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The roles of permitting times and grid expansion capacity in industrial decarbonization – A case study of the electrification of Swedish industry

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ABSTRACT

The industrial sector accounts for almost one-third of global CO_2 emissions, making it an important target for emissions mitigation measures, with electrification representing an important mitigation pathway with reliance on timely permitting procedures and ramping up of electricity grid expansion.

In this work, we investigate the impacts of permitting times and grid construction capacity on the evolution of industrial electrification, using the Swedish basic industry as a case study. We develop and apply an optimization model, with the objective of minimizing the time required to electrify the steel, cement, refinery and chemical industrial processes. The model is applied to different scenarios, within the ranges of 1–9 years of permitting time and 100–700 MW/year of grid expansion capacity, while varying the level of project coordination between the industrial sites and grid infrastructure deployments. In the modeling, we assume that the required CO_2-free power generation is installed alongside the grid expansion. In a scenario with 8-year permitting times and the ability to expand the grid to accommodate 4.5 % (150 MW) of the modeled industrial load per year, the transition to a fully electrified industry takes until Year 2058. For 2-year permitting times and the ability to expand the grid to connect 18 % (600 MW) of the modeled industrial load per year, the modeled sites could be electrified by Year 2037. In addition, the results show that for low levels of coordination, modeled such that industrial actors wait for infrastructure projects to be completed before they initiate their own pre-studies, there is an increase of almost 8 years in the average time taken for sites to be electrified compared to a modeled base scenario.

1. Introduction

The industrial sector is a major contributor to global greenhouse gas (GHG) emissions, making up around 30 % of total GHG emissions [1]. Important long-term solutions aimed at reducing industrial fossil carbon emissions include direct and indirect electrification, fuel switching to biomass, and carbon capture and storage (CCS), with the latter two acting more like temporary bridging technologies. CCS can be seen as a bridging technology due to its continuous reliance on fossil carbon sources. The combustion of biomass is regarded as a bridging technology due to its scarcity as a resource, which means that in the longer run it will have to be prioritized for high-value or long-lived products, in accordance with the cascading principle. This is under the assumption that virtually all industrial processes can be electrified (directly or indirectly).

Sweden is a highly industrialized country, with large energy-intensive industries producing pulp and paper, chemicals, transportation fuels, and steel and cement, with the result that the industrial sector is responsible for around one-third of the territorial GHG emissions [2]. The Swedish climate policy framework has as its goals to reach net-zero GHG emissions by Year 2045, and net-negative GHG emissions thereafter [3]. In line with these targets, a rapid reduction of fossil fuel-based emissions is needed in industry. As the use of fossil fuels decreases and with the provision of effective electrification, electricity use is projected to increase from 134 TWh in Year 2020 to 228–349 TWh in Year 2050 [4]. A large part of the projected increase in demand for electricity in Sweden will come from the electrification of industries, such as steelmaking and petrochemical plants, including those involved in electro-fuel production.

Besides the considerable investments to be made at the site level, the transformation of fossil fuel-powered industries depends on infrastructure development, including expansion of the electricity transmission capacity in the case of electrification, in addition to timely expansion of low-carbon electricity generation. In the EU context, full electrification

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of industrial feedstock and fuel use has been estimated to increase electricity demand by over 1500 TWh in 2050 on top of the roughly 1000 TWh/year used today [5]. Expanding generation and transmission infrastructure alongside the electrification of industrial processes will require strong coordination between actors, industry owners and infrastructure developers [6]. Additionally, lack of grid infrastructure expansion has been highlighted as one main barrier that risks undermining the electrification of industry [7].

From the electricity grid perspective, industrial electrification could provide ancillary services to the power grid, for instance via improving load factors, providing flexibility for the integration of variable renewable generation and synergies with energy storage [8]. Interactions between the electricity grid and industrial electrification have typically been explored in previous works by quantification of how processes impact operation and congestion in the electricity grid [9,10,11,12]. For instance, Stefanussen Foslie et al. [12] studied the potential for process flexibility to alleviate grid congestion. They applied a MILP optimization model to determine cost optimal operation of industrial processes, followed by a power flow model to ensure that grid limitations are accounted for. They show that flexibility can reduce grid load and congestion, indicating that investments in flexibility measures can accelerate decarbonization of the industry sector and energy system. Lieberwirth et al. [11] investigated the impact of industrial electrification on transmission grid operation, looking at the case of hydrogen electrolysis in Germany using a method based on linear optimization. They show that hydrogen electrolysis could have a positive impact on the ability to feed in renewable generation, if electrolysers operate near grid nodes with high curtailment volumes. However, if electrolysers are installed and operated at more distributed industrial sites, they instead contribute to increased stress on transmission lines and increased congestion. Furthermore, energy system modeling approaches have been used to investigate the viability of expanding the electricity grid and transmission capacity from a cost perspective [13,14,15]. The results obtained from these analyses indicate that from a system cost perspective, it would be less costly to build out the electricity grid than it would be to focus on local production or energy storage, in the transition towards a decarbonized energy system.

