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The implications of the basic materials industry electrification on the cost of hydrogen

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Abstract:

This work applies techno-economic optimisation modelling to investigate how electrification of the basic material industry (ammonia, cement, plastics, and steel) impacts hydrogen production costs when considering flexibility options for the electrified industry. The context of the work is a zero-carbon emissions energy system of the EU, including future electricity demands from transport, heat, and industry.

The modelling results show that in the future electricity system, the lowest hydrogen production cost is the outcome of the production with full flexibility, i.e., the flexibility of time and location, and flexibility of CO_2 utilisation. Among the flexibility options, flexibility in time, i.e., the ability to follow electricity price variations, gives the largest reduction in hydrogen production costs in comparison to the scenarios without industrial flexibility options. With flexibility in location, it is possible to utilise solar power sites and remote areas for wind sites to satisfy electricity demand from industry. The difference in hydrogen production cost between scenarios with different combinations of flexibility options decreases with the size of the hydrogen demand. The decreased value of industrial flexibility when electricity demand from industry grows is due to the reduced access to sites with good conditions for VRE and some regions invest in nuclear power which benefits less from the industrial flexibility options. Still, even with the electrification of all ammonia, cement, steel and plastics production in the EU, there remains a value in industrial flexibility options.

Keywords:

Electrification; Industry; Electricity Systems Modelling; Storage; Flexibility; Hydrogen; Renewables.

1. Introduction

In the coming decades, as efforts to meet climate targets intensify, the demand for hydrogen within Europe is expected to significantly increase [1]. Hydrogen has the potential to play a crucial role in eliminating carbon dioxide emissions in the industry and transport sectors [2].

The production of basic materials (ammonia, cement, steel, and plastics) accounts for 70% of European industrial CO_2 emissions (2020), including energy and process-related emissions [3]. The basic materials industry faces two main challenges in achieving carbon neutrality: providing high-temperature heat without carbon emissions, and mitigating process emissions. The decreasing costs and low-carbon environmental impacts of wind and solar power, along with the potential to utilize low-cost electricity for flexible consumers, have made direct and indirect (through hydrogen) electrification a key pathway towards electrification of the basic materials industry [4]. Consequently, there are several ongoing projects related to hydrogen deployment in the basic material industries [5,6].

To implement and utilize hydrogen effectively for emissions reduction, it is crucial to study and analyse the cost of hydrogen. Calculating the cost of hydrogen produced through electrolysis commonly involves using the levelized cost of electricity (LCOE) from wind or solar power, combined with an assumed cost and capacity factor for the electrolyser [7]. In the method of calculating the cost of hydrogen using LCOE is assumed that hydrogen is always available at a certain cost, independently of when and how much hydrogen is required. In addition, the possibility of hydrogen production which follows the electricity price variations using hydrogen storage is not considered. An average annual cost for hydrogen can be a useful benchmark when comparing different energy systems in terms of the role that hydrogen can play and at what cost. However, consideration of the operational flexibility of hydrogen production (including both investments in over-capacity and storage) is an important factor when designing new industries that plan to use hydrogen in their processes.

Walter et al. [8] have shown the impacts of the hydrogen demand (varying it from 0 TWh_{H2} to 2,500 TWh_{H2} in steps of 500 TWh_{H2}) on the future European zero-emission electricity system, taking into consideration flexibility in time (hydrogen storage and investments in overcapacity of hydrogen-consuming industries) and location. They find that the scenarios implementing flexibility options (flexibility in time (by means of both overcapacity and storage), and in location) for the electrolyser have the lowest production costs. However, the location of future industrial plants (including commodities trade) was not analysed in the above works.

By implementing a techno-economic optimisation model of the European electricity system, Öberg et al. [9] have shown that flexible operation of the electrolyser, i.e., the ability to follow electricity price variation due to overcapacity of the electrolyser and hydrogen storage capacities, have significant impacts on the cost of hydrogen. Unlike Walter et al., Öberg et al. considered hydrogen demand connected to its usage, i.e., they consider additional hydrogen demand from transport and industries (ammonia, cement, and plastics). They conclude that the characteristics of the hydrogen demand also impact hydrogen production costs. Flexible operation of industry (i.e., overcapacity is available) can reduce the cost of hydrogen production by up to 35% compared to constant operation of the industrial units. However, the model developed by Öberg et al. does not account for the additional cost for overcapacity of industrial units and storage of the products or intermediate products.

The studies from [8,9] have also shown that flexibility in the time of the electrolyser can have a major influence on the hydrogen production cost. The impacts of industrial electrification on process design (investments in industrial overcapacity and available commodities storage options) are not studied in the previous works.

