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1 Executive summary

This deliverable summarizes different studies performed in the SIDERWIN project and conclude on the life cycle analysis of the SIDERWIN route, its techno-economic assessment, and its compatibility with intermittent sources. The technical performances of the SIDERWIN pilot have also been summarized in this deliverable, as well as its adaptability with alternative raw materials.

The conclusions of these different studies allow to define the following technology performance:

- SIDERWIN technology can contribute to future carbon neutral steelmaking with:
  - Almost no direct CO_2 emissions
  - At least -60 % carbon footprint compared to traditional BF-BOF route
  - Without compromising environmental footprint compared to BF-BOF route
  - Fully electrified primary production

- The pilot technical performances have been validated and optimal parameters for operation have been defined, the SIDERWIN technology has been successfully scaled up. The main results obtained from the pilot trials are:
  - It is possible to use cathode with size up to 1.25 m^2
  - The gas management is key, it has been found that decreasing the solid concentration in the electrolyte is helping to obtain a better gas management without degrading the faradic yield
  - Electrolyte flow uniformity is required, to avoid dendrite formation and the following short-circuits
  - Electrolysis cell energy use confirmed at pilot scale have demonstrated that the 2.7 MWh/t of Fe produced are reachable in optimized conditions
- The SIDERWIN technology can contribute to the balance of the power system with its fully electrified steel primary production. The European power system can meet the additional SIDERWIN demand with carbon-free means. As the SIDERWIN process is a flexible process with a low working temperature, it is compatible with Demand Side Response requirement which can boost the profitability of the process. Finally, the SIDERWIN technology can contribute to the deployment of RES.

- The SIDERWIN technology can contribute to circular economy, via the possible integration of raw materials. Among all the materials tested in the framework of the project, Mill scales from steel industry was the most promising one at this stage of technology development but more work must be done before scaling-up.

2 Technical content

2.1 Definition of the framework of the techno-economic and environmental studies

Prior to the techno-economic and environmental studies, a common framework has been defined between the different parties involved, to ensure a common basis for the evaluation of the investigated technologies. This common basis includes the definition of the scope of the studies (definition of the functional unit, systems to be studied, system boundaries, time horizon, reference technology used for the comparison…) as well as the data collection management plan to ensure good quality of the input data.

The ΣIDERWIN processing route includes not only the electrowinning cell, but the entire treatment pathway imagines around it, from the chemical and physical preparation of the ore to the melting and casting of the hot rolled coil steel. The complete ΣIDERWIN route, from iron ore to hot rolled coil, has been further described in the deliverable D7.3.

Two functional units (FU) have been chosen to realize the studies: the production of 1 t of mild steel as hot rolled coil, and the European total steel production.

Two life-cycle systems, defining the boundaries of the studied system, have been used in this work: a cradle-to-gate life cycle, where the gate refer to the hot rolled coil, and a cradle-to-grave life cycle, that will include the use stage and steel recycling, as illustrated in the Figure 1.

Figure 1 : Cradle-to-grave life cycle system for steel

The main reference system chose to make the comparison is the Blast Furnace system, followed by Basic Oxygen Furnace, referred as BF/BOF route in the following work. The ΣIDERWIN technology has been considered as combined with Induction Furnace (IF), to produce the hot rolled coil. The Direct Reduced Iron (DRI) technology has been set as a second priority.

The techno-economic and environmental studies assess both the current steel production as well as future time horizons. For the current production, data corresponding to the production of steel in 2018 with reference technologies have been used. Two future times horizons have been modelled: 2030, corresponding to the deployment of the first ΣIDERWIN plant and 2050, corresponding to the full deployment of the ΣIDERWIN technology.

As ΣIDERWIN technology is electricity intensive, its industrial development will have an impact on the European electricity system performance. The European power system configuration will then have an important impact on the ΣIDERWIN cost-effectiveness and environmental assessment. Therefore, it has been necessary to define development scenario for the European Power System on the Horizon 2030 and 2050. These two scenarios have been modelled considering the "EU reference scenario 2016 – Energy, transport and GHG emissions – Trends to 2050". For the horizon 2030, the EU reference scenario envisage that renewable energies would represent 50 % of the European net electricity demand. For the horizon 2050, renewable energies would represent almost 70 % of the European net electricity production.

The objective of the D7.1 was to define the data required for the realization of the techno-economic and environmental studies, as well as the study on the integration of the ΣIDERWIN technology in the electricity system with Renewable Energy sources. All the data required have been summarized in the deliverable D7.1 and are given in the Table 1. These data have then been used to realize the different studies that will be summarized in the following sections.

Table 1: summary table of data requirement for tasks 7.2, 7.4 and 7.5

Data type	Data source
T7.2 Data requirements for the process integration with renewable energies	
• Energy mix, demand level, energy prices	Data from EU Reference Scenario 2016
• Grid connections between European countries	Data from ENTSO-E (TYNDP) and e-Highway 2050 publications
• ULCOWIN industrial development hypothesis	Hypothesis and data from European project IERO
• ULCOWIN DSR profile	Data from SIDERWIN – WP2 – T2.5 and WP3 – T3.3
• European steel industry development	Data from professional associations like EUROFER and WORLDSTEEL
• Fixed costs (including investment costs) of electricity plants	Extrapolations based on RTE publications (RTE is the French electricity network operator)
• Minimum ULCOWIN DSR cost taken into account (the loss of income due to production stops)	Provided by N-Side as output of the techno-economic study T7.5
T7.2 output data	
• European energy mix • Electricity and carbon dioxide costs • ULCOWIN DSR contribution	• Data provided by EDF, • Reused for T7.4 and T7.5
T7.4 and T7.5: Technology related data	
• Raw materials input (iron ore, scrap, limestone, oxygen, etc) • Fossil fuel input (natural gas, coal, coke, diesel) • Electricity input • By-product output (oxygen, slag, scrap, etc) and possible waste disposal costs • Polluting gas emissions (CO_2, CO, SO_x, NO_x)	• IERO project • Ecoinvent v3 database • ULCOWIN: T7.3 results
T7.4 and T7.5: Energy market data	
• Electricity prices • Natural gas prices • Coal (and possibly coke) market prices	• EDF T7.2 • Literature or online resources

T7.4 and T7.5: Raw materials and by-product market data	
• Iron ore prices • Scrap buying price • Price of ferroalloys • Price of limestone • Slag reselling price • Scrap reselling price	AMMR, and also extracted from the literature.
T7.4 and T7.5: Environmental costs and restrictions	
• CO_2 emission allowances • CO_2 equivalent factors for other polluting gases (if applicable) • Restriction on maximum allowed emission levels (if applicable, e.g. for SO_x and NO_x) • Acquisition and assembly cost of gas treatment technologies (e.g. for SO_x and NO_x) • Operation and maintenance costs of gas treatment technologies	• Literature • Existing European policies
T7.4 and T7.5: Miscellaneous data and information	
• Technology lifespan through the life cycle length. • Actualisation rate • Various growth rates (on energy prices, prices of raw materials, labour rates, etc)	EDF's and AMMR's estimations
T7.5: Electricity mix data	
• Modelled electricity mix in 2050	T7.2 EDF
T7.4 and T7.5 output data	
• Minimum ULCOWIN DSR cost • LCA and LCC results • Techno-economical analysis results	• Data provided by Quantis and N-Side • Minimum ULCOWIN DSR cost reused by EDF for T7.2

2.2 Material and Energy Balances of the ΣIDERWIN processing route

The material and energy balances of the overall ΣIDERWIN processing route, from iron ore to hot rolled steel coil, have been assessed in the deliverable D7.3. These data were necessary to establish the following Life Cycle Analysis and Life Cycle Cost of the overall ΣIDERWIN process. The study has been made according to the cradle to gate life cycle defined in D7.1, from iron to hot rolled coil (HRC).