Thus, it is clear that grid infrastructure expansion is highly important to enable cost effective decarbonization and electrification, and that integration of electrified industrial processes with the electricity system could, under the right circumstances, provide benefits to grid operation. However, the expansion of grid infrastructure takes time, often due to long permitting times connected to low levels of public acceptance and as a result of conflicts between the public and the grid operators and developers that are particularly hard to resolve [16]. The IEA 2023 report [17] on electricity grids further highlights the importance of electricity grids in enabling the transition to an energy system with high shares of renewable electricity generation and lists important barriers for grid expansion. It often takes 5–15 years to plan, permit, and build grid infrastructure in developed economies, such as the EU, and the report concludes that the most-important barriers to grid development in developed economies relate to public acceptance and regulatory aspects, which implies more drawn-out permitting processes.

These findings are in line with other studies in the research literature, where for instance, Steinbach [18] has pointed out that the main barriers to grid expansion in Germany are the lack of public acceptance and lackluster regulatory frameworks. Similarly, Battaglini et al. [19] have stated that the main barriers to the expansion of EU electricity grids are neither economic nor technical, but are instead linked to a lack of appropriate regulatory frameworks and public acceptance. The Swedish Environmental Protection Agency [20] and Tenggren et al. [21] highlight similar barriers for the transition to climate neutrality in the Swedish context. To account for such aspects, some studies have attempted to integrate public acceptance aspects into techno-economic modeling frameworks (see for example [22,23,24,25]). However, an assessment of how permitting times, the ability to expand the grid at a sufficient pace, and the coordination between industrial and infrastructure projects from the initial pre-study phase to the commissioning phase impacts the time taken to electrify industry is as of yet lacking. This paper sets out to fill this knowledge gap.

The overall aim of this work is to quantify how barriers relating to permitting times, grid expansion pace, and coordination between industrial site operators and grid infrastructure projects impact the transition to electrified industry. More specifically, we aim to investigate how these factors impact the time taken to electrify industry, and the corresponding impact on emissions and reliance on bridging technologies in the system. Towards this purpose, we develop and apply a mixed integer, linear optimization model, to study electrification of the basic material industry. In the modeling, we investigate the potential to ramp up the electrification of industry by minimizing CO_2 emissions given various conditions in relation to permitting times and ability to expand the required grid capacity over time. In the modeling, we also allow for the implementation of CCS as a bridging technology, to reduce emissions while the required electrification capacity is being built up, to investigate potential tradeoffs between rapid emissions reductions and a rapid pace of electrification. The model is applied to the existing Swedish basic material industry with plans and/or potential to electrify some or all their process steps, as a case study.

This paper is organized as follows: Section 2 presents the modeling and its scope together with the Swedish case study, Section 3 presents the results obtained from the work, and Section 4 presents the main conclusions drawn and implications of the results.

2. Method

This section describes the modeling approach developed and used in this work, as well as the case of existing Swedish industries to which it is applied.

2.1. Scope of the model

Considered in the work are the cement, iron and steel, refining and chemical industries. The studied system consists of the electrification projects on the site level, and the infrastructure projects associated with these industrial developments. Fig. 1 illustrates the typical project stages of a large industrial investment project, where the time requirements for the different project stages are included. The project stages considered are general, in order to illustrate the main steps in a large investment project, such as those assumed to occur in industrial electrification projects and electricity infrastructure projects. Thus, we assume that these principal steps are the same for the industry sectors included in this work. The pre-study phase of the project represents the initial scoping and early-stage engineering carried out before permitting applications are submitted. The permitting phase represents the time from which a permitting application for a project is submitted until the time when the permitting application is approved. The design stage represents detailed engineering and design, and the construction phase represents building and commissioning of the project. It should be noted that large projects may consist of several parallel sub-projects with individual project steps and multiple permitting applications. However, for the purposes of the modeling performed in this work, we consider each industrial site's transition to electrification as a single large project. In addition, for the projects related to grid infrastructure, this work

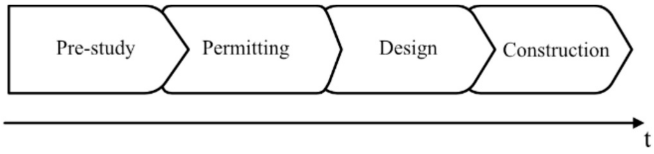

Fig. 1. Overview of the project steps considered in the modeling.

considers a pace of yearly grid expansion capacity to represent the investment and work force demands of the required infrastructure projects.

2.2. Model description

The model developed and used in this work is a mixed integer, linear programming (MILP) model. Using a MILP approach is deemed suitable since there is a need to use binary variables to keep track of completed project steps and their relation to one another. Furthermore, there are no apparent non-linearities (such as e.g., economies of scale) that need to be accounted for in the modeled system. Since the transition towards industrial electrification is driven by the demand to mitigate CO_2 emissions, we opt for an objective function formulation that minimizes CO_2 emissions by electrifying industrial processes over the period. As such, the model is not based on cost-minimization, but rather on implementing industrial electrification as rapidly as possible in a system in which grid infrastructure deployment is constrained. The resulting time-evolution of industrial electrification from the model will represent the pathway towards electrification that yields the greatest emissions reductions under a given set of assumptions related to permitting times and grid construction capacity. The main limitation of the chosen modeling approach is that since cost is not considered, the results obtained from the model do not say anything about when investments should be made so as to minimize system costs or maximize profits for the individual industries. Instead, the results indicate the optimal deployment of electrification from the perspective of CO_2 emissions reduction, given different conditions for grid expansion pace. Thus, the results obtained from this modeling approach complement results from other work that investigates the cost for infrastructure expansion and industrial electrification.

