT

The need for deep decarbonisation in the energy intensive basic materials industry is increasingly recognised. In light of the vast future potential for renewable electricity the implications of electrifying the production of basic materials in the European Union is explored in a what-if thought-experiment. Production of steel, cement, glass, lime, petrochemicals, chlorine and ammonia required 125 terawatt-hours of electricity and 851 terawatt-hours of fossil fuels for energetic purposes and 671 terawatt-hours of fossil fuels as feedstock in 2010. The resulting carbon dioxide emissions were equivalent to 9% of total greenhouse gas emissions in EU28. A complete shift of the energy demand as well as the resource base of feedstocks to electricity would result in an electricity demand of 1 713 terawatt-hours about 1 200 terawatt-hours of which would be for producing hydrogen and hydrocarbons for feedstock and energy purposes. With increased material efficiency and some share of bio-based materials and biofuels the electricity demand can be much lower. Our analysis suggest that electrification of basic materials production is technically possible but could have major implications on how the industry and the electric systems interact. It also entails substantial changes in relative prices for electricity and hydrocarbon fuels.

KEYWORDS

Energy-intensive industry, decarbonisation, breakthrough technologies, electrification of energy demand, basic materials production, scenario analysis

1. INTRODUCTION

The EU objective to reduce greenhouse gas emissions by 80 to 95 per cent by 2050 relative to 1990 includes a suggested industry sector ambition of 83 to 87 per cent reduction [1]. The reduction of greenhouse gases (GHGs) needs to continue down to zero emission in 2060-2070 if EU is to take it responsibility in meeting the <2 °C target agreed in Paris [2].

The three main categories of technical options for reducing carbon dioxide emissions from materials production are (i) improved material efficiency (ii) improved energy efficiency, and (iii) less carbon intensive energy supply or carbon capture and storage (CCS) [3].

The need for energy intensive processing of ores and minerals to usable materials can be reduced through increased use of recycled materials and increased material efficiency via e.g., lighter constructions, extending the life of products, and design of products that are easier to maintain, repair, upgrade, remanufacture. Such measures are central to the circular economy [4] and they are highlighted as important in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC AR5) but the resulting mitigation potential is not quantified [3]. However, even in a resource efficient circular economy there would still be a need to produce virgin materials to replenish the system and for special applications that require high quality virgin materials, e.g., food packaging. There will also be a need to produce new materials as some are consumed or dissipate (e.g., nitrogen fertiliser for agriculture or argon gas for super-insulating windows) and to close the loop on carbon dioxide through carbon capture and use (CCU).

Energy efficiency through applying best available technology in industry can reduce the energy intensity by an estimated 25 % and by an additional 20 % at the most through innovation before approaching technological limits in some energy intensive industries [3]. Ahashi et al. [5] simulate a savings potential of 35% for industry globally by 2030 vs. frozen 2005 efficiency, a result which they note is in line with other studies.

For a deep decarbonisation, material- and energy efficiency will help but will not be able to deliver the reductions needed. For deep decarbonization it is also necessary to focus on the processing of feedstock to usable materials which includes the reduction of process related emissions (e.g. from calcination of limestone to clinker or reduction of iron ore to iron). The main options for deep decarbonisation of the processing step in materials production are shifting to low carbon energy supply via either biomass, nuclear energy, or renewable electricity and/or to use CCS [53].

CCS and bioenergy are the main options that have been assessed so far for deep decarbonisation of energy intensive industries. In the four key sub-sectors (cement, steel, chemicals and pulp and paper) that are assessed in greater detail in IPCC AR5, CCS is essentially the only option presented that can reduce carbon dioxide (CO_2) emissions in the range of 70-90 % [3]. Results along the same lines can be found in the IEA Energy Technology Perspective scenario [6] where most of the 3 $GtCO_2$ equivalent emission reductions when comparing the 4DS and 2DS low demand scenarios result from increased energy efficiency and CCS. Fuel and feedstock switching account only for about 10 % (300 MtCO2-eq) of the reduction. Similar assumptions are made in scenario studies for the EU [1] Italy [8] and the UK [9]. The electrification option is also largely overlooked in a recent roadmap for renewable energy in manufacturing up to 2030 [10] which emphasises that “currently, biomass offers the only renewable energy option to provide high-temperature heat” needed for industrial processes.

One exception to the reliance on CCS and biomass is a study by the German Federal Environment Agency (UBA) [11] which explores more radical technology options. For industry, these mitigation options include power-to-gas methane for fuel and feedstock as well as electrification, assuming 100 % renewable electricity production. Although such options are noted in IPCC AR5 they are not fully included in their analysis since IPCC bases its findings on reviews of the existing literature, where hydrogen/electricity-based chemicals and fuels, and using carbon dioxide as a feedstock, are still relatively unexplored options.

Motivated by this knowledge gap and inspired by the UBA report the implications of electrifying the energy and feedstock supply for the production of seven key basic materials in EU28 are explored assuming a fossil- and nuclear-free future. The analysis is motivated also by the abundance of solar and wind resource potentials in EU. Therefore, a quantitative scenario analysis is done of the potential future electricity demand that would result from a complete electrification of steel, cement, glass, lime, petrochemicals, chlorine and ammonia (including an electricity-based supply of hydrocarbon and hydrogen feedstocks for petrochemicals and ammonia production) and assuming constant production levels in 2050 compared to 2010. The future technologies needed are described and motivated and from this scenario, implications on economy, integration, technology strategy and other barriers are derived.