The mass and energy balances of the overall process have been calculated and extrapolated for a steel production of 4 Mt/year. Some of the steps of the process have not been applied experimentally to the ΣIDERWIN process and are drawn from existing industrial processes such as Bayer process, leaching of nonferrous metals, alkaline water electrolysis… This study only gives the degree of feasibility and technological advancement of each processing step.

The input iron ore chosen has a composition that is representative of the mineral complexity of commercial iron ores, after beneficiation. The output is a Hot Rolled Coil.

The overall ΣIDERWIN processing route is described in more details in the deliverable D7.3. The thermodynamic possibilities of each stage have been proven according to data available on the literature and the technical feasibility is estimated based on commercial processes applied in other metallurgical industries. The Technology Readiness Level of each stage has been determined based on the existing processes in other industries. The equipment is sized to achieve a production rate of 4 Mt/year of HRC.

The ΣIDERWIN process is a complex arrangement of several operations.

The overall energy balance of the ΣIDERWIN process has been established. The process only relies on externally supplied electricity. The most energy consuming step is the electrowinning step, followed by the Induction Melting step and the Steel Hot Rolling Mill step. The total electricity consumption of the overall process is 4.3 MWh/ton of HRC.

2.3 Compatibility with intermittent sources

As ΣIDERWIN is a reactive and flexible electrolysis process enable to participate in the demand-side response (DSR) market, the technology could provide a useful contribution to the European power system. However, the total substitution of the coal based European primary steel industry by ΣIDERWIN technology would implies an important additional electricity demand up to 470 TWh, corresponding to the actual overall French energy demand. This important demand, associated with the ΣIDERWIN's DSR ability, indicate that ΣIDERWIN could play a significant role in the future power system. In this context, the goal of the Deliverable D7.2 was to evaluate the influence of a ΣIDERWIN industrial development on the future European power system, in terms of electricity demand, contribution in grid balancing, while avoided emissions and costs for the system. The horizon of time taken into account is 2050, as in the rest of the WP7.

The methodology developed to realize this study is based on an EDF internal application called Continental. The methodology is further described in the deliverable D7.2. A lot of input data have been needed to define the steel industry and the European power system in 2050, in terms of production level, location of the steel making plants, electricity demand for each European country, grid capacities and interconnections, electricity production mix and climate variations. The dataset used for this study is described in detail in D7.2 and is based mainly on public data, to be consistent with the European Commission's vision of the future. Four different datasets have been generated to evaluate the impact of ΣIDERWIN industrial development on the European power system:

- Dataset 2030 without ΣIDERWIN
- Dataset 2050 without ΣIDERWIN
- Dataset 2050 with ΣIDERWIN but without DSR contribution
- Dataset 2050 with ΣIDERWIN and with DSR contribution

As this study has been performed before the finalization of the D7.3 (defining the Material and Energy Balances of the ΣIDERWIN processing route), the ΣIDERWIN overall process used in this study is not completely the same than the one defined in D7.3. Only the electrolysis part of the process, consuming 2 720 kWh/ton of Fe, is considered as a potential DSR contributor. It has been defined in the study that the overall ΣIDERWIN process is a continuous operation, operating 24h/24h and 365 days per year, with a common 5 % of interruptions for maintenance and regulatory control. The electrical power associated to the electrolysis part is then: 2720 / (365 x 24 x0.95) = 0.33 kW/t_{Fe}/year. According to the deliverable D3.3 of the WP3, only 10 % of the ΣIDERWIN electrolysis power is necessary to be maintained during electrolysis interruption, to ensure a cathodic protection. 90 % of ΣIDERWIN electrolysis power could then be modulated or stopped without Notice Period (NP) and activation/deactivation (AP/DP) period. The available power for a DSR contribution is then: 0.9 x 0.33 = 0.29 kW/t_{Fe}/year. The activation cost for ΣIDERWIN DSR contribution has been determined at 130 €/MWh.

According to the prevision provided by EUROFER association, the European crude steel production would grow by 0.8 % annually and should reach a production of 236 Mt/year in 2050, with a 44 % share of secondary steel making production. The share of primary steel production in 2050 is then estimated at 132 Mt/year. It is considered in the rest of the study that the integrality of the primary steel production will be assured by ΣIDERWIN process in 2050. This yield to an additional electricity demand estimated at 471 TWh per year in 2050. The power demand is evaluated at 53.8 GW at European level, in which 42.8 GW are due to electrolysis. Considering that 90 % of ΣIDERWIN power demand can contribute to DSR, 38.5 GW can be cut-off at European level, corresponding to 8 % of the overall European power demand. The share of the ΣIDERWIN electricity demand compared to the electricity generation of the country has been calculated for some European countries, and the results are given in Figure 2. The ΣIDERWIN electricity demand account for 12 % of the total European electricity production. With the current BF/BOF steel production route, 142 kWh per ton of steel produced are send to the electricity grid, this lack of electricity produced has also been considered in the study.

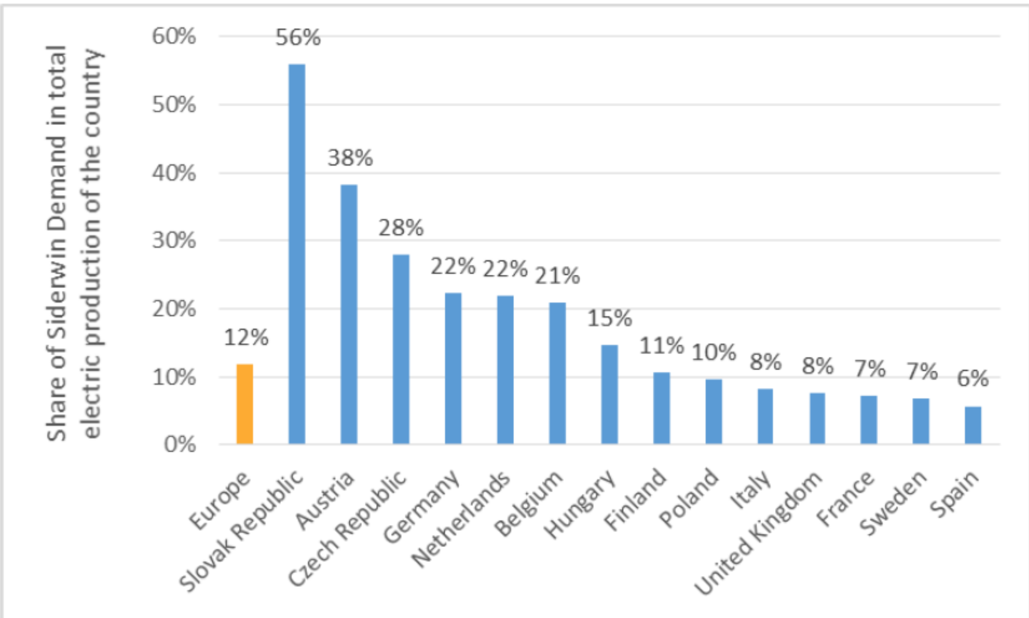

Figure 2: ΣIDERWIN electricity demand compared to the electricity generation

The dataset for the future European system for 2030 and 2050 has been built using the 2016 European Reference Scenario, which provides, from 2015 until 2050, the production and installed capacity by technology (nuclear, wind, solar, etc.) as well as net import by country. The electricity generation mix modelled for 2030 and 2050 are given in Figure 3. The total European generation and demand increase by 15 %, and according to the carbon neutrality objective, the part of coal in the energy mix drops from 12 % to 4 %. In contrast, the share of RES in the mix raises from 46 % to 57 %.