To avoid excess emissions from the system, a CO_2 emissions budget can be set, and CCS can be used to remain within the limits of the emissions budget as the industrial sites transition to electrified operation. CCS is implemented as a bridging technology, since the objective function aims to maximize the mitigation accomplished by electrification, and not by CCS. For the purposes of this work, CCS is chosen as a bridging technology over biomass use, since suitable biomass assortments are constrained and unlikely to be able to supply the demands posed by a large-scale phase out of fossil fuels from industry.

The model is solved over a time-horizon of 30 years, representing the period of 2025–2055, during which extensive electrification of Swedish industrial sectors is planned to take place. The model is implemented in GAMS and solved using the GAMS-CPLEX solver. Fig. 2 shows a visual representation of the model in a network graph. The main modeling steps in the graph are executed from left to right, with the main steps dealing with CO_2 mitigation of an industrial site with respect to electrification and CCS. The sites prioritize working towards electrification and can use CCS as a bridging technology if the constraints on electricity grid expansion prohibit near-term electrification and the CO_2 emissions budget is strict. CCS and electrification will place different demands on the infrastructure in terms of the capacity needed (MW of grid infrastructure, or $MtCO_2$ transported and stored). The model cannot use a technology at a specific plant to mitigate CO_2 emissions before it is fully implemented at the plant. Thus, solutions using a mix of electrification and CCS simultaneously at a given site will only be possible for industries where electrification cannot mitigate all site emissions (i.e., cement industry, where a substantial part of the emissions are process emissions).

The model is based on mass balances of CO_2, where each site i, initially emits CO_2 corresponding to their current emissions. Emissions mitigation is modeled by CO_2 moving from the industrial sites (i) to their electrified (r) or equipped with CCS (u) counterparts. Thus, emissions mitigation is modeled in this work as a flow of CO_2 going from an industrial site to a decarbonized version of the site. The flow of CO_2 should not be interpreted as a physical flow of CO_2 being transported, but rather as the mitigation performed by utilizing either electrification or CCS. The CO_2 mitigation is limited by the installed capacities of the required technologies. Before capacity can be installed in any given project, the preceding project stages need to be completed (see Fig. 1). The projects stages implemented in the modeling are described with respect to the time required for completion and, in the case of infrastructure construction, the yearly limits on the capacity that can be installed.

2.3. Mathematical model formulation

The objective of the model is to minimize the CO_2 emissions from the system through mitigation that is achieved by implementing electrification, as calculated according to Equation (1):

$$\min CO_{2,initial} - CO_{2,electrified-mitigation} \tag{1}$$

where $CO_{2,initial}$ is the total CO_2 emissions from the system without any mitigation implemented, and $CO_{2,electrified-mitigation}$ is the emissions mitigated over the studied period by implementing electrification. $CO_{2,electrified-mitigation}$, is defined according to Equation (2), where $x_{f,r,t}$ is the CO_2 mitigation performed by the electrified industrial site r in time step t, modeled as a flow of CO_2 from node f (electrification projects) to node r (electrified industrial sites), in time-step t:

$$CO_{2,electrified-mitigation} = \sum_{f}\sum_{r}\sum_{t} x_{f,r,t} \tag{2}$$

As can be seen from Fig. 2, the modeling of industry decarbonization includes the project stages outlined in Fig. 1. The binary variable (z) in

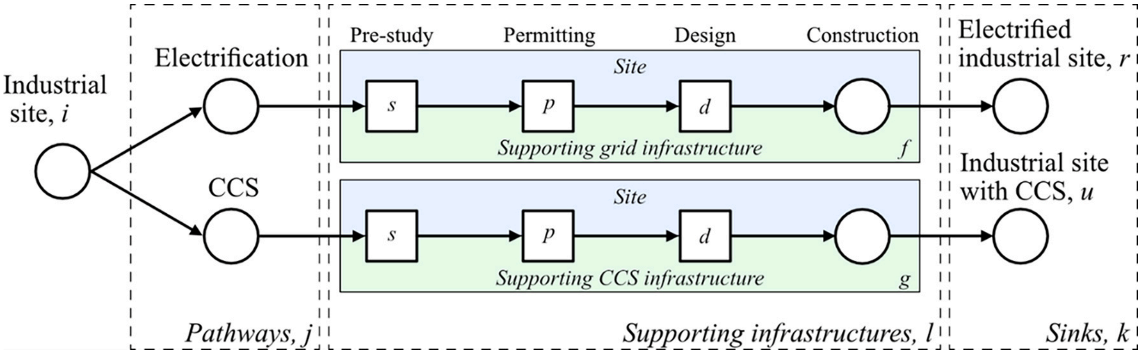

Fig. 2. Schematic representation of the model with indexing according to the equations described in Section 2.3. Each site can initially work towards electrification or CCS, imposing different demands on the supporting infrastructure. To reach the final state (electrified or equipped with CCS), both the sites and the connected infrastructure need to go through the project steps of pre-study, permitting, design, and construction. The squares represent the stages that are controlled by binary variables and act as gates in the model. Once all the project stages are completed and construction is finished, the project can be used for CO_2 mitigation.