Therefore, the aim of this work is to further improve the understanding of the electrification of industries (ammonia, cement, plastics, and steel) impacts on the hydrogen production cost in systems with high shares of VRE taking into consideration industrial flexibility options (flexibility in relation to time, location and CO_2 utilisation). We address the following research questions:

- How the potential future electricity demands from industries that have different types and levels of flexibility influence the cost of hydrogen?
- How does electrification of industry influence a cost-efficient spatial distribution of new locations of electrified industrial plants?

1.1. Electrification of industry

Table 1 lists the assumptions made on electrification options for the basic materials industry, including annual direct electricity and hydrogen demands. Direct electrification refers to the direct use of electricity as an input (plasma rotary kiln, EAF, electrified heat of steam cracker). Indirect electrification is the production of hydrogen and hydrogen-rich fuels and feedstocks from electrolysis.

Table 1. Annual assumed electricity demand for the basic materials industries.

Industry	Electrification option	Basic materials production in the EU[a], Mt	Annual direct electricity demand, TWh	Annual hydrogen demand, TWh_{el}	References
Ammonia	Power-to-ammonia	21	20	185	[10,11]
Cement	Plasma	133	174	-	[12,13]
Steel	H-DR	115	95	279	[14–16]
Plastics	Thermochemical recycling	38	349	436[b]	[17,18]

[a] The geographical scope corresponds to the area of the EU (excluding Cyprus and Malta), UK, Norway and Switzerland subdivided into 22 regions corresponding to major bottlenecks in the transmission grid. These investigated regions are: Northern Sweden (SE_N), Southern Sweden (SE_S), Northern Germany (DE_N), Southern Germany (DE_S), Estonia, Latvia and Lithuania (BAL), Northern Poland (PO_N), Southern Poland (PO_S), Ireland (IE_T), Norway (NO_T), Portugal and Western Spain (IB_W), Eastern Spain (IB_E), Northern France (FR_N), Southern France (FR_S), Switzerland and Northern Italy (ALP_W), Southern Italy (IT_S), Austria, Czech Republic and Slovakia (ATCZSK), Croatia, Slovakia (Slovak Republic) and Hungary (CRSIHU), Romania, Bulgaria and Greece (ROBGGR), Belgium, Netherlands and Luxembourg (BENELUX), Finland (FI_T), Scotland (UK_N) and Southern UK (UK_S).

[b] Depends on CO_2 utilization, i.e., the CO_2 emissions that arise from the process can be captured and converted to olefins through a synthesis process, or they can be captured and stored.

1.2. Process description – electrified ammonia production

The electrified ammonia production is the most hydrogen intensive commodity produced by basic materials industries investigated in this study, with an average hydrogen intensity of 8.6 MWh_{el} per 1 t of ammonia (cf. Table 1).

Figure 1 shows that the electrified ammonia production process includes electrolysis for H_2 production, an air separation unit (ASU) for nitrogen production and the ammonia synthesis via the Haber-Bosch (HB) process.

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An ASU uses a cryogenic distillation process to separate ambient air into nitrogen, oxygen, and argon. All products can be stored in storage tanks [19]. The inlet air compressor is the main electricity consumer of an ASU [20]. The Haber-Bosch process combines hydrogen and nitrogen under high pressure and temperature. The HB process is normally optimized for continuous mass production, however, reconfiguration for dynamic production is possible [11]. The total electricity consumption of the ammonia production process, including electricity for hydrogen is 9.6 MWh/tNH_3.

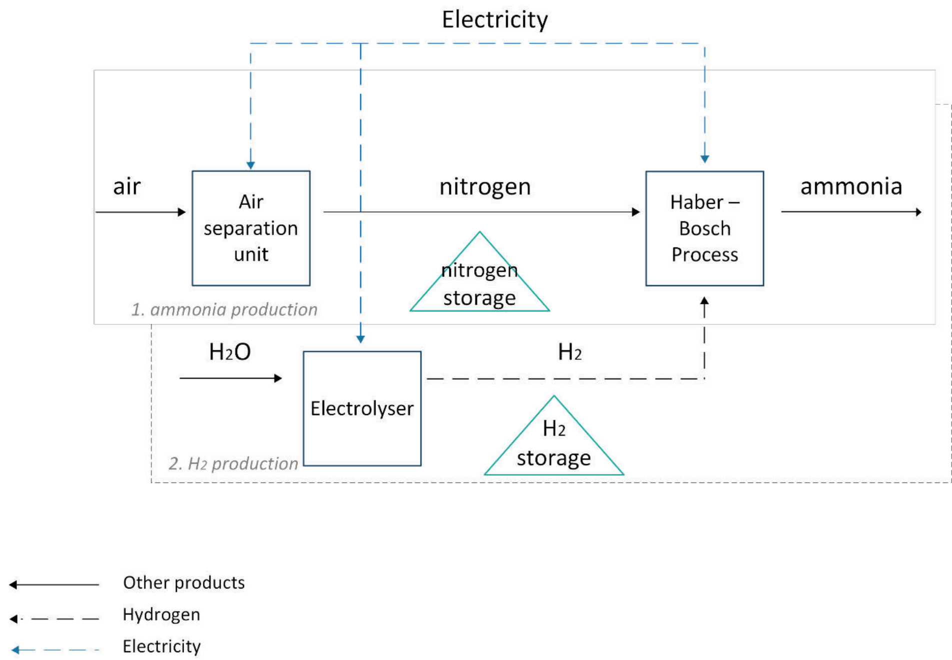

Figure. 1. Schematic representation of the electrified ammonia production process.

