Electrification of primary steel production based on ΣIDERWIN process: simulation on the European power system in 2050

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Abstract

The growing steel industry represents 4 % of the total European carbon emissions (EU27). The current coal based blast furnace process used to make primary steel has been widely optimized over the past decades to become as efficient as possible. Because of limited opportunities for further enhancements in the existing process, the decarbonisation of the primary steel industry requires a breakthrough innovative technology.

At the same time, Europe aims to be climate neutral by 2050 and have net-zero greenhouse gas emissions. To contribute towards reaching this goal, the European H2020 – ΣIDERWIN project aims to develop a breakthrough process for the primary steel production, based on electrolysis, as a low carbon alternative to the current blast furnace.

As it is a flexible and electricity intensive technology, ΣIDERWIN's industrial development in Europe may play a significant role in the European power system in terms of electricity demand, and demand-side response capacity.

This paper focuses on the ΣIDERWIN technology and its contribution to the future European power system. Based on projections of the steel demand in 2050 and the specific energy consumption of this technology, a prospective scenario is simulated in order to assess ΣIDERWIN's contribution in production and demand balancing, and the benefits to the power system. The methodology for this study and the simulated scenario are presented, and the potential reduction of the CO_2 emissions related the flexibility of the ΣIDERWIN technology is assessed. Further steps into the calculation of this potential and the simulation of different scenarios are finally discussed.

Introduction

Europe aims to be climate neutral by 2050 and have net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and the global climate commitment under the Paris Agreement. This means that all sectors of the economy will have to be climate neutral from the power sector to the industry, mobility, buildings, agriculture and forestry. The power sector is at the forefront of the reduction of carbon emissions with the phase-out of carbon-intensive coal production and the development of solar and wind renewables alongside existing carbon-free generation such as hydropower, biomass and nuclear. This gives the opportunity for the industrial processes to switch to carbon-free electricity to reduce their carbon footprint. In this context, innovation is more than ever a necessity to find deep decarbonizing solutions especially for carbon intensive industries, still largely dependent on fossil energy, such as the steel, cement and chemical industries.

For the steel industry in Europe, two technologies are mainly used today: blast furnaces and electric furnaces. The primary steel production, based on blast furnaces, represents nearly 60 % of the European steel production, and the secondary steel production based on electric furnaces covers the remaining 40 % [1]. In existing blast furnaces, coke is used as fuel and reducing agent to reduce iron ore at high temperatures. This process has been widely optimized over the past decades to achieve an optimum in terms of coal consumption, and therefore the potential to further reduce the carbon footprint is limited. However, steel production still represents 4 % of the European carbon emissions (EU27) [2].

To lower carbon emissions of steel production, the European H2020 – ΣIDERWIN project [3], led by ArcelorMittal, aims to develop, build and test a breakthrough alternative electric process for the primary steel production, by implementing electrolysis supplied with electricity from the future European power system, which aims to be carbon neutral in 2050. This technology transforms iron oxides from grinded ores or by-products from other metal industries into iron plates.

Contrary to blast furnaces based on coal, the ΣIDERWIN process generates iron with low direct carbon emissions. Furthermore, taking into account the EU aims to decarbonize the electricity production thanks to a rapid development of renewable electricity generation capacity in most parts of Europe, the indirect emissions related to the electricity intensive ΣIDERWIN technology will also gradually be lowered.

Compared to traditional steelmaking plants, the industrial development of this innovative technology could have several advantages such as [4]:

- A reduction by more than 80 % of the direct carbon emissions because electricity substitutes coal,
- A reduction by nearly 30 % of the direct energy use thanks to a more efficient process,
- The ability to produce steel from alternative by-products rich in iron oxides including from non-ferrous metallurgy residues (for example the bauxite residues from the aluminium industry),
- The potential to contribute to grid balancing as the process can deal with fluctuating electricity supply.

As a European leader of the energy sector fully invested in the energy transition, and as a partner in the ΣIDERWIN project, EDF (Électricité de France) is in charge of a parametric assessment to evaluate the integration of potential ΣIDERWIN plants in the future 2050 European power system. The objective of this work is to define the role this flexible and electricity intensive technology could play in grid balancing and carbon emissions reduction. The aim of this article is to present the methodology developed to analyse the impact of a ΣIDERWIN industrial development, in terms of energy consumption, costs and benefits for the power system, including flexibility potential and carbon emissions reduction.