The approach and key technology assumptions are described in the following sections followed by the scenario results.

2. METHOD AND DATA

The unique timeframe set by climate policy (>2050) is not well suited for formal energy economic modelling, see e.g. [46]. Energy economic models build on known and reasonably predictable costs and relationships within the economy that change only marginally in the analyzed timeframe. It is thus easy to understand that CCS is the favoured and only option for the materials sector in the few long-term models assessing deep decarbonisation to 2050 as it assumes no systemic changes to the energy system (being an “end of pipe” solution). However, both the long time frame and the changes required in society for attaining deep decarbonisation targets to 2050 could well be systemic and thus go beyond what conventional models can assess. Here, a simple but transparent scenario analysis based on technology assumptions is used instead. The aim of using such an approach is not to predict what will happen in 2050 but to explore what the assumed goal (deep decarbonisation via electrification of industry) would mean for the energy system and the economy.

The scenario is calculated based on three steps: (i) future physical production level assumptions, (ii) current and future technology assumptions, and (iii) calculation of resulting energy demand and CO_2-emissions for producing primary and secondary steel, cement, glass, lime, petrochemicals (the basic products for most plastics), chlorine and ammonia.[2].

In the *fist step physical production data* for these products are derived from most recent production statistics (EUROSTAT [13]) and industry association data for steel, cement and chemicals [14, 15]. Data for 2010 was the last year that had consistent production data for all sectors. Production and consumption in the EU28 shows a moderate decline, is stable or is growing slowly for these products. Production is roughly equal to consumption although there are considerable exports and imports of some materials. For the purposes of this scenario a simplified assumption that production in EU28 will be stabilised at about current levels (Table 1) is made. The exception is lime for which consumption and production will decrease due to less demand from coal power plants and conventional primary steel production. These assumptions are in line with recent projections by the International Energy Agency for OECD Europe in 2050 (including Turkey, Norway and some others) [6] which assume a moderate growth over the whole 40 years of 12 to 25% for steel, a stabilisation for cement in the lower scenario and for feedstocks in the high and the low scenario.

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[2] In Lechtenböhmer et al. [12] two of the authors a more detailed modelling approach that covers the whole of industry and takes into account the most important technologies currently in use as well as several technology developments until 2050. This detailed analysis, however, was limited to the German State of North Rhine Westphalia.

Table 1. Global and European production and consumption of seven basic materials and projection for the EU for 2050

in million tons	Global Production	EU 28 Consumption	EU 28 Production	
Product	2010	2010	2010	2050
Steel	**1 431**	**161**	**173**	**180**
• Secondary steel from scrap (Electric arc furnace)	420	----	71 / 71	80
• Primary steel (2010: Blast oxygen furnace; 2050: Electrowinning)	994	----	95 / 101	100
• Primary steel (open hearth furnace)	16	---	0.7	---
Minerals			**253**	**250**
• Cement	3 290	185	192	190
• Glass	n.a.	n.a.	34	34
• Lime	313	26	27	17
Basic chemicals			**69**	**67**
• petrochemicals (HVC)**)	n.a.	43	42	40
• *hereof: ethylene*	*138*)*	*20*	*20*	*20*
• Chlorine	n.a.	9	10	10
• Ammonia	n.a.	17	17	17

*) World capacity in January 2011 of which 24 Mtons (17%) are located in the EU28 [16], **) high value chemicals (HVC) including ethylene, propylene, butadiene and benzene here

Sources: For 2010: Eurostat COMEXT database [13], World Steel (2014) [14], Cefic (2013) [15]; for 2050: own assumption.

In a *second step* the *energy input* in total and per physical unit plus all related CO_2 emissions for the production of each product was estimated. For 2010 an aggregated technology assumption for each of the materials was used. These assumptions represent average input values of the various fuels, feedstocks and electricity as well as the CO_2 emissions from the processes itself over all production sites in the EU. Such a simplification is justified as production technologies for those basic materials are more or less uniform compared to the overall process energy and material use and can thus be reflected by average technology characteristics. For 2050, the energy intensities used for calculating energy were derived from literature, assuming a complete switch to the most advanced break-through technologies described below. Together with these technologies a complete conversion of European electricity production to low carbon sources was assumed in line with the targets for the EU [1].

For *calculating emissions in the third step* the energy demand is converted to CO_2 emissions by applying fuel specific emission factors (see note to Table 2). For the minerals, CO_2 emissions from limestone have been taken into account based on IPCC guidelines [17][3]. For 2050 it is assumed that methane and hydrogen are produced from renewable electricity with typical efficiencies as given in Table 3 (below). Therefore in 2050 CO_2 emissions remain only from material input into minerals production.