A detailed description of the electrification options (cf. Table. 1.) assumed for the basic materials industry investigated in this work is given in [21].

1.3. Industrial flexibility options

Three types of flexibility for the electrified industry were considered in this work: flexibility in relation to time, location, and CO_2 utilisation.

The ability of the industrial unit to vary the output within the load ranges, i.e., operational flexibility, is defined as flexibility in time. The lack of flexibility in time gives the capacity utilisation rate of 100%, i.e., there is no investment in overcapacity and storage. With flexibility in time, storage of commodities (e.g., hydrogen, hot-briquetted iron, nitrogen, and methanol) allows for rescheduling electricity consumption to periods with lower cost when available.

The electrification of the basic materials industry can significantly change cost structures of industrial production and with them the most cost-effective geographic location for production. The optimal location for production may shift from being close to demand and/or raw material supply centres to places where zero-emissions electricity is readily available at low cost, or where there are favourable conditions for CCS [22]. Flexibility in location is defined by the ability to export commodities. With flexibility in location, it is possible to locate new industrial units into regions without existing basic materials industries, increase capacity and/or production in the regions with existing industry, and separate parts of the existing supply chain. Distance-dependent transport costs for commodities are assumed, i.e., we consider the transport distance between regions and the amount of transported commodity. To represent some of the material and immaterial values in the current industrial sites, i.e., regions with existing industries, we apply an investment penalty for investments in new production sites for regions without existing industries: a 50% increase in investment cost—compared to investments in existing sites—for units producing commodities in regions without existing production of that basic material.

For some basic materials, such as plastics, electrification is not enough to eliminate production CO_2 emissions. Here, we assume that for plastics the process-related CO_2 can be captured and converted to olefins through a synthesis process (CCU mode) and/or captured and stored (CCS mode). The term flexibility in CO_2 utilisation refers to the ability of production units to vary between CCU and CCS.

2. Method

To investigate how the potential future electricity demands from industries that have different types and levels of flexibility influence the cost of hydrogen in EU we deploy the cost-minimising electricity system investment model ENODE (Figure 2). The wide range of the electricity generation technologies considered in the model, including storage and transmission technologies. The model accounts for the economic and technical properties of the technologies, including start-up cost, start-up time and minimum load level of thermal generation. In terms of energy storage technologies, investments in lithium-ion batteries and H_2 storage are possible.

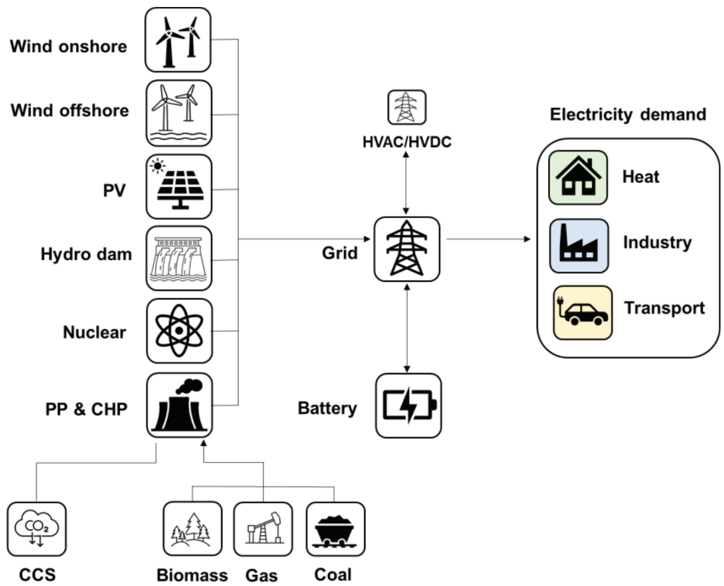

Figure. 2. Schematic representation of ENODE model.