First, the ΣIDERWIN technology and its energy specifications are briefly described. Then, the methodology, input data and main hypothesis used to build a scenario 2050, are presented. Last, first results and future work are mentioned.

ΣIDERWIN technology

OVERVIEW OF THE PROCESS

The ΣIDERWIN process is based on electrolysis to produce iron plates which are then converted into liquid steel in electric furnaces. The different steps of the process are presented in Figure 1.

At first the iron ore is grinded in stirred mills to produce ultra-fine ore. The ultra-fine ore is then mixed with caustic soda and water to produce an electrolyte rich in iron oxide (leaching). In the next step the electrolyte circulates in electrolysers in which the electrochemical decomposition of the iron oxide takes place, resulting in iron deposit on the cathode and thus producing iron metal plates and oxygen as a by-product. Finally, the iron metal plates are washed and extracted from the electrolysers and then melted together with scrap in an electric furnace to produce liquid steel at the end.

ENERGY CONSUMPTION

In terms of electricity consumption, the first study results based on the engineering design from the ΣIDERWIN project are the following:

- Grinding: 66 kWh/t of iron (2 %)
- Leaching: 325 kWh/t of iron (9 %)
- Electrolysis: 2,720 kWh/t of iron (75 %)
- Fusion: 500 kWh/t of iron (14 %)
- Overall: 3,611 kWh/t of iron

These data will be validated in the framework of the ΣIDERWIN project during the test run of the industrial pilot, currently under construction.

DEMAND SIDE RESPONSE PROFILE

Experiences from the aluminium, zinc and chemical sectors show that industrial processes based on electrolysis have the potential to provide flexibility since the process can easily start and stop or modulate alongside the electricity consumption, and therefore contribute to grid balancing. ΣIDERWIN, as an

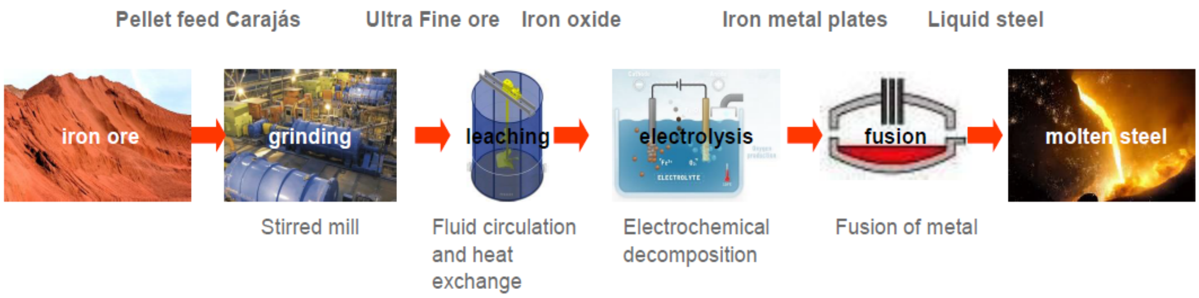

Figure 1. ΣIDERWIN processing route [3].

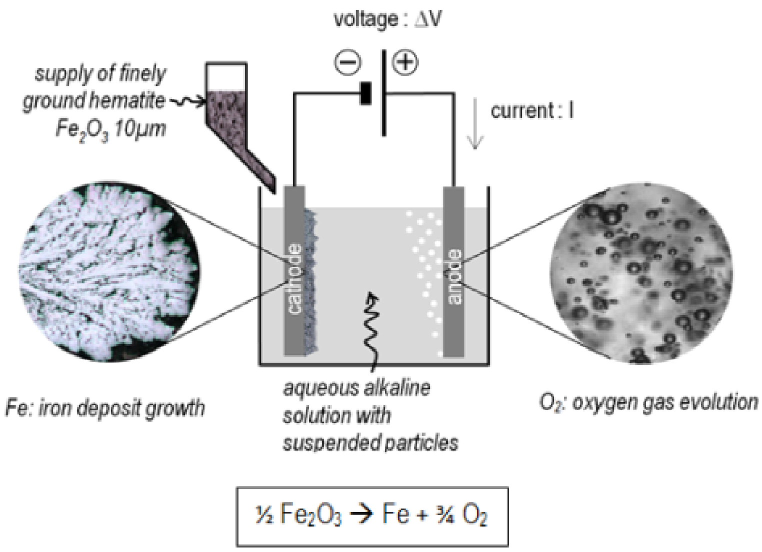

Figure 2. Electrochemical decomposition of iron oxide [3].

electrolysis technology, could thus also play a role in the future Demand Side Response (DSR) market.