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[3] IPCC's 2006 [17] default emission factor for clinker making (tier 1 method) is 0.52 t CO_2 / t clinker. We assume cement production in 2050 to be 50% "low carbon cements" with a 50% reduction in CO_2 emission factor compared to clinker (based on [18]). The other half of cement production consists of 85% clinker and 15% other composites (cp. Section 4.2). The average emission factor for glass production is 0,1 t CO_2 / t glass, accounting for a mix of flat and container glass. For lime IPCC's default emission factor according to the tier 1 method is used (0.785 t CO_2 / t lime).

3 CROSS-CUTTING TECHNOLOGIES FOR ELECTRIFYING BASIC MATERIALS PRODUCTION

Replacing both the fossil fuel used as energy and as feedstock by utilising renewable electricity is at the core of the scenario sketched in this paper. Electricity is a very versatile form of energy and can be used for heating in industry either directly with various electro-thermal processes or indirectly with hydrogen as an energy carrier. It can also, together with CO or CO_2, be used to manufacture hydrocarbons to be used as fuel or as feedstock for plastics. Below, some key cross-cutting technologies for industrial heating and for producing hydrocarbon based feedstock needed in the scenario are briefly described. The detailed technology assumptions for producing each basic material are presented in the following chapter.

3.1 Electro-thermal processes for heating

Industrial processes need heating at low (below 100 °C), medium (100-400 °C) and high temperatures (above 400 °C). Supplying this heat by electricity instead of carbon fuels can be done in several ways.

Electric furnaces supply heat with normal convection heating (same as heating with fuels) in all temperature ranges and heat pumps can supply low- to medium-temperatures at very high overall efficiency by using a low temperature sources (e.g., excess heat in a paper and pulp factory). There are also more advanced electro-thermal technologies that include electromagnetic radiation, heating via microwaves, infrared radiation, radio waves, ultra violet light, induction, electron beams, electric arc and plasma technologies that can potentially supply heat in all temperatures (see EPRI [20] for an overview). Electro-thermal technologies such as infrared and microwave heating are currently used in the food industry for drying and in the automotive industry for curing paints; i.e., applications with a specific need for exact and controlled temperatures and temperature gradients. Paper drying is another area where the use of electricity in infrared dryers could increase and replace gas fired dryers and electric impulse drying could increase overall efficiency [20]. Plasma technology (supplying heat via an electric arc heated ionised gas) can produce temperatures well above 2000 degrees and is used today for waste treatment and in several niches within the steel industry [21, 22]. Electric arc technology has since long been used for steel production from scrap (electric arc furnaces; see e.g. [23]).

Electro-thermal technologies have the potential of being efficient as they promise a more controlled heating process compared to traditional and fuel based heating and can thus heat a very specific area without heating the surrounding material as is the case with conventional convection heating[4]. These technologies are presently used where they offer distinct advantages (e.g., primary energy savings, higher productivity or product quality) or where there are no viable alternatives (e.g., for electric arc furnaces) but deployment has been limited since fossil fuels are generally less expensive than electricity [24].

3.2 **Electrolysis**

Electrolysis is used for separating chemical elements by deploying a direct current to a material placed in an electrochemical cell. Electrolysis is currently used when transforming aluminium oxide to aluminium, for separating a saline solution (sodium chloride and water)

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[4] Infrared radiation heats only the surface, microwave and radio frequencies penetrate the material and heat the volume whereas induction heating limits the heat to the connected material.

into chlorine, sodium hydroxide and hydrogen as well as for separating water into hydrogen (H_2) and Oxigen (O_2). In the future electrolysis could potentially be used for steel making from iron ore, so called electrowinning [25, 26].

Using electrolysis to produce hydrogen from water is a key technology in our scenarios. Renewable hydrogen is used in our scenarios to replace fossil derived hydrogen in the ammonia industry and to produce hydrocarbons such as methane, methanol, Fischer-Tropsch-naptha (FT-naphta) for replacing the fossil feedstock (mainly naphta or ethane) in the petrochemical industry.

Commercial electrolysis technology today is based on alkaline electrolysers with efficiencies ranging from 48 to 83 % [28]. Two future concepts being developed for electrolysis is polymer electrolyte membrane (PEM) electrolysers and solid-oxid electrolyser cells (SOEC). SOEC seems to have the highest potential for efficiency (above 73% power-to-hydrogen), improved investment costs and production capacity, as well as the potential ability to maintain efficiency at lower loads (thus being suitable for power-to-gas concepts with variable electricity supply) [28, 29]. SOEC is a high temperature electrolyser and thus needs steam but this heat demand can be integrated into most processes using surplus heat from, for example, a methanisation step in power-to-gas production. In the scenario an average efficiency of 71% for hydrogen production has been assumed based on a meta-analysis by Fischedick et al. [30].