Equation (3) ensures that projects are not used to mitigate CO_2 before they are fully constructed by limiting the flow of CO_2 to be either 0 or equal to the projects full capacity, represented by the parameter c^{lim}, on any nodes (n). In addition, the flow between nodes is restricted to being below the installed capacity (c^{inst}) according to Equation (3). Thus, Equations (3) and (4) work in tandem to ensure that projects are not used for CO_2 mitigation before construction of the projects full capacity is completed. Furthermore, capacity cannot be increased before an “investment decision” (c^{build}) is made, shown in Equation (5). The decision to build can in turn not be made before the pre-study, design, and permitting stages have been completed. The investment decision is associated with a construction time (t^{build}), implemented in Equation (5) before the project can be in operation. The index n represents all nodes in the modeling.

$$x_{n,n,t} = z_{n,n,t}{}^{*}c^{lim}_{n,n}\forall n \in N, t \in T \tag{3}$$

$$x_{n,n,t} \leq c^{inst}_{n,n,t}\forall n \in N, t \in T \tag{4}$$

$$c^{inst}_{n,n,t} \leq c^{inst}_{n,n,t-1} + c^{build}_{n,n,t-t^{build}_{n,n}}\forall n \in N, t \in T \tag{5}$$

The main mass balance applied in the model is described by Equation (6), which ensures that the flow of CO_2 from all industry sites is the same as the flow to all the end-nodes. Similar mass balance equations are applied over relevant nodes, to ensure that the CO_2 flow follows the intended path. In addition to the general mass balances, the model includes site-specific mass balances for the considered industrial sites, ensuring that all the CO_2 mitigated by site i ends up in the corresponding sink node k, where CO_2 mitigation via electrification is calculated in sink node r, and CO_2 mitigation via CCS is calculated in sink node u. Equation (7) exemplifies such a site-specific balance with the case of electrification at a theoretical site, *Site1*. Such balances are applied to both electrification and CCS, where relevant.

$$\sum_{i}\sum_{n}x_{i,n,t} = \sum_{n}\sum_{k}x_{n,k,t}\forall t \in T \tag{6}$$

$$x_{Site1,Electrification1,t} = x_{ElProject1,Site1Electrified,t}\forall t \in T \tag{7}$$

The pre-study, permitting, design, and construction processes are represented by Equations (8)–(11). The terms d, p, and s are binary variables (as shown in Fig. 2) that indicate whether or not the pre-study (s), permitting (p), and design-study (d) are completed. The binary variable q indicates whether the pre-study has been initiated for a given project. The investment decision on any arc is limited by the design study for the relevant arc that needs to be completed. The design study can, in turn, not be started before the permitting is completed, and the permitting can only be initiated once the pre-study step is completed. Each project stage is associated with a time for completion ($t^{pre\text{-}study}$, $t^{permitting}$ and t^{design}) for the project.

$$c^{build}_{n,n,t} \leq d_{n,n,t}{}^{*}c^{lim}_{n,n}\forall n \in N, t \in T \tag{8}$$

$$d_{n,n,t} = p_{n,n,t-t^{design}_{n,n,t}}\forall n \in N, t \in T \tag{9}$$

$$p_{n,n,t} = s_{n,n,t-t^{permitting}_{n,n,t}}\forall n \in N, t \in T \tag{10}$$

$$s_{n,n,t} = q_{n,n,t-t^{pre-study}_{n,n,t}}\forall n \in N, t \in T \tag{11}$$

In addition, to be able to study the impact of coordination of decisions between the site and infrastructure levels in specific scenarios, equations that control when a pre-study can be initiated on the site level in relation to project steps on the infrastructure level are implemented. Equation (12) exemplifies this, where the pre-study for a hypothetical *Site1* cannot be initiated before the associated infrastructure permitting is completed:

$$s_{Site1,ElecSite1,t} \leq p_{ElecSite1,f,t}\forall t \in T \tag{12}$$

In the modeling, the annual pace of grid infrastructure expansion can be set, to allow studying of the impact of the expansion capacity of the grid on the pace of industrial electrification. Equations (13) and (14) impose limits on the yearly capacities of electrification projects that can be connected to the grid. This constraint reflects the ability to build out the grid infrastructure to accommodate new loads, thus reflecting real-world limitations, such as the investment pace from the TSO and the availability of a workforce for constructing new power lines and transformer stations. The constraint ensures that the investment decisions in grid capacity are lower than the maximum grid building capacity, $l^{grid,build}$. The parameter a^{el} relates CO_2 mitigation for a given project to the yearly grid expansion capacity ($l^{grid,build}$, in MW), to ensure that the demand put by constructing mitigation capacity (c^{build}, in tCO_2) for the projects do not exceed the expansion capacity. Similar limits are imposed on the yearly deployment of CCS infrastructure capacity, according to Equation (14):

$$\sum_{j}\sum_{l}c^{build}_{j,l,t}{}^{*}a^{el}_{j,l} \leq l^{grid,build}\forall t \in T \tag{13}$$

$$\sum_{j}\sum_{l}c^{build}_{j,l,t} \leq l^{CCS,build}\forall t \in T \tag{14}$$

Equation (15) presents the CO_2 limitation on emissions over the period (b^{CO2}) implemented in the modeling, with the parameter m representing the reference CO_2 emissions from site i without electrification or CCS installed. For the first year ($t = 0$) the value of variable b is set to the allowed emissions over the period. In addition, a lower bound of 0 is set for b for all time-steps, ensuring that the only feasible solutions that are generated stay within the limitation.