ENODE was designed by Göransson et al. [23] to investigate the interactions between VRE and thermal generation technologies. Our version minimises the cost for investments in and operation of the electricity system and electrified industry, while meeting the demands for electricity and commodities. The objective function is expressed as:

$$\begin{aligned} min\!: C^{tot} = & \sum_{r\in R}\ \sum_{p\in P\setminus P^{transm}} i_{p,r}(C_p^{inv} + C_p^{O\&M,fix}) + \sum_{t\in T} C_{p,t}^{run} g_{p,t,r} \\ & + \sum_{r_2\in R\setminus r}\ \sum_{p\in P^{transm}} C_{p,r,r_2}^{inv}\, i_{p,r,r_2} + \sum_{p\in P^{ind}\cup P^{transm}}\ \sum_{t\in T} C_{r,r_2}^{transp} e_{p,t,r,r_2}^{pos} \\ & + \sum_{p\in P^{plastic}}\ \sum_{t\in T} C^{st}\, b_{p,t}^{CCS} \end{aligned} \tag{1}$$

where P is the set of all technologies, T is the set of time-steps, and R is the set of the regions. The annualized investment costs, the fixed operational and maintenance costs and the running costs per technology p at time-step t are denoted C_p^{inv}, $C_p^{O\&M,fix}$, and $C_{p,t}^{run}$, respectively. The variable $i_{p,r}$ is the capacity investment per technology p installed in region r, and $g_{p,t,r}$ is the generation of electricity and production of commodities per time-step t and region r, respectively. For the product trade that is transmitted/produced by technologies P^{transm} (the subset of P for transmission lines) and P^{ind} (the subset of P for commodity production units) between regions r and r_2 at per time-step t, the costs C_{r,r_2}^{transp} are considered. The CO_2 emissions $b_{p,t}$ from technology $P^{plastic}$ at time-step t are captured and stored at cost C^{st}.

Equation (2) represents the H_2 balance. Hydrogen is produced in the electrolyser and used to satisfy demand from basic materials industries. Hydrogen can be traded via a pipeline network.

$$g_{P^{Electrolyser},t,r}\eta_p + \sum_{p\in P^{H_2}} z_{p,t,r}^{dis} \geq \sum_{p\in P^{ind}} g_{p,t,r}\, a_p + \sum_{p\in P^{H_2}} z_{p,t,r}^{ch}$$

$$\forall t\ \in\ T, \forall r\ \in\ R \tag{2}$$

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where a_p is the coefficient applied to relate commodities (ammonia, cement, steel, and plastics) production to H_2 demand for technology $p \in P^{ind}$. The efficiency of electrolyser is written as η_p.

The cost of electricity and hydrogen for the basic material industries is calculated according to Eq. (3),

$$C_i = \frac{\sum_t C_{t,i}^{maginal} g_t}{\sum_t g_t} \quad (3)$$

where the marginal cost ($C_{t,i}^{maginal}$) of electricity or hydrogen (i) per time-step (t) is weighted by the amount of electricity or hydrogen demanded by commodities production units (g_t) in each time-step. The marginal cost of electricity is taken as a proxy for the electricity price and is a result of the modelling, i.e., the marginal value from Eq. (1). The marginal cost of hydrogen is the marginal value of Eq. (2). The marginal value reflects the cost to supply one additional unit of electricity or hydrogen to the energy system.

The ENODE model is a green-field model, in which a new system is designed from scratch. A full mathematical description of the original eNODE model is given in [8].

2.1. Electricity demand

In the ENODE model, the electricity demand is classified into four categories: present demand used as a base level for the hourly demand profile and new electricity demand from transport, heat, and industry. The present electricity demand is determined on annual electricity consumption levels of the European countries obtained from Eurostat [24] and is subject to an hourly demand profile obtained from ENTSO-E [25]. The electricity demands from transport and heat are exogenously added to the present electricity demand. The electricity demand from heat is the electricity required to replace individual natural gas-based heating for decentralised heat pumps in Germany and the UK [26]. The electricity demand from the transport sector is modelled based on [27]. Full electrification of the passenger car fleet and partial (60 %) electrification of the heavy-duty vehicle fleet is considered in this model. The annual demand for commodities production (cf. Table 1) is given exogenously while the hourly electricity demand from basic materials industry is endogenous, thus investments in units producing commodities as well as the dispatch of these units are a result of the optimisation. The current production of commodities in the investigated regions is used as the regional demand for commodities in all scenarios to reflect the connection of the basic materials industry to the location of other industries.

2.2. Scenarios description

Figure 3 shows that the scenarios in this work vary in the type of industry that is electrified (ammonia, cement, steel, plastics) and the flexibility options that can be applied (flexibility in time and location and flexibility in CO_2 utilisation, the square under the parameter name indicates "yes" if included). The electrified ammonia industry is used as the reference industry to investigate how the electrification of industries impacts hydrogen production costs, since ammonia production is the most-hydrogen-intensive industry and has the highest operational flexibility among all the industries investigated in this study. The names of the scenarios with all flexibility options start with *Flex*; with limited flexibility in time - *Inflex_time*; with limited flexibility in location - *Inflex_location*; and with both limited flexibility in time and location – *Inflex_time_location*.