In order to evaluate the ΣIDERWIN DSR potential in the future European power system, the theoretical DSR profile has been defined on the basis of ΣIDERWIN specifications and feedback from industrial partners. The theoretical DSR profile has been validated afterwards in laboratory conditions thanks to the contribution of the University of Aveiro (Portugal), another partner of the project, who has studied the impact of interruptions and modulation on the iron produced.

The ΣIDERWIN DSR profile considered in the parametric assessment is:

- Energy consumption: 2,720 kWh/t iron (electrolysis item) or 2,693 kWh/t steel
- Available power (P): 92 % of the electrolysis power (not 100 % because of process constraints on some auxiliaries)
- Notice period (NP): reactive model (without notice period for modelling)
- Activation/deactivation period (AP/DP): reactive model (without AP/DP period for modelling)
- Duration (D): no limit (minimum thermal inertia issues because of a low temperature process <120 °C)
- Frequency: no limit (no impact on the iron product)
- Calendar: no limit (not a seasonal process)

To contribute in the DSR market, an electrolysis process has to maintain the temperature and the circulation of the electrolyte during interruptions in order to prevent cell damages and to be able to restart quickly. The advantage of the innovative ΣIDERWIN technology is that it can operate at low temperatures (a hundred degrees) in comparison with other electrolysis processes such as the aluminium electrolysis (nearly nine hundred degrees). Consequently, a ΣIDERWIN plant would be able to stop or to modulate its production without important thermal constraints. Whereas the available power in the industry is between 8 % and 75 % [5] [6], this advantage enables the ΣIDERWIN process to stop nearly all of the electrolysis power demand.

ΣIDERWIN industrial development and integration in the future European power system

METHODOLOGY

A deep decarbonisation strategy applied to the European primary steel industry, and based on the industrial development of ΣIDERWIN process, an electricity intensive and flexible technology, can have a significant impact on the European electricity system. We wish to analyse the impact and the interest of a potential ΣIDERWIN industrial development for the European electricity system, in terms of energy consumption, costs and benefits, flexibility potential and carbon emissions reduction for the power system at a time horizon of 2050.

This study requires a detailed modelling of the future European power system to assess the difference in dispatching as well as costs between two scenarios, with and without ΣIDERWIN in the power system, and on a European-wide scale. To do so, we use a state-of-the-art unit commitment model, Continental, that has been developed by EDF. It optimizes and simulates the power system over a set of 20 interconnected countries. Continental was used for public studies and in particular for recent European projects. For example, it has been used to perform an extensive publicly available study on integrating 60 % renewables into the European power system [7], or more recently in EU-SysFlex European project (Pan-European System with an efficient coordinated use of Flexibilities for the integration of a large share of renewable energy sources) [8].

Continental requires a large volume of input data including the power generation mix of each country through a detailed description of the generating facilities (installed capacities and technical and economic characteristics of each generation unit as well as unplanned outages scenarios), and the hourly load factors of fatal generation, as well as hourly load curve by country. The countries are then linked by interconnection capacities which must be consistent with the European grid operators' development projects. Because weather data is playing a foremost role for generation of renewables (i.e. hydro, wind and solar) as well as in the profile and level of demand, meteorological uncertainty is taken into account through a large number of climate scenarios. This is particularly important at future horizons to have a good sizing of the system and in particular the peak demand, sensitive to climate variations, which has a major impact on the benefits that ΣIDERWIN could provide in terms of flexibility.

Based on this data, *Continental* optimizes the generation fleet's schedule and produces a detailed hourly description of the power system by country: generation and participation in system services of each power plant, marginal cost and average cost of the system, number of hours of failure, flows at interconnections, CO_2 emissions of the electricity generation, etc.