$$b^{CO_2}_{t} = b^{CO_2}_{t-1} - \sum_{i}m^{CO_2}_{i,} - \sum_{l}\sum_{k}x_{l,k,t}\forall t \in T \tag{15}$$

2.4. Swedish case study

For the electrification of industrial sites in this work, the technologies envisioned for electrification differ according to the type of industry. For cement manufacturing, electrification is considered through the implementation of plasma burners, and CCS is needed to mitigate fully the remaining process emissions. For iron and steel manufacturing, the use of green hydrogen for the reduction of iron ore, combined with electric arc furnaces for steel production, is considered. In the case of refineries and chemical manufacturing, green hydrogen, to enable the input of more bio-based feedstock, is considered. The reasoning behind including these technologies and thus implicitly excluding others, is that they are either investigated by the industries themselves (e.g., hydrogen direct reduction in the Swedish iron and steel industry and hydrogen electrolysis in petrochemical industries), or represent electrification options that could provide substantial emissions reductions (e.g., implementing plasma burners in the cement industry). In this work, it is assumed that all the electrification projects require expanded grid infrastructure, since the industries are located in places that currently have constrained grid capacity, and the additional electricity demands for the investigated electrification projects are significant.

2.4.1. Industrial sites

Industries considered for electrification include existing refineries and petrochemical, iron and steel, and cement industries. This work does not account for the fact that other industrial activities, such as the establishment of new electro-fuel, battery, and fertilizer production facilities or developments in the existing forestry industry, could also be part of a future electrified industry system. It is also assumed that the industries considered in this work will still operate with maintained outputs in the future. Table 1 provides an overview of the industries included in this work, the main technologies considered for electrification of their processes (or part thereof) and the estimated increase in electricity demand if applying the electrification technologies. Additionally, the current Scope 1 (direct emissions from the industries) and the part of the Scope 3 CO_2 emissions that could be mitigated as a result of the transition, associated with the use of products downstream for iron ore mining and refining industries, are listed. Scope 3 emissions associated with downstream product use or processing have been identified as significant contributors to total emissions in the oil and gas and mining sectors, whereas for the cement, chemical and steel sectors, Scope 1 emissions and emissions from purchased goods and services are more relevant [26]. Additionally, reducing the downstream emissions is part of the main reason for decarbonization efforts for the refinery and iron ore mining sectors in the Swedish context [27,28], and as such, they are included in this work. Electricity generation (current level and that required for electrification) is considered to be carbon–neutral, given that Swedish electricity generation is presently almost CO_2-free.

Refineries: There are three refineries located on the Swedish west coast, two of which are owned by the Swedish company Preem and one by the Finnish company St1. The refineries plan to switch their production from fossil feedstocks to bio-based (or recycled) alternatives. In doing so, the demand for hydrogen will increase, due to the relatively low hydrogen content of the biomass-based feedstock compared to crude oil. The additional hydrogen demand is planned to, at least partly, be covered by electrolysis (indirect electrification). For refineries, Scope 3 emissions dominate (>80 %), i.e., mainly through the combustion of the fossil fuels in vehicles. It is important to note that in addition to hydrogen, acquiring a biogenic (CO_2 or biomass) or waste-based feedstock is necessary to enable decarbonization. However, in this work, we focus on the electrification part of the transition and assume that there will be sufficient availability of carbon feedstock. For the refineries, the hydrogen, and thus the electricity demand, is based on taking a value on the lower side of the interval of the estimated future hydrogen demand on the Swedish west coast from the work of Edvall et al. [29], and allocating this value to the sites operated by St1 and Preem.

Chemical manufacturing cluster: The chemical manufacturing cluster located on the Swedish west coast consists of several different companies producing a broad range of products. The largest CO_2 emissions source in the chemical cluster is the cracker plant operated by Borealis, and the CO_2 emissions from the chemical cluster applied here correspond to this site. In similarity to the refineries, the future hydrogen demand for chemical manufacturing is based on the work of Edvall et al. [29].

Cement: There are two cement manufacturing plants located in Sweden, one on the island of Gotland, off the east coast of Sweden, and one located inland on the Swedish mainland, in the city of Skövde. Both sites are owned by Heidelberg Materials (hereinafter abbreviated as HM). Around two-thirds of the CO_2 emissions from cement manufacturing are process emissions from the calcination of limestone, and the remaining one-third is associated with the combustion of fuels to supply heat to the process. The fuel emissions can be mitigated by, for instance, switching to bio-based fuels, or by electrifying the process heat, e.g., by implementing plasma burners (direct electrification) or by the use of electro-fuels (indirect electrification). CCS is necessary to mitigate the process emissions.