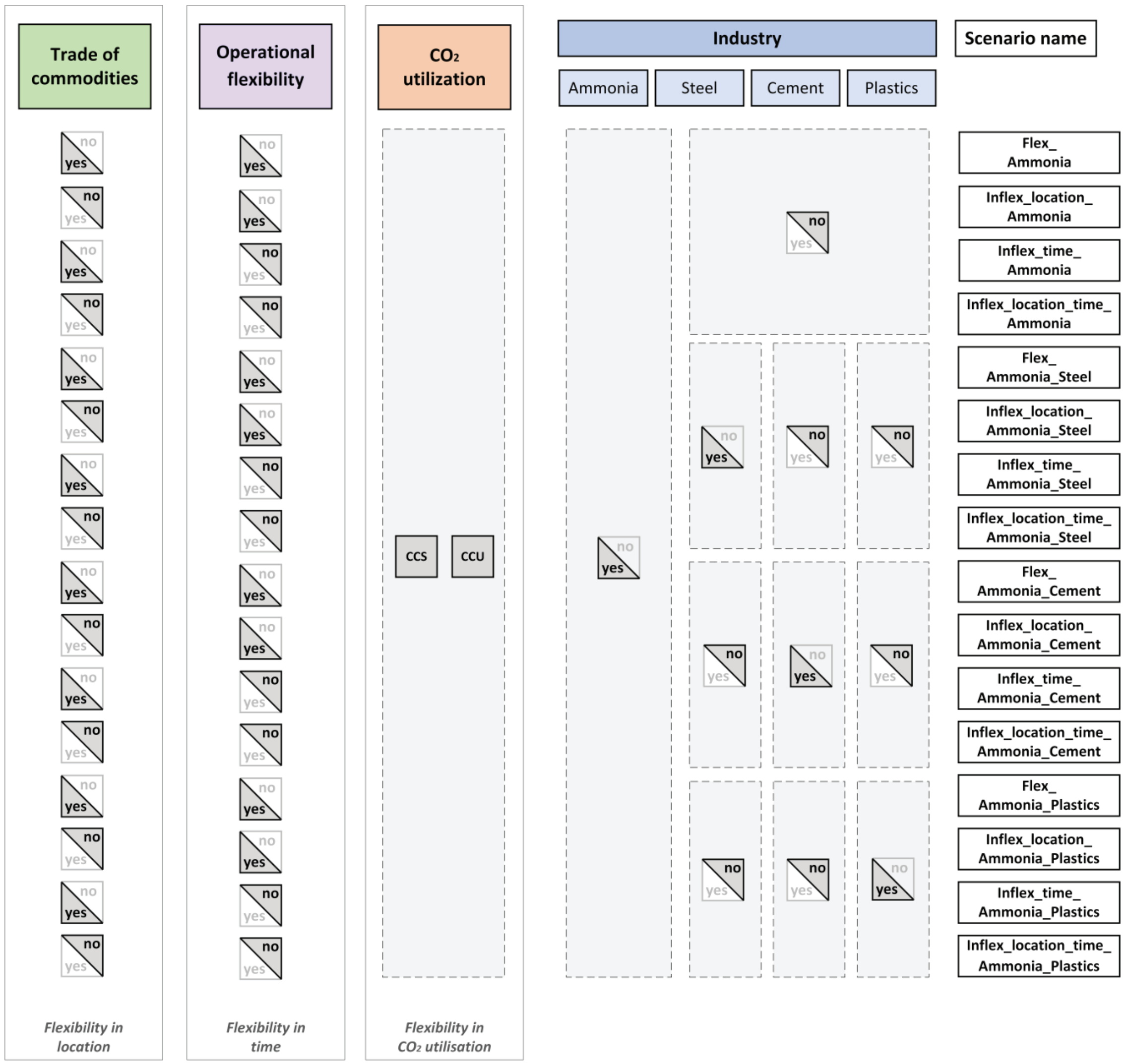

Figure. 3. Schematic overview of the parameters that define the investigated scenarios.

3. Results

The result presentation is divided into the following two parts: how electrified basic materials industries influence the production cost of hydrogen for the investigated scenarios (Section 3.1) and the location and production levels of the electrified industrial unit (for the example of direct reduction shaft furnace (DR shaft)) for the investigated scenarios (Section 3.2).

3.1. Hydrogen production cost

Figure 4 shows the break-down of the hydrogen production cost per MWh for the scenarios in which: only the ammonia industry is electrified; the ammonia and steel industries are electrified; and all the investigated industries (i.e., ammonia, cement, steel, and plastics) are electrified. The model results for the scenarios with electrified ammonia and cement industries, as well as with electrified ammonia and plastics industries are given in Figure A.1, Appendix A. Hydrogen production cost includes the annualized investment cost, the fixed O&M costs, the electricity cost, and hydrogen transportation costs for the investigated scenarios.