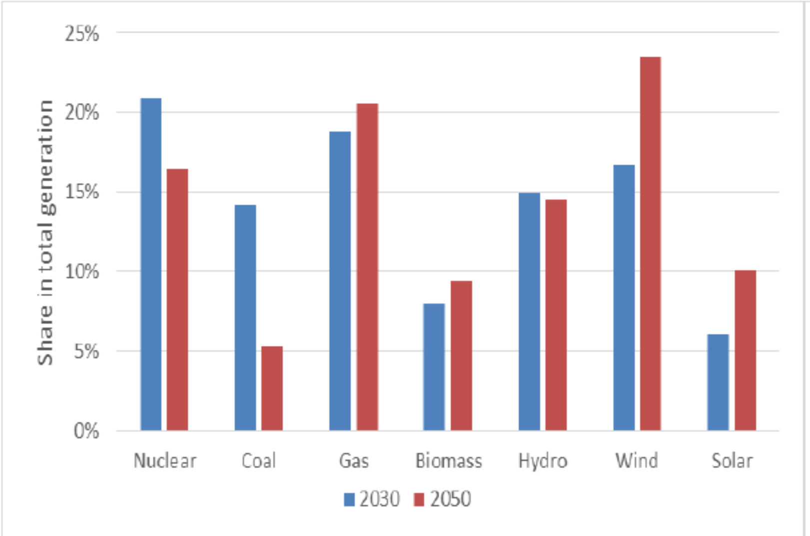

Figure 3: electricity generation mix in Europe in 2030 and 2050 (without ΣIDERWIN)

To model the ΣIDERWIN impact on the electricity demand, two sources have been considered as the best candidate to meet the additional ΣIDERWIN demand: nuclear and offshore wind. Three strategies have then been studied for the adaptation of the power system to supply the ΣIDERWIN additional demand:

- With a nuclear generation only (noted "Nuclear" in the rest of the study)
- With a mix of 50 % offshore and 50 % nuclear (noted "Combined" in the rest of the study)
- With offshore generation only (noted "Offshore" in the rest of the study).

The details of the locations of the additional electricity generation needed for ΣIDERWIN are given in the deliverable D7.2. Almost 60 % of the additional nuclear power generation would be located in France and Great-Britain and almost 60 % of the additional offshore power generation would be located in France and Germany.

All these data have then been used to model the impact of the ΣIDERWIN demand and its flexibility potential on the European power system by analyzing the following elements:

- The transformation of the European power system: evolution of the installed capacity and generation of each type with their respective share, and load factors,
- The direct CO_2 emissions of the power system,
- The cost of the power system,
- Interconnection flows countries.

The evolution of the generation mixes in Europe for 2050 considering the impact of the ΣIDERWIN demand is given in Figure 4, "Initial" referring to the scenario without ΣIDERWIN. It appears that in the Nuclear-only variant scenario, the nuclear share in the energy mix increase from 16 to 25 %, corresponding to a 70 % increase of capacity, this increase being distributed between the European countries that have not decided to go out of the nuclear power. For the offshore wind only scenario, the share of this sector increases from 8 % to 17 % of the overall production mix, this increase being distributed between countries with access to the sea. The "Combined" scenario leads to an increase from 16 to 20 % of the share of nuclear power, with an increase from 8 to 12 % for offshore power. The integration of ΣIDERWIN doesn't have a significant impact on the thermal generation (noted gaz in the figure), for the 3 scenarios studied.

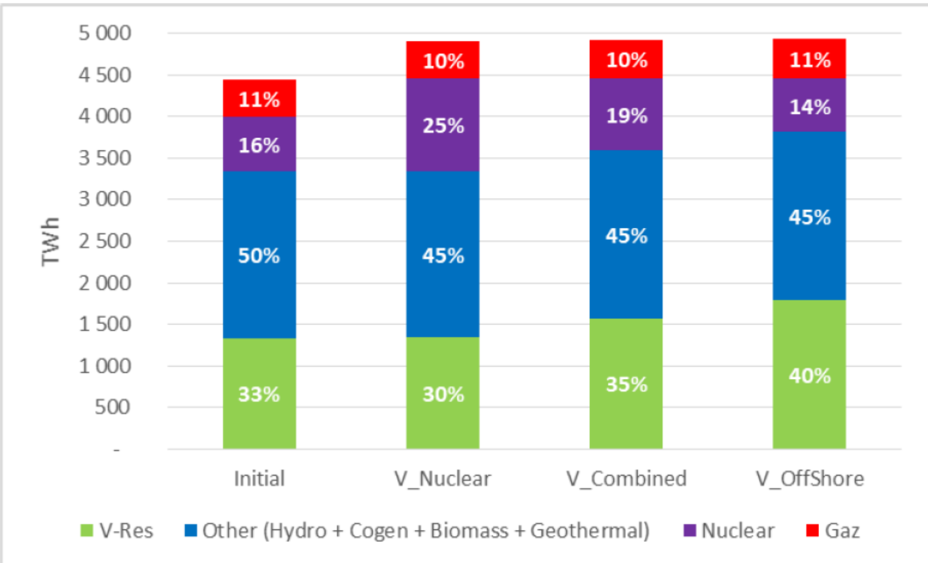

Figure 4: evolution of generation mixes in Europe in 2050 considering the impact of the ΣIDERWIN demand

It also comes out of this study that adapting the power system to ΣIDERWIN additional demand has very low impact on nuclear load factors.

As the ΣIDERWIN additional demand will be provided only by carbon-free energy sources (nuclear and offshore wind turbines), ΣIDERWIN will have no negative impact on CO_2 direct emissions for the electricity generation. A more detail analysis of the impact of ΣIDERWIN on CO_2 emissions is given in D7.2.

The impact of ΣIDERWIN on the generation costs of the electrical system has also been studied. These costs are used to estimate the electricity prices up to 2050 and the cost of cut-off activation, which can be defined as the loss of income due to the loss of steel production because of cut-off activation. The estimation of the electricity prices for 2050 poses some methodological difficulties, then 3 different approaches have been used for the estimation, described in detail in D7.2:

- Use the short-term marginal cost, which corresponds to the variable cost of the most expensive technology activated at each time in the merit order
- Use of average full cost per MWh
- Use of long-term marginal cost, representing the increase of total production cost due to the insertion of ΣIDERWIN use, by comparing full cost of generation fleet with and without ΣIDERWIN consumption.

The results obtained are described in detail in D7.2.

The impact of the DSR service of ΣIDERWIN has also been evaluated, as it gives the possibility to replace a large part of the peak-load means (OCGT) at periods of high demand and/or low-RES generation. This DSR service generates significant savings on the European power system, that can be calculated as the difference between the full generation cost of the power system with and without DSR service, for each of the adaptation variants, integrating both the gains and CAPEX/OPEX. The DSR profile, depending on the cut-off activation of the different European countries, has been determined and deeply discussed in D7.2. The average cut-off time is estimated around 4 % of the time on average in each country. The number of cut-offs is a few dozen per year, depending on climatic years (around 40 in France and 70 in Germany). About a third of them have a duration of less than two hours, about 10 % last more than ten hours with even rare episodes of more than one day.

2.4 Life Cycle Analysis

The LCA study has been realized by Quantis in the D7.4 and D7.5. The objective of the study is to determine whether the ΣIDERWIN technology can be an appropriate solution to reduce the greenhouse gases emission of the steel industry, to achieve a low carbon economy by 2050.