Iron and steel: The iron and steel industry in Sweden consists of iron ore mines and steel manufacturing plants. The iron ore mining operations, located in northern Sweden, are run by LKAB. Steel manufacturing is primarily carried out by the company SSAB, which operates the three large steel mills in the country. Two of these mills produce steel from raw materials and one uses recycled steel as feedstock. In addition, there are 11 steel mills owned by multiple industrial actors in the country, although 10 of these produce steel from scrap, and the other is relatively small in terms of emissions (<200 $ktCO_2$/year) compared to the mills operated by SSAB. Thus, in this work, we choose to focus on the operations of LKAB and SSAB and exclude new industrial establishments (such as Stegra, previously H2 Green Steel), due to the uncertainty regarding their time-plans for implementation. SSAB and LKAB are planning to transition to fully electrified operations, where the conventional blast furnace, basic oxygen furnace production route is replaced by hydrogen direct reduction of iron ore, followed by electric arc furnaces. LKAB plans to reduce the iron ore currently sold on the global market in Sweden using direct reduction with hydrogen. This would lead to a considerable reduction of Scope 3 emissions and significant increase in electricity demand. For the Swedish iron and steel industry, the power demand for decarbonization is, thus, based on the assumption that all of the mined iron ore, i.e., both currently exported and refined within Sweden, will be reduced with hydrogen produced by electrolysis in Sweden. Steel manufacturing is based on current production levels of steel and implementation of electric arc furnaces. The electricity demand for hydrogen direct reduction is based on the work of Toktarova et al. [30].

2.4.2. *Permitting and construction capacity*

Table 2 shows the assumed number of years for the pre-study,

Table 1

List of industries included in this work, their current CO_2 emissions levels, electrification technologies and corresponding increases in electric power demand.

Site	Industry sector	Current site emissions ($ktCO_2$/year)	Scope 3 emissions, only from downstream product use ($ktCO_2$/year)	Electrification technology	Increased power capacity (MW)
Preem, Lysekil	Refinery	1,110	36,000***	Hydrogen electrolysis	150¤¤
Preem, Göteborg	Refinery	570	16,000***	Hydrogen electrolysis	150¤¤
St1, Göteborg	Refinery	530	11,890#	Hydrogen electrolysis	150¤¤
Chemical Cluster, Stenungsund	Chemicals	632*		Hydrogen electrolysis	100¤¤
HM, Skövde	Cement	441*		Plasma burner	108¤
HM, Slite	Cement	1,540*		Plasma burner	359¤
LKAB, Kiruna	Iron ore mining	445	39,550**	Hydrogen electrolysis for direct reduced iron (DRI)	2,000¤
SSAB, Luleå	Steel production	3,200*		Hydrogen electrolysis for DRI plus electric arc furnace (EAF)	213¤
SSAB, Oxelösund	Steel production	2,060*		Hydrogen electrolysis for DRI plus EAF	96¤
Total increased power capacity					3,326

*Chalmers Industrial Case Study Portfolio, ChICaSP (for more information, see [31]).

**LKAB https://lkab.com/en/press/positive-decision-on-support-for-lkab-and-hybrit/.

***Preem Sustainability Report[27].

#St1 Game Changer Report [32].

¤Based on [33].

¤¤Based on [29].

Table 2
Estimates of the times (in years) for the pre-study, permitting, design, and construction phases for electrification and CCS implementation at the studied sites, and for the related electricity grid expansion.

Phase	Site-level time requirements for electrification (years)	Site-level time requirements for CCS (years)	Electricity grid time requirements (years)
Pre-study	1	1	1
Permitting	4	1	4[*]
Design	1	1	1
Construction	1	1	Modeling output[#][*]

[#] The total time taken to fully construct a project is a modeling output, made up of the time needed for the model to install full capacity into a project, given the limited yearly grid construction capacity. From the point that the decision is made to install full capacity in a project, there is a one-year period before the project can be used, ensuring a minimum construction time of one year.

[*] Electricity grid permitting and minimum construction times are set at 5 and 2 years, respectively, for Heidelberg Material's site in Slite, which due to being located on the island of Gotland requires more time for completion.

permitting, design, and construction steps involved in electrification and CCS implementation for the sites in Table 1, as well as for the associated electricity grid expansion. The electricity grid construction time is a modeling output, made up of the time needed for the model to invest full capacity into a project, given the limited yearly grid construction capacity. A lower limit of one year is imposed from the point where the decision is made to install full capacity at a project, to when the project can be used, ensuring that there is always a minimum of one year between the completion of the design study and the project becoming operational (i.e., a minimum construction time of 1 year). We assume that the pre-study, permitting, design, and construction times for electrification and CCS on the site level are the same for all the industrial sites listed in Table 1. Furthermore, for the grid infrastructure, we assume that the pre-study, permitting, design, and minimum construction times are similar for all sites, except for the cement plant HM Slite which is located on the island Gotland (due to the specific location of this site entailing more time-consuming grid-expansion [34]). In the Swedish context, the environmental courts at the County Administrative Board evaluate the permit applications according to Swedish environmental law. The permitting times applied are based on a report published by the Swedish Environmental Protection Agency [35], which has assessed the permitting times for previous projects from application to initial decision. The study includes all permit applications to the environmental courts in the County Administrative Board during Years 2020 and 2021. The reported permitting time for the 90th percentile of applications sent to the environmental courts is around 2.5 years. We then add an additional 1.5 years to account for the fact that consultations with the public and other stakeholders are not included in the reported time, and that the first decision for some applications can result in a need to supplement the application with information, adding to the time before construction of the project can be started (assuming that it is approved). The reason for choosing the 90th percentile of the application as the basis for this analysis is that the industrial electrification processes considered in this work are likely to involve relatively complex and time-consuming application processes, so it is assumed that the application times are longer than for smaller projects.