Continental can also iteratively define the economically optimal generation fleet. This optimization is generally only used for the thermal fleet. Figure 3 maps how *Continental* works.

SCENARIO 2050 – INPUT DATA

In order to evaluate the potential contribution of a primary steel industry, based on ΣIDERWIN technology, in the future European power system, it is necessary to first define the future power system and the future steel industry on the European scale in 2050.

Two kinds of input data and hypotheses are needed:

- A scenario for the power system: installed capacities, climate data, electricity demand, grid interconnections, CO_2 price, carbon intensity of power generation and fuel costs.
- Data for the steel industry: growth rate of the European primary steel industry, location of the future plants, electricity consumption of a ΣIDERWIN plant and its DSR profile.

These different input data are presented in more detail in the two following parts.

Scenarios for the power system

We build a scenario based on the European Union reference scenario for 2050, in its 2016 version (latest version available at the start of the study) [9], as a starting point.

This scenario is a projection up to 2050 of the European energy system, based on all EU policies and directives adopted before December 2014. It has been developed by a modelling consortium led by the National Technical University of Athens, based on the PRIMES model, using assumptions provided by experts from different countries. It serves as a reference point for assessing new public policy proposals.

The European Union reference scenario provides, from 2015 onwards in 5-year increments until 2050, the production and installed capacity by technology (nuclear, wind, solar, etc.) as well as net import by country. To simulate the power system in Continental we combine these annual data with input from other public data sources in order to build an hourly data set that can be used by Continental to simulate the power system. The detailed method is presented in EU-SysFlex project [8].

The sources used to complete the data of the EU reference scenario are mainly the public EU database SETIS for wind and solar hourly profiles [10], "Big & Market" scenario from e-Highway for interconnection flows [11], RTE Long Term Adequacy Forecast 2017 for electric vehicle profile generating fleet [12], ENTSO-E Ten Years Network Development Plan (TYNDP) scenarios [13] for the technical-economic characteristics of the thermal groups (allowing in particular to calculate the variable production costs). The assumptions for fixed production costs (capital costs and O&M costs) are based on the International Energy Agency's Word Energy Outlook (WEO) 2018 scenario [14]. Carbon intensity and technical features for thermal power plants are consistent with EU-EUCO30 scenarios [15].

The scope of the study covers twenty interconnected countries in Western Europe: Austria, Belgium, The Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Luxembourg, The Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, and the United

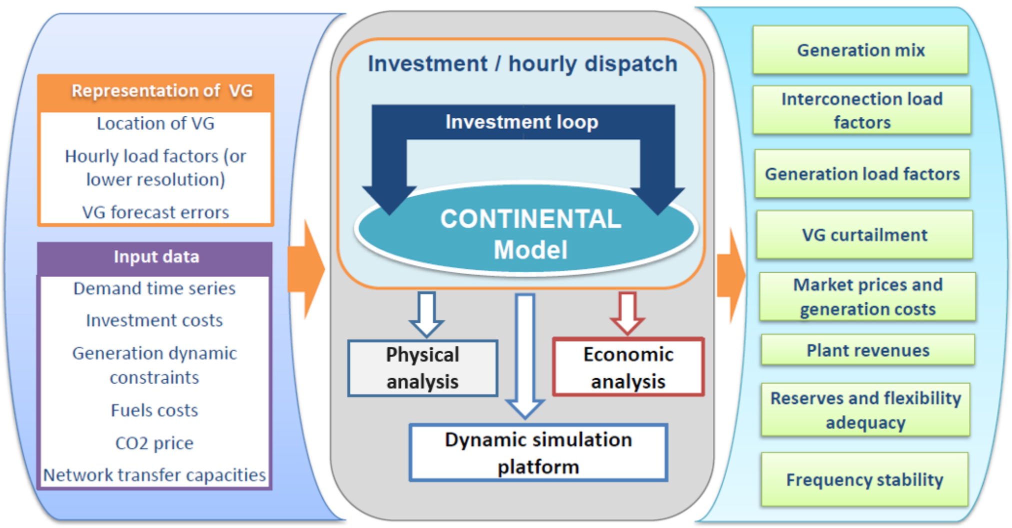

Figure 3. Continental methodology [7].