2.4.1 Context and objectives

The European Commission has set a long-term goal of becoming carbon neutral by 2050. As the steel industry is responsible for around 5% of Europe's GHG emissions, the steel sector needs to use breakthrough decarbonized technologies to contribute to this goal. One such potential technology is the SIDERWIN technology which aims to electrify the steel production process. The work performed in D7.4 and D7.5 focusses on assessing the environmental performance of the technology. The goal is to assess how well the SIDERWIN technology performs environmentally compared to the reference technology Blast Furnace followed by Basic Oxygen Furnace (BF-BOF) as well as the hydrogen direct reduced iron (H-DRI) technology, another low emitting technology currently being developed.

2.4.2 Methodology

This LCA follows the International Organization of Standardization (ISO) 14040 and 14044 standards for a comparative assertion and public disclosure. This study assesses the life cycle of steel with a focus on its manufacturing, from the extraction and processing of all raw materials through the end-of-life of all components. The main functional unit for this assessment is 1 t of hot rolled coil (HRC). Hence, the results are shown per t HRC. For each technology, two different scenarios are assessed, which come from different electricity mixes which are used to cover the energy demand.

One scenario is based on the electricity mix developed by EDF in D7.2 of this project, which includes demand side response (DSR). This is an electricity mix which is a realistic projection for the European grid electricity mix in 2050. The other scenario uses a fully renewable mix, meaning it's the same mix as for the latter scenario only without gas and coal with CCS. It is a hypothetical mix which is hardly realistic in the timeframe of this study. On a longer term, a fully renewable mix might be possible. It was added to the study in order to understand the maximum potential of SIDERWIN if a renewable mix was available.

For BF-BOF, the two scenarios refer to the addition or not of metal alloys to produce steel. The "BF-BOF Ecoinvent non-alloyed steel (BAT)" was included to provide an approximation of the average low alloyed steel grades while the reference scenario ("BF-BOF Ecoinvent low alloyed steel (BAT)") is considering steel with high ferronickel content which is not representative of low alloyed steelmaking production. To have a full picture of the environmental impact of all assessed technologies, not only climate change impacts are considered but also other indicators such as water use, land use, human health, ecosystem quality and energy demand. However, the focus lies on climate change as this is the main driver for the development of this technology. This assessment is based on electricity mixes and projections of the SIDERWIN performance for 2050. However, for the model only databases for 2020 exist. Hence, the model does not consider that other sectors, such as iron ore mining or producers of additional inputs such as titanium might decarbonize as well. Hence, it is possible that the calculated results are slightly overestimating SIDERWIN's emissions.

The three routes studied in the report do not have the same technology readiness level. The BF-BOF is fully industrial and proven, which is why a lot of real industrial data are available. The data used in this project for the BF-BOF route are taken from ecoinvent. The dataset can only be considered as an approximation for today steelmaking since some of the original data sources are partly outdated. The H2-DRI route is based on the DRI technology, which is also well proven, except that there is no industrial example of DRI using hydrogen. It was thus not possible to use industrial data but instead, this study uses adapted ArcelorMittal internal data. Finally, the SIDERWIN route is a complete breakthrough route. Data used are coming from the mass and energy balance developed in this project (D7.3).

2.4.3 Results and discussion

Figure 5 shows that the SIDERWIN and the H-DRI technology perform better in term of carbon footprint than the currently used BF-BOF. For the SIDERWIN technology with DSR, mixed, the carbon footprint amounts to 0.9 t CO_2eq which is 60% lower than the BF-BOF technology. With the renewable electricity mix, the total carbon footprint is 0.6 tCO_2eq which is a reduction of 74%. The H-DRI technology has a similar carbon footprint than SIDERWIN with 1.1 t CO_2eq with DSR, mixed and 0.7 t CO_2eq with DSR, renewable, which represent reductions of 50% and 71%, respectively. The uncertainty of the inventory data for SIDERWIN and H-DRI is high, which is why compare the environmental preferability of these two technologies has not been compared in the deliverable 7.4 and 7.5.

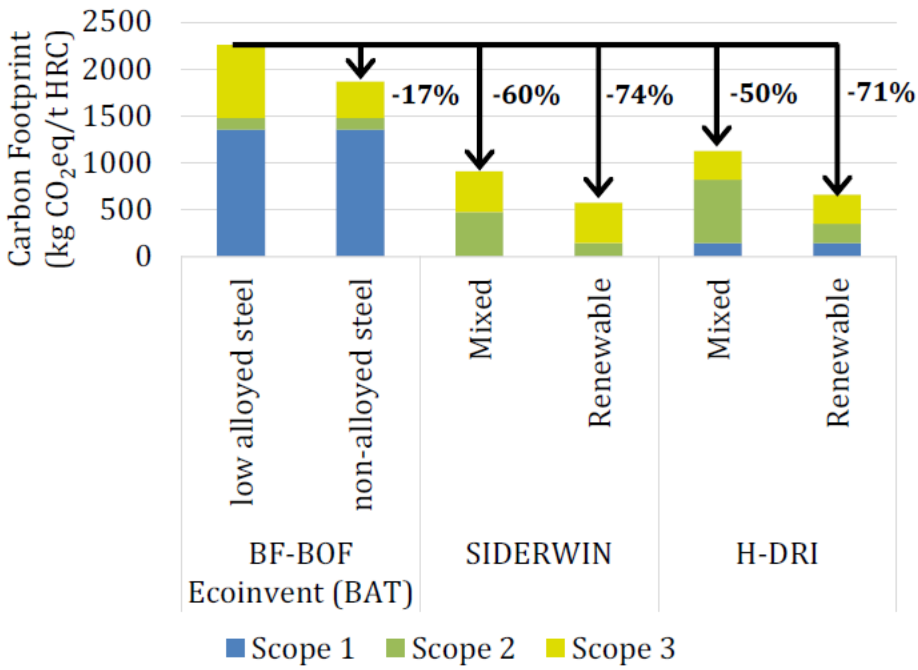

Figure 5: Total carbon footprint of SIDERWIN, once with DSR, mixed and once with renewable electricity mix, compared to BF-BOF and H-DRI

When looking at the scopes, it can be seen that SIDERWIN has no direct emissions which occur on site as it doesn't use any natural gas or coal compared to BF-BOF. Thereby, it has to be noted that the SIDERWIN route developed in this project was optimized to have no scope 1 emissions. The industrial feasibility of such a route has still to be proven. Scope 2 emissions, which are indirect emissions coming from the electricity mix, on the other hand, play a very important role for SIDERWIN as well as H-DRI. A similar impact comes from scope 3 emissions, which are indirect emissions from purchased goods used for the production of steel.

These results show that SIDERWIN has a lower carbon footprint compared to BF-BOF. However, the other indicators show some trade-offs. SIDERWIN with DSR mixed has a 9% higher water consumption than BF-BOF. This mainly comes from evaporated water during hydropower production. Meanwhile, land use is 126% higher with SIDERWIN than with BF-BOF. SIDERWIN has a 43% lower human health impact and a 15% lower energy demand than BF-BOF. Given that globally, the influence of the steel industry on water consumption and land use is relatively low, the materiality of these two indicators is lower than for human health and energy demand.

Hence, it can be concluded that overall, the environmental impact of SIDERWIN allows a carbon footprint reduction with reduced trade-offs compared to BF-BOF.

If 100% of Europe's steel production (corresponding to 5% of the current CO2 EU emissions) was produced using the SIDERWIN technology in 2050, the steel industry could contribute to Europe's emission reduction goal with a reduction of 3%.