3.3 Producing hydrocarbons from hydrogen, CO_2 and syngas

For replacing the fossil feedstock currently used for the production of petrochemicals renewable hydrogen and renewable (or recirculated) carbon are needed. The carbon is derived either from captured CO_2 or as the CO_2/CO part of syngas (CO_2/CO + H_2). The hydrogen is supplied either from renewable electricity through electrolysis or from the hydrogen in syngas produced from biomass (e.g. waste or woody biomass). Both methane and FT-naphta to replace fossil feedstock can be produced in well-known processes from syngas [31, 32]**.** The syngas can be produced by gasification or pyrolysis of woody biomass, biogenic waste [34] or plastics [35] and boosted with hydrogen. Biomass gasification is normally divided in two steps, first a reversed water gas shift reaction for generating a suitable balance of CO and hydrogen in the syngas, followed by a methanisation process [36, 37]. Future development of supercritical gasification could produce syngas efficiently from wet biomass such as household waste streams [38]. Indirect gasification in smaller to medium size scales can also convert a major share of the biomass to methane directly [39].

Methane can also be produced using hydrogen and CO_2 in the Sabatier process. With suitable catalysts this process can convert from hydrogen and CO_2 to methane in one step. The Sabatier process is exothermic producing surplus heat that, for example, can be used for heating the electrolyser used for producing the hydrogen. Process integration and co-production is important for energy and resource efficiency [35].

The carbon used for manufacturing renewable hydrocarbons can come either from captured CO_2 or from biomass. CO_2 can be captured and recycled either from flue gases, from air capture or even from sea capture in a future scenario [40]. Biomass gasification has a hydrogen deficit resulting in carbon leaving the process as CO_2 and not as useful hydrocarbons. This carbon can be utilised by adding hydrogen to the process and thus boost the syngas production and hydrocarbon yield [41].

There are many possible routes for producing petrochemicals from CO_2 and hydrogen. In the scenario described here (see Table 3 below) the FT-naphta route has been assumed based on [33].

4 A SCENARIO ON DECARBONISING BASIC MATERIAL PRODUCTION

In 2010 the EU28 produced 495 Mtons of the eight basic materials discussed here with the bulk being cement and steel, followed by petrochemicals and glass (see Table 1). The use of fossil energy plus significant amounts of non-energy related CO_2 emissions from cement, steel and glass making generated 380 Mton of CO_2 in 2010 (see Table 2). Furthermore, electricity consumption accounted for another 41 Mtons through indirect emissions. In total, the production of the eight basic materials was responsible for approximately 421 Mton of CO_2 which is equivalent to almost 9% of total EU28 GHG emissions [19].

For 2050 it is assumed that the analysed energy intensive production will be based completely on renewable electricity and hydrogen and syngas/FT-naphta. The specific technology assumptions are presented below followed by the results presented in Table 2 and Table 3.

4.1 Iron and Steel

Over 90% of the carbon dioxide emissions of steel production result from the primary steel route. Here the reduction of iron ore into iron accounts for about 80% of the emissions. Apart from increasing the percentage of scrap-based production (which is not assumed here), to find new reduction agents is the most important step towards decarbonising the steel industry. Three alternatives exist; to use hydrogen, to reduce iron ore in electrolysis or to use bio-char instead of coke. It is assumed here that by shifting primary steel production from oxygen to electrowinning [25, 26], steel production can be completely electrified. In this way final energy demand for steel making can be reduced by almost 30% compared to 2010 levels.

Electrowinning involves two major technical steps for primary steel production: First, iron ore is either solved or suspended in an acid or alkaline solution or it is melted in a saline solution for high temperature electrolysis (above 1600 °C). If the iron is not melted the electrolysis can be performed at 110 °C. Available studies show that 2.8-3.2 MWh of electricity per ton of sponge iron is needed for the electrowinning process [25, 26]. If electrowinning in an acid or alkaline solution, or hydrogen reduction is used, the iron ore is reduced in solid state, creating sponge iron which must be melted afterwards for alloying purposes. EPRI [20] suggests using plasma or induction ovens for smelting. The key benefits besides lower emissions will be higher thermal efficiency than with the use of electric arc furnaces and fewer waste products. With electricity for melting included this would be approximately between 2,6 to 3,7 MWh/ton steel depending on technical development [27, 43].

An indirect route to electrification would be the use of hydrogen in a direct-reduced iron (DRI) process which is currently used with natural gas as a reduction agent. This route could also be utilised as a means of energy storage or load smoothing in the electricity grid if implemented in a smart way.

In this scenario it is assumed that 2.6 MWh electricity per ton of steel is needed in the primary route and that 0.5 MWh/ton is needed in the secondary route.

4.2 Minerals, Cement, Glass and Lime

The most relevant products of the mineral industry with regards to GHG emissions are cement, glass and lime manufacturing. These industries have in common that they need high temperatures, usually above 1400 °C for processing mineral feedstock such as limestone and sand into useful materials such as clinker, glass or lime. Recycling is an option for glass industry (apart from flat glass production) and is common already today for economic reasons. Cement products (concrete) can be reused as building material, road filling etc. but are seldom reprocessed to new clinker and lime.

Cement: Emissions of greenhouse gases in cement production are caused by two factors; burning of fossil fuels for heat (40%) and in the calcination of limestone to chemically reactive calcium oxide (60%). For cement manufacturing it is theoretically possible to replace current clinker with other materials. The options of reducing the share of limestone as feedstock and thus avoiding process-emissions look promising but are not yet commercial. Options include magnesium- and clay-based cement or cement made from sewage sludge [45]. In our scenario we have assumed that new, low clinker cements achieve a market share of 50%. At the same time, some clinker substitutes such as fly ash and slag from blast furnaces for conventional oxygen steel production will be reduced in a future low carbon scenario. So we assume that the rest of cement production is supplied by cement clinker (85%) and other substitutes like limestone and gypsum. High temperature heat production can be converted from using carbon fuels to using electricity by e.g. future adaption of plasma technologies to cement production.