Kingdom. Two of these countries are not included in the scope of the EU reference scenario: Switzerland and Norway, for which we use data from the "Sustainable transition" scenario of the ENTSO-E TYNDP [13]. The dataset used for the power system modelling covers the total European primary steel production capacity, that is all European producing countries converted to ΣIDERWIN technology for the study, with the exception of Romania. For this country, the electricity demand of its ΣIDERWIN production is transferred to the neighbouring countries modelled (30 % for the Czech Republic, 30 % for Poland, 30 % for Slovakia and 10 % for Hungary).

From these data, the Continental model allows us to reconstruct a coherent dataset guaranteeing the supply-demand balance in each country. The installed capacity of gas-fired generation units Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT) in each country is automatically optimized by Continental on the basis of economic criteria.

This dataset has the following main features for the year 2050:

- A high rate of renewable Energy: 66 % of Renewable Energy Sources (RES) in Europe, relative to net demand, with variable renewable energy (solar and wind) representing 35 % of net demand.
- 25 % of the generation is from thermal plants, 20 % of which are gas powered.
- 17 % of nuclear generation which is carbon-free.
- A high penetration rate of electric vehicles: almost 50 % of the whole estimated vehicle fleet.
- Whereas the future CO_2 price is uncertain, here the CO_2 price has been set at €90 per ton. This price is currently around €25/ton but is set to increase significantly in 2050. The hypothesis is consistent with the current vision of the European Union, but well below the carbon's tutelary value, which defines the price to be set for carbon to enable the financing of the actions and investments needed to achieve the carbon neutrality objective, with reference to a given energy scenario. The carbon's tutelary value is therefore set in such a way that "any action that reduces emissions and has a cost lower than the carbon's tutelary value makes sense for the community and must therefore be undertaken" and is estimated, for example, at around €775/ton in 2050 for France [16]. This hypothesis, has a significant impact when it comes to costs and economic analysis of the power system. So far no sensitivity analysis has been performed but the impact of changes in the CO_2 price will be evaluated in later work.
- Increases in the number and capacity of interconnections, anticipating major transmission line developments to allow in particular the integration of variable renewable energy sources.

At this stage of the study, the only storage taken into account in the simulation is pumped hydro storage, which represents significant storage capacities at the European level. No stationary batteries are modelled at this stage. Demand Side Management is not optimized dynamically by the model but the shape of the demand curve takes into account demand side management implicitly for water heaters and 60 % of the electric vehicle fleet. A more complete integration of the different forms of storage and Demand Side Management is planned in a later stage of the study.

Steel industry related data

In the first assessment, to model a development scenario for the steel industry in 2050, we consider no relocation and reorganization of the European steel industry (conservative hypothesis in terms of market organization and employment), that is to say the European steel-producing countries will remain the same in the future in comparison with 2017. A map of the current European steel industry is given by the international and European steel industry associations [17].

The European steel production is expected to grow in the future because of an increasing demand in some steel intensive markets such as the construction and automotive sectors. The average growth rate considered in the study is 0.8% per year [18]. Arise in the share of secondary steel is also considered for 2050 according to the source [18].

In order to observe the impact of a total decarbonisation of the steel industry, according to the carbon neutral European policy, a total substitution of the blast furnaces with ΣIDERWIN technology is considered in the scenario 2050. Thus, all coal used in the European primary steel industry is assumed to be replaced with electricity in accordance with the ΣIDERWIN process electricity consumption described above. This hypothesis, combined with the steel industry projections, enables to define the electricity demand of the European primary steel industry in 2050.

In the study, those projected electricity consumptions per each European steel-producing country are taken into account as an additional electricity demand compared to the EU Reference Scenario [9], and the electrolysis power calculated is used to model an additional and distributed flexibility potential for the power system, limited by the grid connections capacities.

ADAPTING THE POWER SYSTEM MODEL TO MEET ADDITIONAL ΣIDERWIN DEMAND

Basic assumptions

The initial dataset defining the European power system, in line with EU Reference Scenario 2016 to 2050, is then adapted to take into account the additional demand linked to the industrial development of ΣIDERWIN. Assuming a 0.8 %/year growth in the steel production in Europe, the conversion of the steel industry to ΣIDERWIN process yields an additional demand estimated at 471 TWh per year in 2050 for Europe (54 GW) corresponding to approximately 12 % of the total electricity consumption estimated for 2050 within the scope of the study, with strong variations depending on the country as shown in Table 1.