2.5 Techno-economic analysis

The techno-economic analysis has been realized by Recoy in the WP7 and is described in detail in D7.6. It gives insights on the economic viability of the SIDERWIN Technology. The methodology of the techno-economic analysis is described in detail in D7.6. The objective of the analysis is to assess the profitability of the SIDERWIN technology. It would help bridge the "valley of death" between technology readiness level (TRL) 6 and 8, where investments in new technologies are on the one hand too risky for commercialization and on the other hand are too high for pure research programs. The TRL for every SIDERWIN process step was established in report D7.3.

The financial metrics are calculated over the whole lifetime of a SIDERWIN plant. With the lifetime assumed to be 20 years, for the financial metrics to be calculated for 2050, the final year that data will be calculated for is 2070. This is illustrated in Figure 6.

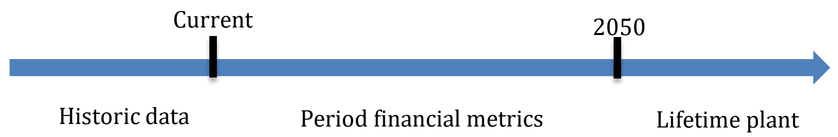

Figure 6: timeline of the techno-economic analysis

- 2020 = beginning of the SIDERWIN industrial development (first plant), reference year of used databases.
- 2050 = end of the SIDERWIN industrial deployment[1] (100% of the European primary steel production), modelled year (based on electricity mixes).

It was decided not to use BF-BOF technology (this is Blast Furnace followed by the Basic Oxygen Furnace) as a reference technology as the goal is to replace it. The main focus of the techno-economic analysis was the SIDERWIN technology. However, H-DRI was used as a reference technology and compared financially, as it is a competitive technology of SIDERWIN.

The different metrics used to perform the analysis are described in D7.6.

Overall, the analysis integrates three distinct factors of influence:

1. the technology (SIDERWIN route),
2. the time horizon (e.g., now, 2030 and 2050),
3. the assumed scenario characterizing future market trend.

In order to frame the techno-economic analysis, for each analysis parameter (such as electricity price or electrolysis cell efficiency), the impacting factors of influence have been identified, i.e., the factors that have an influence on the parameters' value.

As it is common practice in long term techno-economic assessment, this analysis relies on three main scenarios to characterize future market trends. The main parameters making up the scenarios are the Iron ore price, the Electricity price and the HRC Steel price.

1. A standard scenario: it assumes a continuum on the evolution of RES development in Europe and progressive decarbonisation based on EU countries commitments and targets. This scenario has served as a baseline.
2. A favourable scenario: in this scenario, the integration of RES in European energy mix exceeds the usual expectations, leading to decreased electricity prices. This scenario is obviously favourable to the integration and development of the SIDERWIN technology.
3. An unfavourable scenario: this scenario is basically the opposite of the previous one. In this case, it is assumed that decarbonisation targets of the European member countries are only partially met, with electricity prices staying relatively stable in terms of average value over the 2050 horizon. This scenario is once again referred to as *unfavourable* with respect to the SIDERWIN technology characteristics.

The different assumptions made to define boundaries to the techno-economic assessment are described in the corresponding deliverable.

In order to assess the economic robustness of the SIDERWIN steel production technology, the assessment requires cost data (CAPEX and OPEX) as well as

[1] assumption made for the purpose of this study, business plan and penetration to be further studied

economic data (revenue data, electricity prices, etc.). The data for the SIDERWIN production pathway is based on specific data from ArcelorMittal. The data from the pilot plants is used and extrapolated for this study. It was mainly taken from D7.3, and some additional information was provided by ArcelorMittal directly. All these data are summarized in the D7.6 together with the growth rates of materials input and output prices.

The findings of a comprehensive life cycle cost analysis that includes a net present value analysis and internal rate of return for multiple scenarios, have been presented in the results section of the deliverable D7.6. The study considers various scenarios to evaluate the financial implications of different investment options. These scenarios include different electricity prices, iron ore prices and HRC steel prices over the lifetime of the system. The net present value analysis takes into account the time value of money and discount rates to determine the present value of all costs and benefits associated with each scenario.

Overall, the life cycle cost analysis and net present value analysis provide a comprehensive understanding of the long-term financial implications of various investment scenarios.

2.5.1 Life cycle cost analysis

The five cost factors considered are Energy, Consumables, reactants and other utilities, Direct operating labour, Maintenance, Overhead, and Capital recovery. Energy costs are associated with the use of electricity, fuel, and other forms of energy. Consumables/Direct Operating Labour costs are related to the use of materials and labour needed to keep the process running. Maintenance costs are associated with upkeep and repair of the equipment used in the process. Overhead costs include administrative expenses such as office space and salaries. Capital Recovery costs represent the costs of financing and recovering the initial capital investment in the equipment used in the process.

The calculation of the total LCC for the entire electrolysis steel-making process is detailed in the deliverable D7.6. The LCC per ton HRC represents the value of the LMC KPI using the current data, with the cashflows discounted over the assumed lifetime of 20 years of a SIDERWIN plant. How this influences the valorisation of SIDERWIN's flexibility and how it changes the NPV over the coming decades will be discussed next.

2.5.2 SIDERWIN operational flexibility value

Energy consumption flexibility has become an increasingly valuable asset in recent years due to the volatility of prices in the electricity markets. The need for flexibility arises due to the inherent intermittency of sustainably produced electricity through solar and wind. In order to safeguard the integrity of the network, balancing services are required which the network operator can obtain through various commercial mechanisms, such as so-called imbalance and reserve markets.

These markets operate on a supply and demand basis, and prices can fluctuate significantly based on factors such as weather conditions, changes in consumer demand, and availability of generation resources. As a result, businesses and that are able to adjust their energy consumption patterns in response to these price fluctuations can potentially save significant amounts of money on their energy bills. This flexibility can be achieved through a variety of means, such as using energy storage systems, implementing demand response programs, or simply adjusting energy usage patterns to take advantage of low-price periods.

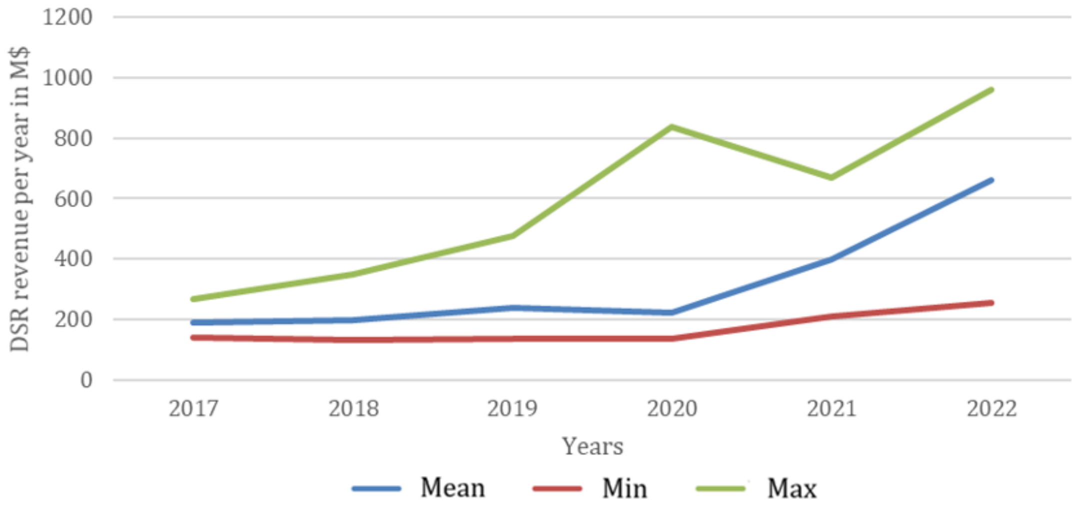

Figure 7: Graph showing the mean, min and max DSR revenue

Figure 7 above shows the value of flexibility that the SIDERWIN technology has as an average, min and max value in Europe over the last 5 years. What shows is that (i) the values are increasing over the years with the introduction of more and more intermittent production and (ii) that the values are significant.