The yearly electricity grid expansion capacity is set at 300 MW/year, based on the historical expansion of industrial electricity use (assuming industrial operation times of 8,000 h/year) in Sweden for the period of 1982–1987, which is the period with the most-rapid increase in electricity use since the 1970's [36]. This number is used as a proxy for grid expansion connected to industrial electrification, since no numbers detailing the historical grid expansion pace were found.

For the CCS infrastructure, we assume that the deployment is limited to a maximum of 2 $MtCO_2$/year from the start of the modeled period in Year 2025 (not including the site level pre-study, permitting, design, and construction times shown in Table 2), to allow for CCS to be used as a bridging technology that can potentially be ramped up more rapidly than electrification. In the modeling, the additional electricity demand for CCS, which arises primarily from CO_2 conditioning, is considered. Furthermore, it is assumed that the CO_2 transportation infrastructure can be deployed at this rate, since the most likely initial CO_2 transportation option with relevance for Sweden is ship transportation, which is relatively flexible in terms of scaling up. This rate of CCS infrastructure deployment would limit CCS to around 2–5 full-scale capture units per year.

2.4.3. Scenarios

Table 3 presents the scenarios modeled in this work that vary the permitting times for electrification projects, the yearly grid expansion capacity, and the relationship between when decisions can be made at the site level compared to on the infrastructure level (referred to as 'coordination' in this work). In the modeling, varying the permitting times will influence how much time it takes before capacity can start to be installed in a project. On the other hand, varying the grid construction capacity will affect how rapidly a given grid project can be built up to full capacity once all the preceding project steps (pre-study, permitting, and design) are completed. Thus, these scenarios are designed to reflect the varying conditions that could be faced by electrification and grid expansion projects. The variation of grid expansion capacity aims to represent different conditions in terms of investment levels and the available workforce for grid expansion. The variations of permitting times represent differences in terms of public acceptance or the general efficiency of administrative processes that can influence the permitting procedures. The *Best-case* scenario (presenting highly favorable conditions for electrification) and *Worst-case* scenario (presenting highly unfavorable conditions for electrification) are frequently compared to the *Base* scenario to obtain an indication as to how the transition to electrified industry is affected by highly favorable and unfavorable

Table 3
Overview of the scenarios modeled in this work.

Scenario	Electricity grid permitting time (years)	Electricity grid expansion capacity (MW/year)	Coordination between site and infrastructure projects
Base	As in Table 2	300	High coordination: site and infrastructure pre-studies, permitting, and design can be performed in parallel.
Best-case	50 % of values in Table 2	600	High coordination
Worst-case	200 % of values in Table 2	150	High coordination
Half permitting times	50 % of Table 2 values	300	High coordination
Double permitting times	200 % of Table 2 values	300	High coordination
Half electricity grid expansion capacity	As in Table 2	150	High coordination
Double electricity grid expansion capacity	As in Table 2	600	High coordination
Medium coordination	Same as *Base* scenario	Same as *Base* scenario	Sites cannot start pre-study procedures before grid permitting is completed
Low coordination	Same as *Base* scenario	Same as *Base* scenario	Sites cannot start pre-study procedures before grid construction is completed
Sensitivity analysis	1–9	100–700	High and low coordination

conditions in terms of infrastructure deployment.

Regarding coordination between projects at the site and infrastructure levels, this is varied in two scenarios according to Fig. 3. These types of interdependencies are likely to be of importance, where multiple actors need to make decisions without being in control of the entire decision-making chain. These scenarios aim to capture the impact on the system development if the industrial actors adopt an approach that reduces their risk linked to investing in a technology without knowing whether the requisite infrastructure will be in place to support it. As a baseline, *High coordination* is applied, defined in this work as the only limitation being that decisions at the site level to build cannot be taken before construction has commenced on the infrastructure level. This means that the pre-study, permitting, design, and construction processes can be run in parallel at the site and grid infrastructure levels. The *Medium coordination* scenario applies a more-restricted approach, where the sites cannot initiate pre-study procedures before the grid permitting has been approved. In the *Low coordination* scenario, we apply an even more-restrictive approach, where the sites cannot initiate their pre-study procedures until construction of the relevant grid connections has been completed. *High coordination* is applied as a baseline for most scenarios to allow the investigation of how the grid expansion pace and permitting times impact the transition to electrified industry in isolation. The subsequent scenarios varying coordination are investigated add the dimension of coordination between site and infrastructure projects, and the impact it has on the time taken to electrify the studied industrial system.