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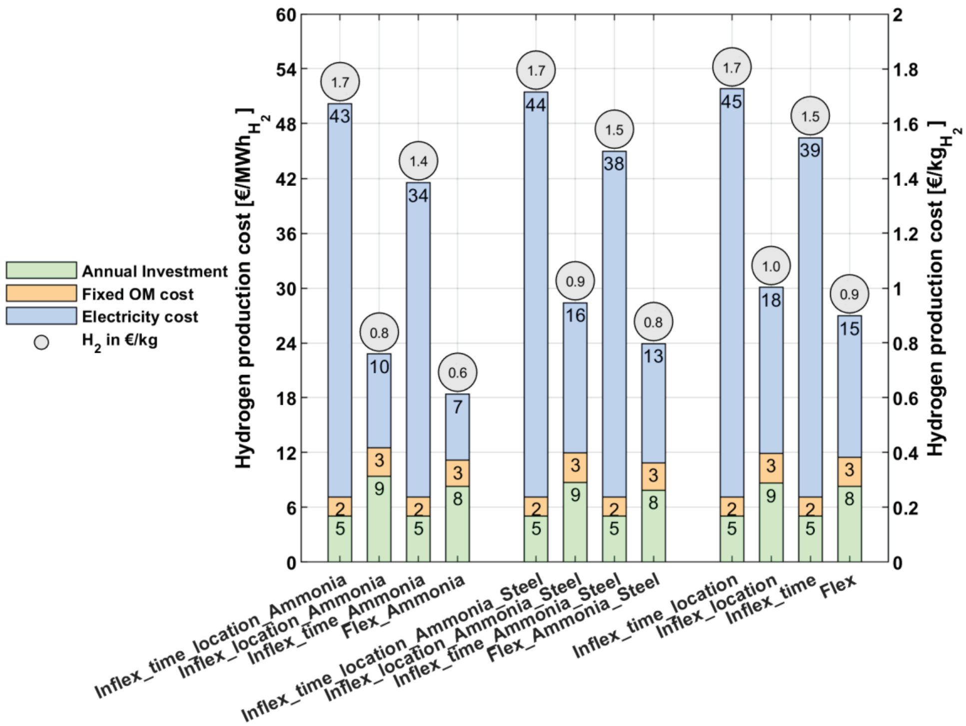

Figure. 4. The hydrogen production cost obtained from the modelling for the scenarios in which only the ammonia industry is electrified, scenarios in which the ammonia and steel industries are electrified, and scenarios in which all industries are electrified (i.e., ammonia, cement, steel, and plastics) are electrified. The scenarios with all flexibility options begin with *Flex*. Scenarios with limited flexibility in time or location are denoted by *Inflex_time* or *Inflex_location*, respectively. Scenarios with limited flexibility in both time and location are titled with *Inflex_time_location*.

The modelled costs given in Figure 4 yield a hydrogen production cost that ranges from 18 to 44 €/MWh$_{h2}$ (corresponding to 0.6–1.7 €/kg of hydrogen) for the investigated scenarios. The relatively low hydrogen cost obtained in this work is due to the ability of the electrolyser to follow electricity price variations. The range of hydrogen costs projected by the IEA is 1.1–4.0 €/kg of hydrogen. The electricity cost constitutes 55% of the total hydrogen production cost obtained from the IEA, if in regions with good access to renewable energy, the cost of electricity (mainly from solar power) for hydrogen production is 14 €/MWh and that the electrolyser operates for 2,600 full-load hours. According to the IEA projections, by Year 2030 the electrolyser investments cost will have decreased to 300–500 €/kW compared to the current levels (1,400–1,770 €/kW), due to the scaling up of electrolyser capacity [28]. Because of the falling costs for electrolysers, BloombergNEF [29]projects that renewable hydrogen could be produced for 0.6–1.4 €/kg in most parts of the world before Year 2050. The current work and other projections [8,9]suggest that two important factors are crucial to decreasing the cost of producing hydrogen: the flexible consumption by the electrolysers of the electricity supplied from VRE; and the scaling up of the electrolyser capacity.

The modelling results show that in the future European electricity system, the lowest cost for hydrogen production arises from production with full flexibility, i.e., flexibility in both time and location, and flexibility of CO_2 utilisation. The limitation of the flexibility in time for the industrial units has a stronger impact on the hydrogen production cost compared with the scenarios in which the flexibility in location is limited. For scenarios with limited flexibility in time, the hydrogen cost increases by 100%, and for scenarios with limited flexibility in location the hydrogen cost increases by 20%, as compared with the scenarios in which all flexibility options are available.