To meet this new demand, without jeopardizing the EU climate target, it is necessary to cover the additional demand with low carbon intensity generation sources.

Gas capacity is therefore not increased a priori: Gas fired means are used as an adjustment variable to obtain a generation mix that allows to balance supply and demand, with at most 3-hour of loss of load (as an average for the different climate scenarios), which is a regulation limitation imposed in many countries. The gas generation installed capacity is therefore

Table 1. Primary steel production per European country and projected electricity consumption.

European steel producing countries	Primary steel production 2050 (Mt)	SIDERWIN electricity consumption (GWh)	Electrolysis electricity consumption (GWh)	Electrolysis power (MW)
Austria	9.2	32,783	24,769	2,976
Belgium	6.6	23,665	17,880	2,149
Bulgaria	0.0	0	0	0
Croatia	0.0	0	0	0
Czech Republic	6.4	22,813	17,237	2,071
Finland	3.0	10,550	7,971	958
France	13.2	46,911	35,444	4,259
Germany	39.4	140,490	106,148	12,755
Greece	0.0	0	0	0
Hungary	1.7	6,202	4,686	563
Italy	9.3	33,115	25,020	3,007
Latvia	0.0	0	0	0
Luxembourg	0.0	0	0	0
Netherlands	8.9	31,742	23,983	2,882
Poland	6.3	22,519	17,015	2,045
Portugal	0.0	0	0	0
Romania	2.5	8,908	6,731	809
Slovak Republic	5.6	19,997	15,109	1,816
Slovenia	0.0	0	0	0
Spain	5.5	19,775	14,941	1,795
Sweden	4.0	14,408	10,886	1,308
United Kingdom	10.4	37,139	28,061	3,372
Total EU	132.2	471,018	355,880	42,764

automatically adjusted by a module of Continental (iterative investment/disinvestment loop).

Furthermore:

- No additional potential is considered for the Carbon Capture and Storage plants (CCS) given the debates surrounding this technology.
- Fuel plants are almost inexistent in the dataset.
- Neither hydropower nor co-generation potentials have been modified as it is considered that there is no additional potential to develop hydropower in Europe, and that the development of co-generation will not depend on electricity needs.
- As far as the biomass is concerned, only one scenario integrating an increase in its potential was studied. For all the other scenarios, biomass potential has not been modified, considering that conflicts of use [19] and the impact on biodiversity of this resource limit its use for electricity needs.

Finally, to meet the additional demand, we assume that the installed capacity of the following low carbon technologies can be increased: nuclear, off-shore and on-shore wind and solar. This increase is considered in accordance with the potential of these energies, knowing that each assumption of increasing capacity can be questionable.

- For nuclear, there are enough eligible sites (even if global warming may eliminate certain sites along rivers).
- For offshore wind, the latest studies by organisations such as Wind Europe [20] show an important potential of 450 GW, whereas the EU Reference Scenario uses less than 100 GW. Therefore, it does not seem unrealistic to consider offshore wind turbines dedicated to ΣIDERWIN production.
- For On-Shore wind, the technical potential is also important. Thus, [21] shows that, even if only 10 % of the land technically eligible for wind energy is retained, this would lead to a total deposit of 170 GW in France, compared to the 58 GW retained for on and off shore wind in the EU Reference Scenario for this country.
- Similarly, technical potential is very high for solar energy.

The real limits are thus rather related to the acceptability of these technologies, which is multifactorial and specific to each country. These are not absolute constraints that would invalidate the assumptions made, but rather a cost-benefit balance.

For nuclear in particular, we have considered that the phase-out decisions of some countries were irreversible. We have therefore only increased nuclear capacity only in countries that already have this technology in the EU Reference Scenario.

Selected scenarios

Since the results of the study are highly dependent on the power mix adaptation strategy, we have selected several scenarios for the assessment, in accordance with the principles defined above:

- A conservative scenario, where the increase in the share of low carbon technologies (nuclear, solar, on and off-shore wind and biomass) is uniform.
- A conservative scenario very close to the previous one, but without increasing biomass.