In the scenario electric heating using plasma or another high temperature electro-thermal process is assumed. The basic heating demand stays the same apart from normally assumed better integration of heat use all along the production chain with new and modern facilities that will be built. Here it is assumed that 0.9 MWh electricity per ton of clinker is needed which includes a 12% efficiency improvement in thermal demand compared to today.

Melting of glass currently uses mainly natural gas for heating. This can be replaced either by methane of renewable origin or by electric furnaces as assumed in our scenario in combination with the use of scrap glass as input (60% in UBA [11] by 2050). For glass production electric melters are already in use in certain productions on a smaller scale but need to be up-scaled and proven for all qualities of glass. Current fuel based heating is quite inefficient compared to what potentially could be achieved with electric heating. Due to the conversion to electric ovens an overall increase in final energy efficiency of glass production by about 68% from approximately current 2.1 MWh/ton down to 0.85 MWh/ton is assumed here, which is slightly more conservative than the 0.65 MWh/ton used by UBA [11] because their assumption on 100% waste heat recovery is probably too optimistic.

Lime: The demand for lime will decrease substantially following the phase out fossil fuels in electrictiy generation and thus the need for desulphurisation or liming of acidified lakes. For the burning of limestone the same process with some efficiency improvement leading to a reduction of final energy demand by 20% but no major technical breakthroughs are anticipated. The currently preferred fuels, natural gas and coal, will be changed upstream to high temperature electro-thermal processes.

4.3 Basic Chemicals: Chlorine, Ammonia and petrochemicals

The production of chlorine and ammonia is a major consumer of electricity and natural gas today.

Chlorine is produced by electrolysis of sodium chloride solutions (brine). It is a very energy intensive process consuming large amounts of electricity. An average EU chlorine production uses 3.6 MWh/ton Chlorine. It is assumed here that this can be reduced to 3 MWh/ton in 2050 by advanced membrane technology and partly oxygen consuming cathodes and will be supplied fully by renewable electricity.

Ammonia is the basic building block for producing fertilizers. It is manufactured in the Haber-Bosch process by combining nitrogen and hydrogen to form ammonia. Today the hydrogen is derived from reforming natural gas but this can be changed to hydrogen from electrolysis of water. In scenario it is assumed that the hydrogen is produced from electrolysis instead of natural gas reforming which enables final energy demand reduction of ammonia production by 36%. CO_2 needed to process ammonia further to urea is not taken from fossil energy sources such as gas or petroleum but from capture from combustion or air capture and thereby closing the carbon loop here.

Petrochemicals production will be fed by synthetic gases derived from zero carbon electricity via hydrogen and carbon sources using Fischer-Tropsch synthesis. While feedstock use remains stable due to the assumption of constant production volume process energy demand will be decreased by almost 50% among others by modernisation of crackers etc. Persistence of naphtha-fed steam cracking route to produce hydrocarbons implies that there is a typical yield structure consisting of high value chemicals (ethylene, propylene, butadiene and benzene) and (not desired) low value chemicals which are used energetically in refinery processes.

In the scenario it is assumed that 14.8 MWh FT–naptha per ton of high value chemicals (HVC) is needed for feedstock[5] and another 2.7 MWh per ton for processing. The demand for naptha results in a total electricity demand of 27 MWh/ton of HVC and that the roughly 3.1 tons of CO_2 needed for the production of each ton of HVC are captured from e.g. flue gases and readily available based on [47, 48].

4.4 The resulting electricity demand in 2050

The resulting demand for electricity, hydrogen and syngas/FT-naphta in the scenario is presented in Table 2 together with the estimated energy demand and CO_2 emissions for 2010. For producing also the hydrogen and syngas/FT-naptha from electricity and CO_2, further electricity is needed as presented in Table 3. Figure 1 gives an overview of the changes in energy and feedstock supply as well as CO2 emissions in 2010 as well as 2050.

In total the above mentioned deep changes in processes would make for a complete conversion of the final energy mix for production of basic materials from 87% fossil fuels (851 TWh) and 13% electricity (125 TWh) in 2010 to 83% electricity (512 TWh) and 17% syngas (106 TWh) in 2050 (including energetic use only).

At the same time total energy demand can be reduced by 25%, from 1648 TWh to 1289 TWh with energy content of feedstock included. However, these savings in final energy and feedstock use are compensated for by conversion losses of about 29% and 36% from producing also the hydrogen and the syngas from electricity. In total, the hydrogen and syngas production needs 1201 TWh of primary electricity to produce 671 TWh of feedstock plus 106 TWh for energetic use (in total 777 TWh) which implies total energy losses of 424 TWh[6] (see Table 3). Thus, the primary energy demand in 2050 is almost the same as in 2010 if the conversion losses for electricity production in 2010 are not taken into account.