The hydrogen production cost is affected by not only industrial flexibility options but also by commodity demands. The low-medium operational flexibility of plasma kilns makes it challenging to follow electricity price variations. Nonetheless, the electrification of both the ammonia and cement industries, when at least one flexibility option is available, leads to a 1%–4% increase in the hydrogen cost compared to electrifying only the ammonia industry. In contrast, electrification of the ammonia and steel industries results in an 8%–23% increase in the hydrogen cost, and electrification of ammonia and plastics production processes leads to a 2%–17% increase in the hydrogen cost. The lower increase in hydrogen cost when the ammonia and cement industries are electrified, as compared to the scenario where the ammonia industry is electrified along with steel and plastics production, is attributed to the low total electricity demand from cement production driven by the demand for cement. In other words, the lower hydrogen cost increase can be attributed to the fact that the cement industry requires less electricity in total (under the given assumptions regarding the cement demand) than the steel and plastics industries.

Among the scenarios in which only two industries are electrified, the highest cost for hydrogen production arises when the ammonia and steel industries are electrified. The high electricity demand driven by the steel demand reduces access to sites with good conditions for VRE. Thus, the number of high electricity price events increases, and this diminishes the value of the operational flexibility of the steel production units.

When electrifying the plastics and ammonia industries, flexibility in CO_2 utilisation compensates for the limited flexibility in time. Thus, the ability to switch between CO_2 utilisation modes (i.e., between CCU and CCS) allows the industrial units to avoid the consumption of electricity during high-cost events, which also implies increased costs for feedstock and CCS.

3.2. Locations and sizes of industrial units

Figure 5 presents the location and size of the DR shaft furnace capacity (in ktonnes) for two scenarios (*Flex* and *Flex_Ammonia_Steel*) in which the industrial units have full flexibility. In the *Flex* scenario, all the investigated industries are electrified, while in the *Flex_Ammonia_Steel* scenario, only the ammonia and steel industries are electrified.

Figure 5 shows that electrification of only the ammonia and steel industries, as applied in the *Flex_Ammonia_Steel* scenario, leads to the clustering of the DR shaft furnace capacity around countries that have good conditions for VRE and low-cost access to iron ore, such as FR_N. The electrification of the ammonia, cement, steel, and plastics industries (*Flex* scenario) results in investments, and investments in DR shaft furnace capacity increase in the regions that have existing steel production in UK_S, SE_N and FI_T, as compared with the *Flex_Ammonia_Steel* scenario.

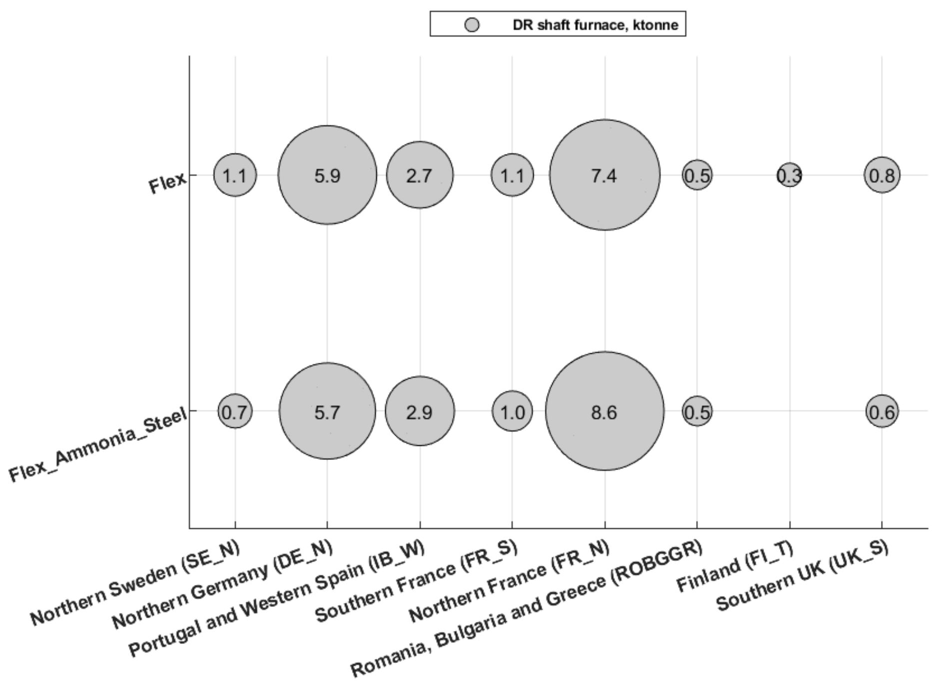

Figure. 5. The modelling results for the regional allocations of the steel production capacities in terms of the DR shaft furnace (in ktonnes) for the *Flex_Ammonia_Steel* and *Flex* scenarios.