2.5.3 Net present value analysis

Net Present Value (NPV) analysis is a widely used financial tool that helps assess the viability of an investment project. An NPV analysis for the SIDERWIN technology has been realized in the D7.6, taking into consideration all the CAPEX and OPEX including from the three components that are varied in the scenarios, namely the electricity price, iron ore cost and hot rolled coil price. The purpose of this analysis is to evaluate the financial feasibility of the technology under the three different scenarios: unfavourable, standard, and favourable. The results of this analysis provide valuable insights for the stakeholders of the technology and can help them make informed decisions based on the expected returns and risks involved. The detailed results are discussed in the corresponding deliverable.

The economic results show that the SIDERWIN technology has sufficient economic potential to be profitable from 2030 onwards.

This is true if sufficient recognition is given to the value of flexibility inherent in the technology. It is important in the design of future plants based on the SIDERWIN technology to take this into account. In addition, there may be further commercial benefit to the sustainable nature of the technology through the issuance of green certificates. However, the exact size of this benefit is hard to assess given the uncertainty as to the size of the market of these certificates and the prevailing prices at the time of commercialization of the SIDERWIN technology.

Whilst the current assessment is positive, there is still a lot of uncertainty surrounding the technology. This is mainly so because of the TRL at the current stage of the SIDERWIN development. The uncertainty manifests itself both through the remaining technological developments and hence the costing as well as the commercial parameters impacting on the economic business model (i.e. electricity prices, steel prices etc.).

As a conclusion, the techno-economical study has shown the potential of the SIDERWIN technology in terms of economic viability in its current stage of development. Therefore, there is no reason not to consider moving the development further towards commercialization from an economic point of view.

2.6 Pilot Technical performance

2.6.1 Presentation of the pilot

The task 5.1 of the SIDERWIN project was focused on the pilot commissioning. The activity started at the end of June 2021. The full commissioning and the description of the pilot is given in the deliverable D5.1. The commissioning was performed in a tight collaboration between John Cockerill and ArcelorMittal.

Figure 8 : The SIDERWIN pilot after the end of the assembling phase

2.6.2 Operation of the pilot for iron production

2.6.2.1 Optimization of the cell gas management

The first trials on the pilot have been realized in the previously defined optimal conditions, based on the ULCOWIN experiments: 50 wt. % NaOH electrolyte containing 33 wt. % of synthetic hematite. The cathode used was a graphite cathode with a size of 2.75 m^2. The anode was a honeycomb nickel anode. The applied current was 2 750 A corresponding to a current density of 1 000 A/m^2, as previously defined in ULCOWIN pilot. The 2 trials lead to the obtention of a fragmented iron deposit, as illustrated in Figure 9.

Figure 9: top view of the cathode covered by the fragmented iron produced during the trial carried out on April 22.

The fragmentation of the deposit has been attributed to a bubble accumulation inside the cell, which could lead to non-uniformity of the current density and imply fragmented deposition.

Some modifications have then been made on pilot to have a better gas evacuation: opening the evacuation on the top of cell, reducing the electrolyte flow, reducing the hematite concentration from 33 wt. % to 15 wt. % and reducing the current to 1 000 A. These modifications have been tested on 2 trials which lead to less fragmented iron plates, and some further modifications have been made to further improve the gas management. These modifications are described more in details in the deliverable D5.2 and briefly consisted of a reduction of the cathode size and a reduction in the current density. These modifications led to the obtention of the first non-fragmented iron plate in July 2023, as illustrated in the Figure 10.

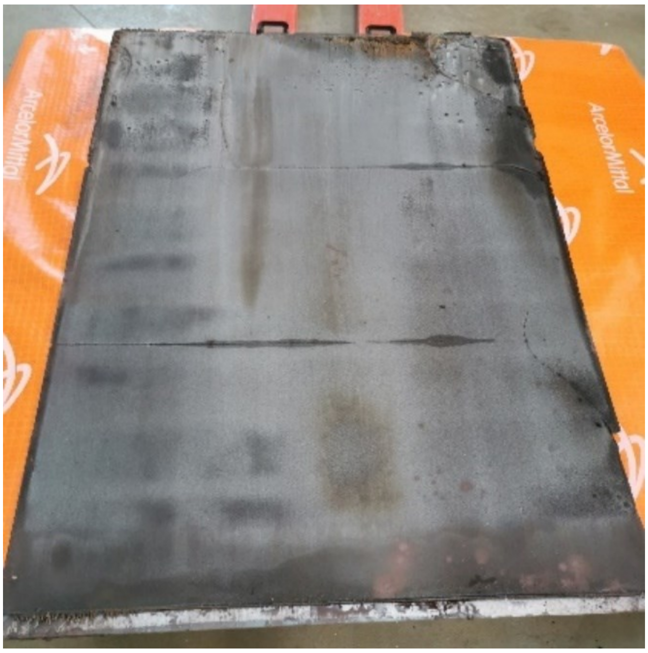

Figure 10: Iron plate produced on the Siderwin pilot with the reduced cathode (15 kg).

2.6.2.2 Optimization of the electrolyte flow circulation

The development of dendrites has been observed during this last trial, which grew and touch the anode, causing shorts-circuits between the two electrodes. This resulted in a loss of current instead of using it for iron production. The dendrites on the iron plate were observed mainly near the electrolyte inlet, where a gap of a few millimeters before the cathode electrolyte inlet caused interference with the electrolyte flow. To solve this issue, a PEEK plate has been positioned in the electrolyte entry before the graphite cathode to ensure a well-steady regime when the electrolyte reaches the cathode. As a result of these modifications, an iron plate without dendrites was produced, as shown in Figure 11.

Figure 11: Iron plate produced on the Siderwin pilot with the modifications made on the cell to improve the electrolyte flow.

2.6.3 Iron plate quality

The iron plates produced on the 6 trials with the reduced cathode have been analyzed by XRD. The results are given in the deliverable D5.2 and it is observed that the average metallic iron content across the different trials was found to be around 96% and can be up to 98.7 % under stable working conditions, the magnetite content was less than 4%. Additional analysis have been carried out by SEM and EDX to examine the surfaces and cross-sectional structure of the deposits. These results are described in detail in the deliverable D5.2. The cross-section analysis reveals that the deposit is compact and homogeneous when the experiment is performed without interruption.

The EDX analysis reveals the presence of some polluting element like Ca, Si and Ni which can come from different pollution sources. Oxygen was also present on the two electrode surfaces, which reveals the presence of iron oxide.

The faradaic yields corresponding to these 6 trials performed on the mini cathode have been determined and are summarized in the deliverable D5.2. The faradaic yields have been determined by 2 distinct technics, based on the weight of the iron plate produced for the first one, and on the amount of hydrogen produced for the second one. It has been shown that it is possible to reach high faradaic yield, close to 90 %, under stable working conditions.

2.6.4 Energy consumption

The energy consumption of the cell during the different trials carried with graphite mini cathode was evaluated, and the results are presented in Figure 12 and described in detail in deliverable D5.2. The figure demonstrates that achieving the specified energy consumption of 2.7 MWh/t is possible under optimized conditions (i.e., thermal stability, good gas management, and uniform and stable electrolyte flow), such as those observed in trials #2, #3, and #6. However, in trials #1, #4, and #5, the specific energy consumption was higher due to short circuits caused by dendrites or/and non-optimized operating conditions or/and equipment issues.