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[5] Feedstock demand is defined here as the energetic value of all products of naphtha steam cracking consisting of high value chemicals with an energy content of 13.9 MWh/t HVC and low value chemicals (1.9 MWh/t HVC) minus endothermic energy demand of processing (1.0 MWh/t HVC) which is allocated to fuel demand. Fuel demand is the sum of endothermic energy demand and energy losses. Energy credit of low value chemicals is not regarded.

[6] The fact that the losses for hydrogen and synfuel production overcompensate energy efficiency gains do not lead to higher primary energy use for industry, as the losses for fossil electricity generation in 2010 (which can roughly be estimated to about 200 TWh) have not been accounted for in this paper.

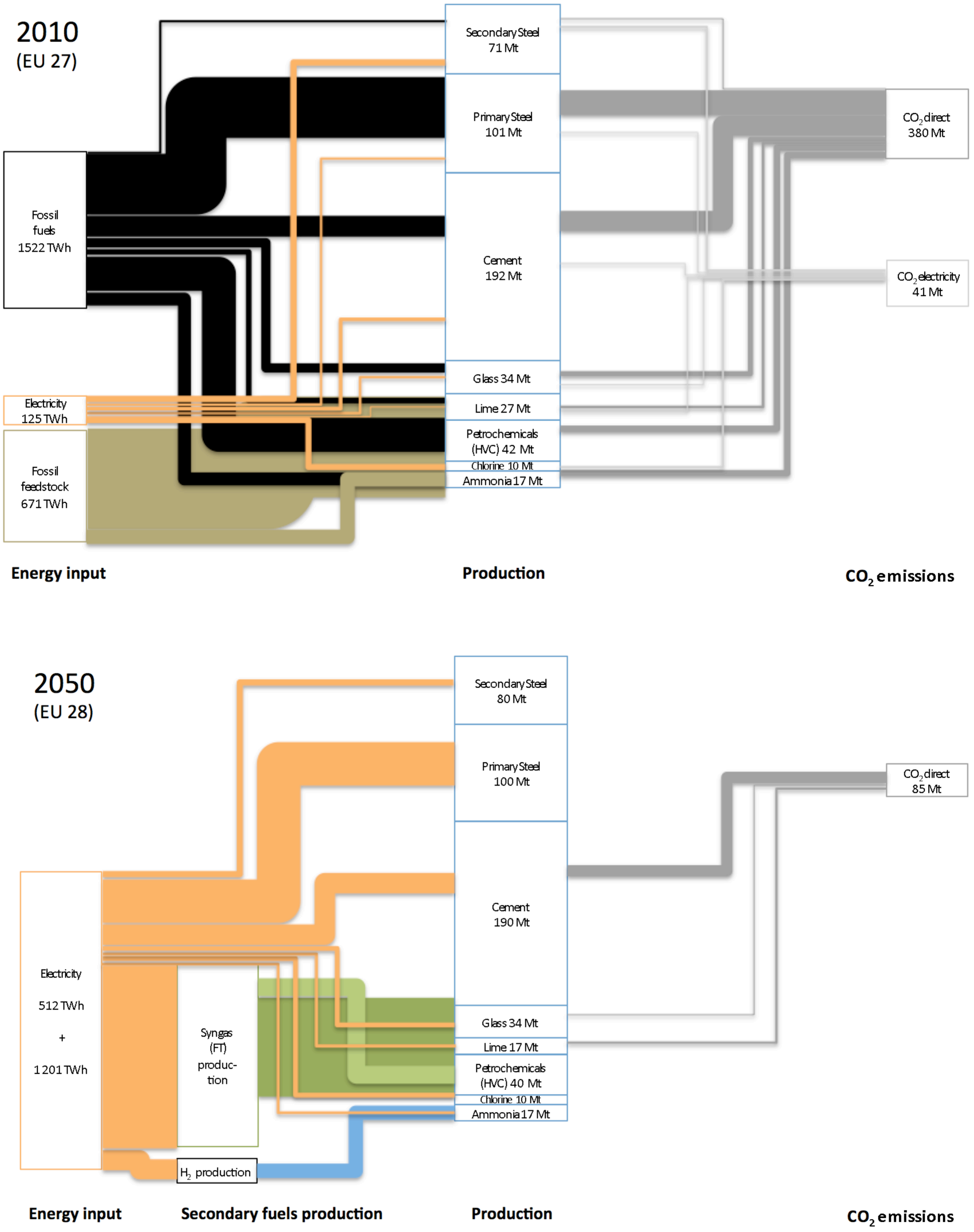

Figure 1: Energy input (TWh), production levels (Mt) and CO_2 emissions (Mt) for basic materials in 2010 and a scenario for 2050 with complete electrification of production processes (see Tables 2 and 3 for data)

Table 2. Final fuel and feedstock demand of seven basic industrial products in 2010 and projection for 2050