The effects of electrification, such as the cost of hydrogen production for the industry, may vary depending on whether one or multiple sectors are electrified simultaneously. Investment decisions regarding industrial units, such as those in over-capacity and storage to take advantage of electricity price variations, which are made by the "first" industry that electrifies its production could impact the investment decisions of subsequent industries. Furthermore, the benefits of the industrial flexibility options provided by electrification might lessen as more industries electrify their production processes. Thus, further analysis is needed to understand the different stages of the industrial transition toward electrification.

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4. Conclusions

This work applied a techno-economic optimisation model to analyse and discuss how electrification of energy-intensive basic materials industry impact hydrogen production cost, considering industrial flexibility options. The model is developed for a zero-carbon emissions electricity system of the EU that considers the current electricity demand as well as future demands from the transport, heat, and industrial sectors

The modelled costs yield a hydrogen production cost that ranges from 18 to 44 €/MWh$_{h2}$ (corresponding to 0.6 – 1.7 €/kg of hydrogen) for the investigated scenarios. Full flexibility (flexibility with regards to time and location, and flexibility of CO_2 utilisation) of the energy-intensive basic materials industry yields in the lowest hydrogen production cost.

The results indicate that in a future electricity system with more fluctuating electricity prices (in comparison to today's price fluctuations), the production of the basic materials which follows electricity variations gives lower hydrogen production cost, as compared to the scenarios with the optimised geographical location of industries. The electricity price following production would require investment in over-capacity of industrial units (i.e., electrolyser) and commodities storages (i.e., hydrogen).

In the scenarios with flexibility in location which are defined by the ability to export commodities, the basic materials industry capacity and/or production increase in the regions with existing industry and access to low-cost electricity. As a result, it is possible to utilise solar power sites and remote areas for wind power generation sites to satisfy the hydrogen demand from industry.

Finally, the modelling results indicate that as the demand for hydrogen increases, the difference in hydrogen production cost between scenarios with different combinations of flexibility options decreases. The decreased value of industrial flexibility when the electricity demand from industry grows is due to the reduced access to sites with good conditions for VRE and the fact that some regions invest in nuclear power, which benefits less from the industrial flexibility options.

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Appendix A - Model

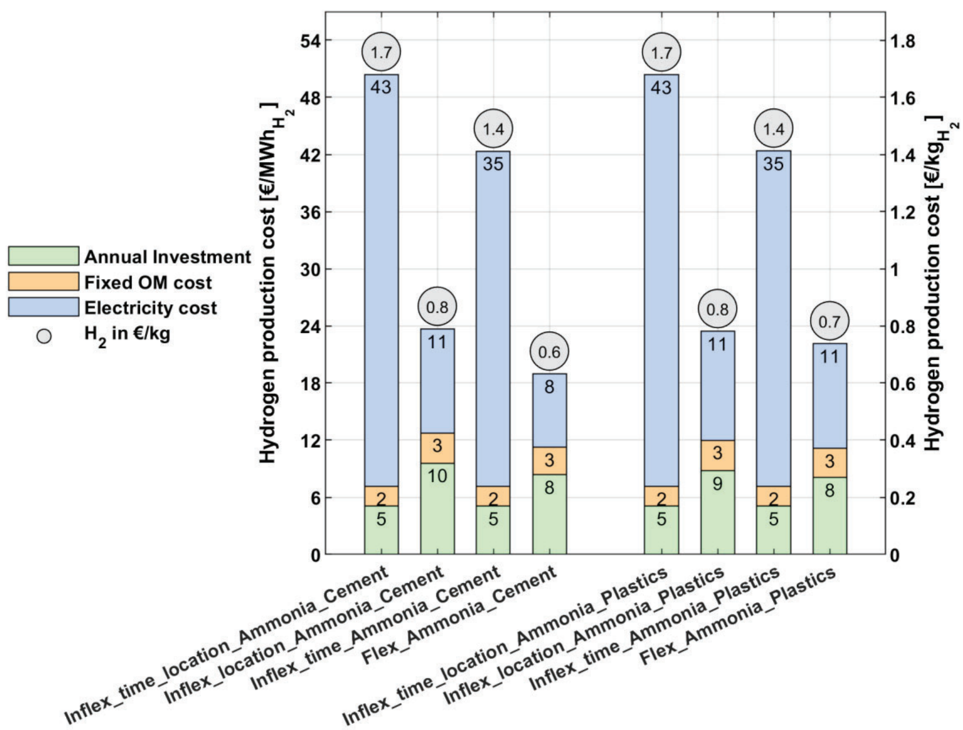

Figure. A.1. The hydrogen production cost obtained from the modelling for scenarios with electrified ammonia and cement industries and for scenarios with electrified ammonia and plastics industries. Hydrogen production cost includes the annualized investment cost, fixed O&M costs, electricity cost, and hydrogen transportation costs for the investigated scenarios. This study uses an electrolyser investment cost of 550 €/kW$_{el}$ [30].

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