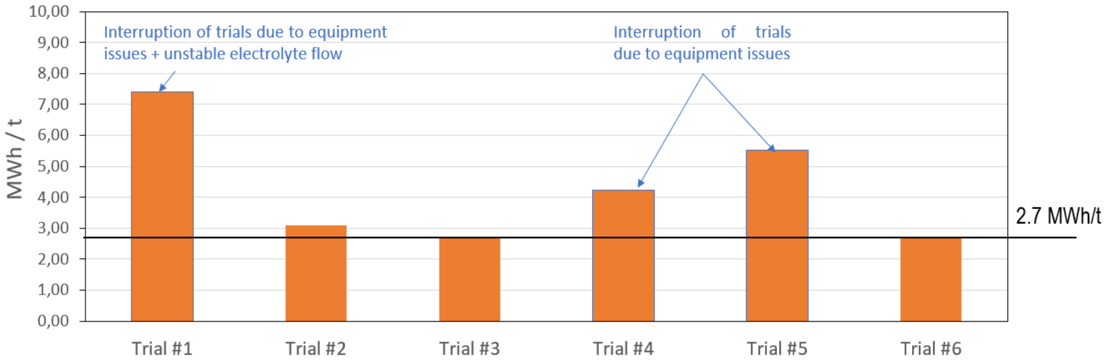

Figure 12 : Specific energy used for iron electrolysis (MWh/t) during the different trials performed on the pilot plant with the graphite mini cathode.

2.7 Validation of the ability to operate in and on-demand mode

The power demand of the cell and its ability to interrupt temporarily its consumption in accordance with the grid operators' specifications was evaluated in the task 5.4 and described in the deliverable D5.4.

Because the electrical heating operations represent an important part of the pilot's power demand, so an additional and significant flexibility reserve, the objective of the task has been extended to the entire process, not only the cell.

In the test procedure carried out in this task, the load curve of the SIDERWIN pilot is characterized for a production cycle of an iron plate under specific conditions, considering several technical and organisational evolutions implemented during the operating tests to stabilise the process. The pilot's electricity consumption for an entire production cycle is 622kWh. The power demand is flat and set on the nominal power for each stage of the cycle. In addition, this report highlights the significant share of the heating elements in the electricity consumption (almost 85%) and the level of power demand at each stage of a production cycle.

The graph below summarises the load curve of the pilot and the level of erasable power at each stage of a production cycle (1/ Preparation of the electrolyte; 2/ Introduction and heating of the electrolyte in the loop; 3/ Electrolysis; 4/ Hot rinsing followed by 3 flushes and extraction of the plate produced).

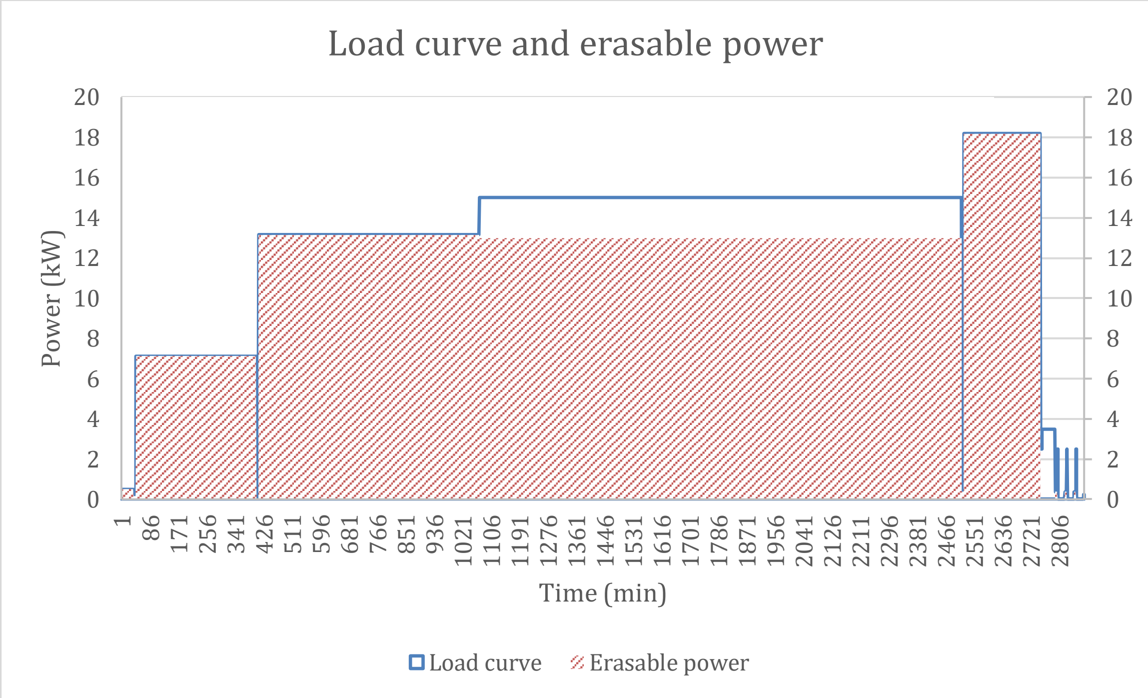

Figure 13: Load curve of the pilot and erasable power

The level of reactive power and the power factor were defined thanks to measurements carried out on the general power supply of the pilot during the electrowinning stage. The reactive power is about 30% of the active power and is satisfactory in comparison with the billing limit set in France at 40% but could be improved by the implementation of a compensation system (correction capacitors).

The pilot's ability to ramp up and down on demand was validated by the flexibility test procedure for each stage of a production cycle. The main electrical consumers, heating elements and electrolyser, implemented at the different stages of the process, are easy to control independently and have an excellent responsiveness to cut-off as the power can drop from full power to 0 in less than 100 ms on request. This level of responsiveness means that this process could, at an industrial scale, be positioned on the most challenging and profitable demand response markets, such as the *interruptibility* mechanism in France, which requires a maximum delay of 5s.

With the objective to take part of the demand response markets, the SIDERWIN process could integrate cut-off sequences in its programmable logic controller, differentiated for each production stage, making it possible to target interruptions to the desired consumers, while keeping active some other equipment required to prevent damage or quality defect (agitators, circulation pumps, heating elements during the electrolysis phase, etc.). Within the framework of the test procedure, these targeted interruptions were simulated manually with the monitoring system.

For the flexibility tests, interruptions of the heating elements were maintained for more than an hour for the electrolyte preparation, electrolyte heating in the loop, and rinsing phases. Naturally, because of heat loss during the interruption periods and despite the insulation implemented, a relatively long recovery phase is systematically observed at the restart of the heating elements to recover power and temperature setpoints because of the heating elements' power limits. This deactivation period increases the production cycle duration and the specific power consumption. However, this is not the case for the electrolyser, for which the power and production recovery is almost instantaneous provided that the temperature conditions remain stable during the cut-off period.

During the electrolysis phase, the electrolyser interruption was too short to observe the effects of a prolonged shutdown on the behaviour of the pilot. In addition, due to technical difficulties encountered during the operating tests, it was not possible to achieve a stabilised and reproducible production cycle, and so to compare a reference iron plate with a plate from an interrupted cycle. Consequently, the potential effects of interruptions on the product quality were not evaluated. This was the limit of the flexibility test procedure, but it should be pursued in the future.