- Several scenarios that take into account the specificity of ΣIDERWIN demand (constant demand throughout the year). We therefore favour baseload technologies such as nuclear and off-shore wind power, adjusted into three alternative scenarios: adaptation of the power system only with nuclear generation, only with off-shore generation, and finally with a mix of 50 % Off-Shore and 50 % nuclear.

Allocation of ΣIDERWIN demand and power generation

As shown in Table 2, the share of ΣIDERWIN demand in the total electricity demand of each steel-producing country varies considerably from country to country, from 0 % to +48 %.

The share of power generation eligible for an increase (nuclear, wind, solar) is also highly variable. And if we consider that each steel producing country has to cover its own additional electricity demand, it means that the carbon-free share of electricity will need to be increased independently in each country to meet this additional demand. For example, in Austria, the carbon-free generation mix that can be scaled up represents 23 % of the country's total generation and the additional steel demand represents 37 % of the total demand. Therefore, it would be necessary to increase the carbon free generation by 165 %, which appears unrealistic. As a consequence, we choose to rely on the high volume of interconnections to match the additional demand allowing us to use the European RES potential, with the possibility to adapt the ratio for each generation technology.

In the conservative scenarios, where all carbon-free technologies that can be mobilised are increased using the same proportions, we have chosen to apply the same ratio in all countries. Production and demand in each country are therefore balanced by using the available interconnections.

In scenarios that make massive use of off-shore generation, capacities are located by taking into account the proximity to ΣIDERWIN demand and the quality of the off-shore potential (winds in the North Sea are more favourable than in the Atlantic or the Mediterranean sea, for instance). Thus, for example, Germany's offshore generation is increased to meet the needs of Austria, or Poland's to meet the needs of the Czech Republic. Compatibility with interconnection constraints will have to be validated by simulations.

Method for evaluating the Demand Side Response (DSR) potential

The next part of the study will focus on the evaluation of the ΣIDERWIN DSR potential, in particular its electrolyser potential, which represents a meaningful share of the total electricity demand. Given the electrolyser specifications, ΣIDERWIN should offer a great flexibility capacity, of up to 39 GW in a European scale, with great responsiveness and without duration or repeatability constraints. ΣIDERWIN could therefore contribute to the balance of the power system, and in particular replace at least part of the peak needs covered, in the initial scenario, by OCGT plants.

The curtailment of ΣIDERWIN to replace peaking OCGTs should have a positive impact on the CO_2 emissions of the electrical system, further improving the environmental balance of the steel industry. It would also mean a contribution to grid balancing by helping intermittent RES integration. In addition, financial gains might appear, either by avoiding the variable costs of thermal generation, and the fixed costs of building OCGT plants or by providing system services.

In the current article, we focus on the analysis of the potential environmental gains related to the DSR potential of ΣIDERWIN, based on one studied scenario. As mentioned before, several scenarios still need to be assessed in order to obtain consolidated data.

Preliminary results

In this section the results from one of the simulation scenarios are presented and discussed. The dataset analysed here concerns the conservative adaptation scenario, corresponding to a uniform increase in nuclear, solar, and on and off-shore wind power.

As these technologies account for 50 % of the total European electric generation, their production rate would need to be increased by 24 % in order to achieve a 12 % increase in the total electricity production in response to the additional ΣIDERWIN demand. Taking into account a slight decrease in the load factor

Table 2. Additional demand compared to adaptable generation by country.

Country	Siderwin Electric Demand (TWh)	% of Siderwin Demand in Country's Electric Demand	% of carbon-free generation that can be increased (Nucl + Wind + Solar)	% to be applied on Nucl + Wind + Solar
Europe	**471**	**12 %**	**50 %**	**24 %**
Germany	140	21 %	42 %	50 %
France	47	7 %	76 %	9 %
Great Britain	37	8 %	58 %	13 %
Italy	33	8 %	36 %	22 %
Austria	33	37 %	23 %	163 %
The Netherlands	32	21 %	29 %	71 %
Belgium	24	25 %	35 %	73 %
Czech Republic	23	24 %	61 %	39 %
Poland	23	9 %	44 %	20 %
Slovakia	20	48 %	64 %	75 %
Spain	20	6 %	71 %	8 %

of the nuclear power plants and an increase in the production curtailment related to the increase of solar and wind capacities, this number is adjusted to 30 %.