	2010				2050			
	Energy demand (TWh)		Direct CO_2-Emissions (Mt) *)	CO_2 Em. from electricity (Mt) ***)	Energy demand (TWh****)			Direct CO_2-Emissions (Mt) *)
Sources	[42]		calc. based on [42, 49]		own calculations			calc. based on [16, 17]
Product	elec-tricity	Other fuels and feedstocks	CO_2	CO_2	elec-tricity	H2	Syngas / FT naphta	CO_2
Steel	**52**	**367**	**147**	**17**	**296**	**0**	**0**	**0**
Secondary steel from crap (electric arc furnace)	37	14	3	12	38	0	0	0
Blast oxygen furnace	14	354	144	5	0	0	0	0
Electrowinning	0	0	0	0	258	0	0	0
Minerals	**39**	**210**	**164**	**13**	**169**	**0**	**0**	**85**
Cement	22	122	117	7	122	0	0	67
Glass	15	55	30	5	29	0	0	4
Lime	2	33	16	1	19	0	0	14
Basic chemicals	**35**	**945**	**70**	**12**	**47**	**85**	**692**	**0**
Petrochemicals (HVC)	0	198	38	0	0	0	106	0
Chlorine	35	0	0	12	29	0	0	0
Ammonia	0	76	15	0	17	0	0	0
Fuel use as raw material								
*Petrochemicals (HVC) **)*	*0*	*586*	--	--	*0*	*0*	*586*	--
*Ammonia **)*	*0*	*85*	*17*	--	*0*	*85*	*0*	--
Total (including feedstock)	**125**	**1 522**	**380**	**41**	**512**	**85**	**692**	**85**
Energy total (incl. feedstock)	**1 648**		**---**		**1 289**			**---**

*) Includes non-energy process-related emissions, **) CO_2 from feedstocks that is temporarily bound in products (base chemicals) amounts to additional 160 Mton of potential CO_2 emissions (own calculation based on carbon content of feedstocks). ***) 331g/kWh [49]; ****) by 2050 all fuels are assumed to be zero carbon electricity or derived from zero carbon electricity.

Source: EUROSTAT Energy balance [42] and [15, 16, 49] for 2010, own calculations for 2050

Table 3. Conversion balance of electricity to hydrogen and synthetic fuels for feedstock and energetic use in basic material production, Scenario for 2050

	Fuel demand 2050		Efficiency	Electricity demand
in TWh	Energy	Feedstock		
Hydrogen	0	85	71%	119
Syngas / Fischer-Tropsch naphta	106	586	64%	1 082
Total	106	671		1 201

Source: Own calculations based on a conversion efficiency of 71% for hydrogen generation [30] and assuming high temperature electrolysis (SOEC) with excess heat integration of the FT process [33].

5 Discussion

The scenario presented in this paper assumes a complete electrification of the production of the most energy intensive materials. This includes the supply of feedstocks for the main bulk chemicals from hydrogen and synthetic gases derived from renewable electricity and CO_2. For this scenario, a staggering 1 713 TWh of extra renewable electricity would be needed. This can be compared to the current total electricity use in the EU of 2 780 TWh (the industry share of which is about 1 000 TWh). Below, the implications of this increasing electricity demand for the energy system are discussed.

5.1 The rationale for electricity as the main future energy carrier in a decarbonised world

In a decarbonised world, the main options available for deep emission reduction for the processing of basic materials are the use of CCS, shifting to biomass and electrification with renewable electricity. The rationale for assuming electricity is that CCS remains currently in limbo with many opponents and might be a limited option in the future and that sustainable harvested biomass is also limited with potentially strong competition for this resource in the future.

Primary electricity from either solar, wind, geothermal or other renewables seems currently be the option with least resource restrictions in the long-term. Electricity is also a carbon free and versatile energy carrier. Other sectors also look at renewable electricity as a key energy carrier in a decarbonised future. A meta-analysis of five decarbonisation scenarios on the EU 27 energy system shows that the transport sector is expected to consume between 372 and 1 628 TWh of electricity in 2050, compared to 68 TWh in 2010. In addition, between 57 and 700 TWh of electricity may be used for heat pumps in residential, commercial and industry buildings [44].

The potentially large electricity demand increase raises the question of availability. However, the perception of the potential for renewable electricity production in Europe has changed dramatically in the last years and is orders of magnitude greater than this. Hoefnagels et al. [51] calculated an EU27-potential of 2 000 TWh only for onshore wind, realisable in 2050. For Europe and North Africa a potential of 47 000 TWh available at 5 euro-cents per kWh in 2050 has been modelled and the technical potential amounts to 105 000 TWh [52].

In the real world, and in a circular economy with increased focus on material efficiency and the concurrent development of bio-based materials, electricity demand will be lower than calculated above. The scenario results therefore represent an extreme case. But, even if electricity based virgin material production was only half or a third of what has been calculated here, the resulting electricity demand is still substantial.

5.2 Relative prices between energy carriers and overall costs of an electrification scenario

Increased use of electricity is limited today for economic reasons as the cost of electricity as an energy carrier is higher compared to using e.g. natural gas or biomass. The scenario presented here assumes that this logic is reversed as available renewable hydrocarbons (biomass) will become substantially higher priced due to strong competition in a decarbonised world. An economy based on renewable electricity as the "primary fuel" will thus have a different energy price logic compared to the current fossil fuel based economy. Today, two or three units of fuel are used to produce one unit of electricity, which is reflected in relative prices between energy carriers. With renewable electricity as the primary energy source it will take two units of electricity to produce one unit of fuel. Thus, relative average prices for electricity and hydrogen or hydrocarbons will change.