In conclusion, apart from the above-mentioned limitations of the procedure, the flexibility tests have shown that the SIDERWIN process is easy to control (targeted interruption sequences could be easily programmed in the PLC), flexible and responsive, and that its behaviour, extrapolated at an industrial scale, is compatible with the specifications required by the most challenging and profitable demand response markets. On the other hand, due to the importance of heating operations in the power demand of the pilot, it is recommended that the further development of this technology should consider the thermal integration possibilities with other cells or nearby electric arc furnaces, in order to minimise the power and cost of the electrical equipment and the energy consumption for which heating represents almost 85% at this stage.

2.8 Alternative supply of iron oxide

Several alternative raw materials for use in the SIDERWIN process were tested during the project in lab scale and have been reported in deliverables D5.5, D6.2, D6.3 and D6.5. The most promising results were delivered with the use of iron mill scales.

Iron Mill scales were provided by Sidenor Steel Industry S.A. (Greece) and ArcelorMittal S.A. Two samples were provided by Arcelor Mittal, one sample containing less than 1% organic matter (industrial oil) and one sample produced by hot rolling of slabs.

The mill scales sample coming from Sidenor has been analyzed and is composed of a mix of iron oxide (FeO, Fe_2O_3 and Fe_3O_4). Galvanostatic experiments were performed at different current densities, at 138 and 388 A/m^2 in 50% wt. NaOH - 10% wt. Mill Scale electrolyte, Temperature 95°C, and stirring rate 500 rpm, 2 h electrolysis). The obtained faradic yields obtained are high, at 92 % and 97 %, respectively for 138 and 388 A/m^2. This mill scale sample then appear as a possible alternative iron sources for the pilot, however further tests must be done at lab scale on this material with 1000 A/m^2 to meet the desired pilot parameters.

Concerning the mill scales sample from Arcelor Mittal, which contains 1 % of organic matter, a preliminary thermal treatment at 700 °C for 4 hours has been performed, to eliminate the organic species and to partially oxidize the magnetite and wustite content to hematite. 0.5 and 2 hours electrolysis experiments have been performed at different current densities and the results are given in the Table 2.

Table 2 : Current efficiency and average cathodic potential during electrolysis at different applied cathodic current for 0.5 and 2 hours

0.5h			
i/A	**j/Am^{-2}**	**Current Efficiency %**	**$Aver.E_{cath}/V_{Hg\|HgO}$**
0.06	68.6	75	-1.1
0.138	141	70	-1.26
0.370	200	83	-1.34
2 hours			
0.06	68.6	92	-1.2
0.260	136	72	-1.23
0.99	1100	-	-2.2

We can see that the faradic yields obtained at low current densities are in an acceptable range but are reduced when the current density is increased. At the current density aimed at the pilot – 1000 A/m^2- the deposit obtained is no longer adhering to the cathode (attributed to a higher production of hydrogen) which make the material not suitable for the SIDERWIN pilot.

It seems then that the different mill scales exhibit different response to the electrolysis, which make them unsuitable for the current pilot without further studies to avoid the variability of the adherence of the deposit. Still, they are great promise for use of iron mill scales in the process, either exclusively or as a partial substitute of hematite concentrate.

3 Conclusions

As a conclusion, several studies performed in the different WP of the SIDERWIN project have been summarized in this deliverable. The different studies were the following: the compatibility of SIDERWIN with intermittent sources, the life cycle analysis of the SIDERWIN route, its techno-economic assessment, the pilot technical performance and the alternative supply of iron oxides.

The conclusions of these different studies allow to define the following technology performance:

- SIDERWIN technology can contribute to future carbon neutral steelmaking with:
    - Almost no direct CO_2 emissions
    - At least -60 % carbon footprint compared to traditional BF-BOF route
    - Without compromising environmental footprint compared to BF-BOF route
    - Fully electrified primary production

- The pilot technical performances have been validated and optimal parameters for operation have been defined, the SIDERWIN technology has been successfully scaled up. The main results obtained from the pilot trials are:
    - It is possible to use cathode with size up to 1.25 m^2
    - The gas management is key, it has been found that decreasing the solid concentration % in the electrolyte is helping to obtain a better gas management without degrading the faradic yield
    - Electrolyte flow uniformity is required, to avoid dendrite formation and the following short-circuits
    - Electrolysis cell energy use confirmed at pilot scale have demonstrated that the 2.7 MWh/t of Fe produced are reachable in optimized conditions
- The SIDERWIN technology can contribute to the balance of the power system with its fully electrified steel primary production. The European power system can meet the additional ΣIDERWIN demand with carbon-free means. As the SIDERWIN process is a flexible process with a low working temperature, it is compatible with Demand Side Response requirement which can boost the profitability of the process. Finally, the SIDERWIN technology can contribute to the deployment of RES.

- The SIDERWIN technology can contribute to circular economy, via the possible integration of various by-products materials as alternative iron sources, which can come from different industries like steel industry, aluminum industry, nickel hydrometallurgical purification, and copper or ferronickel production. Among all these materials tested in the framework of the project, Mill scales from steel industry was the most promising one at this stage of technology development. Almost all alternatives were promising from lab-scale studies, but more work must be done before scaling-up.

Based on what has been learnt all along the project and especially from the validation of the pilot operation, we have been able to imagine the next steps for the development of the SIDERWIN technologies. Thanks to the results obtained, we are now able to identify the main barriers and technical bottleneck to work on for the next version.

These barriers will be tackled in the next version of the technology, on which AMMR is starting to work and should go for an investment approval from 2025. The envisaged roadmap for the development of the technology is illustrated below (Figure 14).

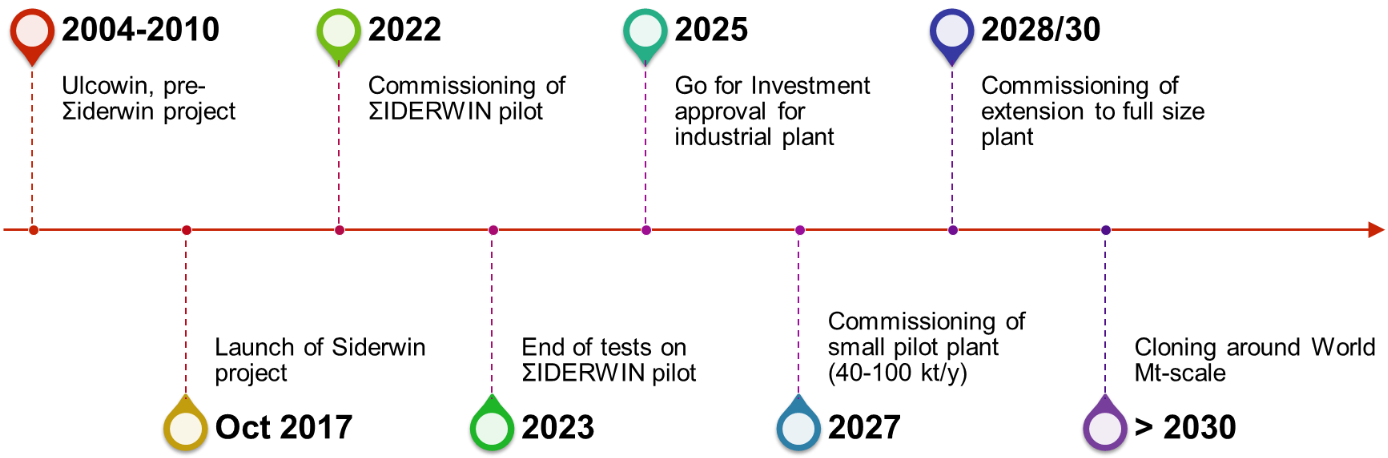

Figure 14: roadmap of the industrialization of SIDERWIN process