On this adapted fleet, the production of the thermal gas resources decreases by 8 % due to a drop in the load factor of the CCGTs. As a result, CO_2 emissions also decrease slightly (under 10 %): the impact on the decarbonisation of the mix is therefore positive in this scenario. More precisely, 13 million tons of CO_2 are saved in the conservative adaptation scenario studied and with the emission rate assumptions adopted, derived from [13] (350 g/kWh for the CCGT and 540 g/kWh for the OCGT). As a comparison, this corresponds to over a quarter of the CO_2 emissions of the French power system, which is already highly decarbonised. It should be noted that the closer we get to the decarbonisation objective, the more difficult it gets to eliminate each tonne of CO_2.

Curtailment, which corresponds to overproduction compared to consumption and occurs generally at times of high solar production, also increases, from 25 to 75 TWh. This volume remains marginal (less than 2 %) compared with the total European production (4,375 TWh). Nevertheless, it becomes significant in relation to solar production (15 %). And above all, it represents more than half of the solar production added compared to the reference data set (even if curtailment cannot be solely attributable to solar). This curtailment is mainly concentrated in Spain and Portugal, which already seem to be saturated in the EU Reference Scenario. This result illustrates the fact that the increase of the solar plants, whose generation is highly variable depending on the time of day and year, is not adapted to the ΣIDERWIN baseload demand.

Moreover, this simulation shows an additional potential for CO_2 emissions reduction related to the OCGT installed capacity: 55 GW are installed for an annual generation of 6 TWh (i.e. a load factor of 1.3 %). As ΣIDERWIN's cut-off capacity has a maximum of 39 GW in Europe, it could replace at best 70 % of the OCGT installed capacity and thus saving around 2 additional million tonnes of CO_2 for this adaptation scenario and the assumptions adopted.

A cut-off in electricity consumption of 4 TWh, which corresponds to this DSR profile, would lead to a very limited drop in steel production, of the order of one million tonnes out of a total of 132 million planned annually.

In addition, ΣIDERWIN's DSR service could also replace part of the OCCGs, further improving the carbon footprint. These results, which are only valid for the scenario studied, will be refined and compared with other adaptation scenarios in the coming months.

Conclusion – Future work

This paper presents a methodology that will be used to assess the impact of the ΣIDERWIN technology on the European power system with vary large share of renewable energies at the 2050 time horizon.

Lowering carbon emissions from heavy industry is a major goal for Europe in order to be carbon-neutral by 2050. The total substitution of present blast furnaces with the ΣIDERWIN technology in 2050, requires an adaptation of the electricity generating fleet to meet an additional demand of 470 TWh. This represents 12 % of the total European electricity consumption expected by 2050 and is of the same order of magnitude than as the consumption of France today. Adapting the European generation mix will require to take into account various constraints: political constraints linked, for example to the phasing out or capping of nuclear power and the acceptability of the development of renewable energies; but also physical constraints linked to the development potential of these renewable energies depending on their location and climate variations (particularly for off-shore wind energy). These constraints may lead to question the relocation of part of the steel plants close to the carbon-free generation or the resizing of interconnection capacities.

In this paper, starting from the reference scenario established by the European Union in 2016 for the horizon of 2050, a new dataset that describes the conservative adaptation scenario was established and studied, taking into account the additional ΣIDERWIN's electric demand. Considering an increase in solar, wind and nuclear production, the *Continental* software has optimized the thermal installed capacities (gas-fired power plants) and simulated the operation of the power system in Europe, showing the generation mix per country, the CO_2 emissions and the congestion at interconnections between countries. This first simulation shows a beneficial effect on CO_2 emissions for the adjusted electricity mix and an additional potential of further decarbonising the electrical system by the DSR contribution of the ΣIDERWIN plants.

In the coming months, more adaptation scenarios will be studied and compared in order to consolidate the results. In addition, more aspects will be assessed such as the economic aspect of the DSR flexibility of the ΣIDERWIN plants and its potential to replace part of the OCCGs, further improving the carbon footprint.

The results of this study [22] will be available in October 2020 and transmitted to the European Commission within the framework of the H2020 – ΣIDERWIN project [15].

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