Even if the potentials for renewable energy are realised, electrification would still involve substantially higher production costs for materials. Åhman et al. [53] indicates that the production cost of basic materials such as steel and cement may typically increase between 20 and 100% assuming a carbon price of 100 EUR/ton CO_2. Producing ethylene and polyethylene from renewable electricity/hydrogen and CO_2 may be two to three times more expensive than today´s fossil based production [35]. Such production cost increases, with rather small or sometimes no co-benefits, makes decarbonisation a challenge from an implementation point of view, especially in a world without universal climate policies. It is, however, not likely to be a problem for the economy as a whole since basic materials account only for a small share. They were found to account for about 4 % of all consumption and investment in some EU member states [56]. Also, the basic material cost share of most products is very small. For example, a doubling of cement prices will only increase the cost of a normal residential building with <1 % [54]. The basic materials cost for a car is about 5 % of the final price and the cost of steel beams accounts for about 4 % of the cost of a steel-frame commercial building [55].

5.3 How can an electrified industry co-evolve with the electricity system?

An electricity system based on variable renewables in the scale envisioned in our scenario will function in a completely different way compared to the existing system based on dispatchable thermal power plants and the concept of “base load” in the power system [57]. Geographical, temporal and consumer flexibility are here three necessary building blocks in a future power system that can accommodate the large amounts of variable renewable electricity supply assumed in our scenario. Consumer flexibility can be enhanced with increased integration and significant studies have been made focussing on integration of the heat [58] and transport sectors [59, 60] but less focus has been on integrating industry with the notable exceptions of [61, 62]. With renewable electricity as the least cost primary energy source in a future without fossil fuels and nuclear power, it is plausible that future energy intensive processing industries become flexible “swing consumers” that convert electricity into materials (power-to-products) rather than spilling “surplus” solar and wind. Swing production of hydrogen for nitrogen fertiliser, plastics, and steel production, or for increasing yields in bio-based processes, could be a very large flexible load in the future power system.

Such significant changes in economic rationalities would also have consequences for the location of energy intensive industries. Historically the basic material industries have located close to raw material feedstock or energy (e.g., the Ruhr area). In the hypothetical future as sketched here, industry might move closer to renewable electricity sources but it is uncertain whether this rather would mean a shift towards hydro/wind-production at northern latitudes or a much more geographically dispersed location around PV-based electricity production in sun-rich regions. Alternatively, assumed electricity will be available in large quantities in many places, this could also result in a shift of material intensive industries closer to the resource supply, e.g. to big ports that offer transport cost advantages as discussed for German steel industry in [63].

5.4 How big are the technical challenges?

Another important issue is the availability of the technologies assumed in the scenario. However, much of the electro-thermal, electrolysis and power-to-gas technologies already exist. Electro-thermal processes were perceived as an important technology in the 1980’s post oil-crisis when nuclear optimism was high. We may now have a situation where they become crucial again as renewable electricity is increasingly replacing fossil fuels and at least theoretically capable of supplying huge amounts of additional electricity. Electro-thermal technologies are already extensively used in applications where they offer advantages (e.g., process control, product quality and lower energy cost) e.g. in induction heating, UV-curing and microwave drying. In the scenario sketched here these would need to expand to further applications, particularly high temperature heat generation, e.g. via plasma technology. Electrolysis is another key technology in our scenario. It is needed for hydrogen production and would have to be developed further for increasing overall system efficiency and reducing costs. To make it applicable also for electric primary steel making, however, needs ramping up the technology from lab-scale to industrial scale. Power-to-gas concepts are already being demonstrated and processing methane or FT-naphta from renewable electricity would not be different from processing fossil feedstocks.

A major barrier to the further expansion of electricity based technologies is the price of electricity compared to the price of fossil hydrocarbons. But, as noted, relative prices between electricity and hydrocarbons will be different in a zero-emissions world. A decarbonised society will still use carbon in many materials and closing the loops on CO_2 is another important component of such a scenario.

6 Conclusions

The potentials for renewable electricity production are enormous and electrification is one of several options to decarbonise the energy intensive basic materials industry but it is still a relatively unexplored option. The “what-if” analysis presented here shows that an entirely electricity based production of basic materials in EU28 will be possible in the future from a renewable energy resource and technology point of view. With stable production volumes it implies a large increase in industrial electricity demand – more than 1 500 TWh in 2050 on top of the 1000 TWh used today, but the number could be much lower with improved materials efficiency and biomass feedstock. The implications of such a scenario are several. The relative prices between using electricity compared to sustainable biomass or CCS need to change for making electrification a competitive option. This implies a need for very high carbon prices, or other policies with similar effects, which currently presents a large barrier to implementation. Many of the basic electro-thermal technologies already exist but in order to scale up, some new key technology building blocks were identified such as electrolysis, the Sabatier process and electrowinning. The future integration and co-evolution with a 100% renewable electricity system is an area with currently several knowledge gaps where the potential for industry to act as swing producers requires more knowledge concerning various technology and system options as well as potential barriers.

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