3. Results and discussion

3.1. *Transition to electrification for different electricity grid expansion capacity and permitting times*

Fig. 4 shows the modeled timelines for electrification of Swedish industries for: a) the *Base* scenario; b) the *Best-case* scenario; and c) the *Worst-case* scenario. The model initiates the pre-study procedures to allow for construction to commence as early as possible given the applied constraints on permitting times and construction capacity. The modeling gives that several projects in Fig. 4 a (for instance, the HM cement plants and the Stenungsund Chemical Cluster) initiate their pre-studies later on in the period, showing that in the *Base* scenario, the grid expansion capacity becomes the limiting factor for the optimization. If the grid expansion capacity is not limiting, all the projects can be started and constructed in parallel. However, due to the limitations imposed on capacity in infrastructure construction, there is instead competition for grid construction between the projects in the model. For each scenario, the model will prioritize those projects that can deliver the greatest CO_2 reductions over time through electrification, given the assumptions regarding emissions mitigation and power demand, and the limitations imposed on the infrastructure related to the electrification projects. This results in a “merit order” in which the projects are implemented according to their emissions mitigation potentials in relation to how much grid infrastructure capacity they require (tCO_2/MW). The results in Fig. 4 show that projects that can yield significant emissions reductions at a relatively low increased demand for grid capacity, e.g., refineries, tend to be prioritized over projects that achieve relatively small emissions reductions, e.g., cement-making, in the modeling. The focus in the model on electrifying sites in accordance with this “merit order” is due to the objective function formulation of minimizing the difference between the reference emissions and the mitigation through electrification, i.e., maximizing the emissions mitigation performed with electrification. With this modeling approach, the electrification projects will be implemented according to how much emissions mitigation they will achieve, in relation to how much grid infrastructure they require to do so. Projects that have a relatively high potential for emissions mitigation and a low requirement for grid infrastructure will thus be implemented early. Furthermore, since all projects need to go through similar project stages before capacity is built up and they become operational, prioritizing relatively low-effort projects (from an additional grid capacity point of view) that nonetheless yield significant emissions reduction for early implementation means that the benefit of these emissions reductions will be seen for a longer period.

In the *Base scenario*, the modeled time for project completion ranges between 7–14 years. For most projects, the construction time for grid expansion is 1–2 years, due to the projects having a relatively small demand for capacity in relation to the set yearly grid expansion pace. However, for the project connected to LKAB, 7 years are required from the first installation of grid capacity until it is fully constructed, owing to the high additional grid capacity needed to get the project operational. The modeled time needed for the electricity grid expansion projects are in line with times reported by The Swedish Energy Markets Inspectorate, who report typical lead times for electricity grid projects of around 7–15 years, out of which the construction times make up between 1–4 years [37].

Looking further into the *Base* scenario, all the included industrial sites have electrified their operations by Year 2043 in the modeling, which is in line with the national Swedish target of reaching net-zero emissions by Year 2045. However, this does not account for the fact that other industries and sectors, not included in this study, will likely also need new grid capacity in an evolving industrial and energy system, creating increased competition for investments in infrastructure projects. A report from Swedenergy (a Swedish energy company trade organization) estimates that sectors outside the scope of this paper, such as transportation, fertilizer production, and battery manufacturing, could have an electricity demand of 37 TWh/year by Year 2045, with the majority coming from the transport sector [38]. The sites included in this work are calculated to present an additional demand of around 26 TWh/year. The substantial demand posed by sectors outside the scope of this paper will to some extent compete for additional grid infrastructure and in so doing, impact the time taken to electrify the system covered in the present work. This means that the timelines shown in Fig. 4 are to some extent optimistic estimates due to not including all industrial sectors and developments, and the impact on the grid from electrification of the transportation sector.

In addition, some of the industries included in the modeling have net-zero emissions targets that are more ambitious than the national targets, in that they are aiming to decarbonize their operations already around Year 2035. Reaching such targets could prove challenging considering that four out of the nine industrial sites included are

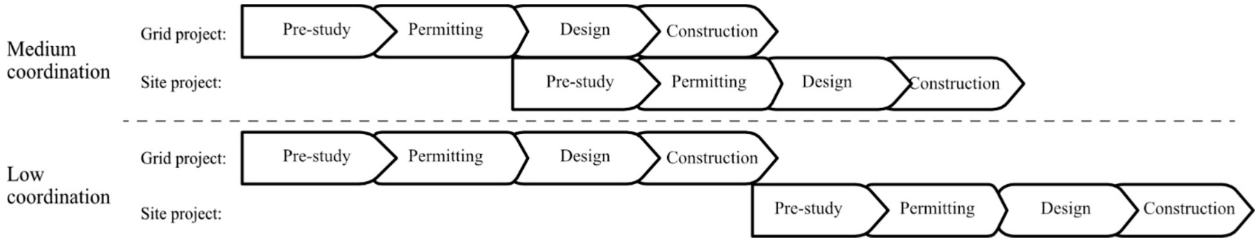

Fig. 3. Illustration of the dependencies between the project steps on the site and infrastructure levels in the Medium coordination and Low coordination scenarios.

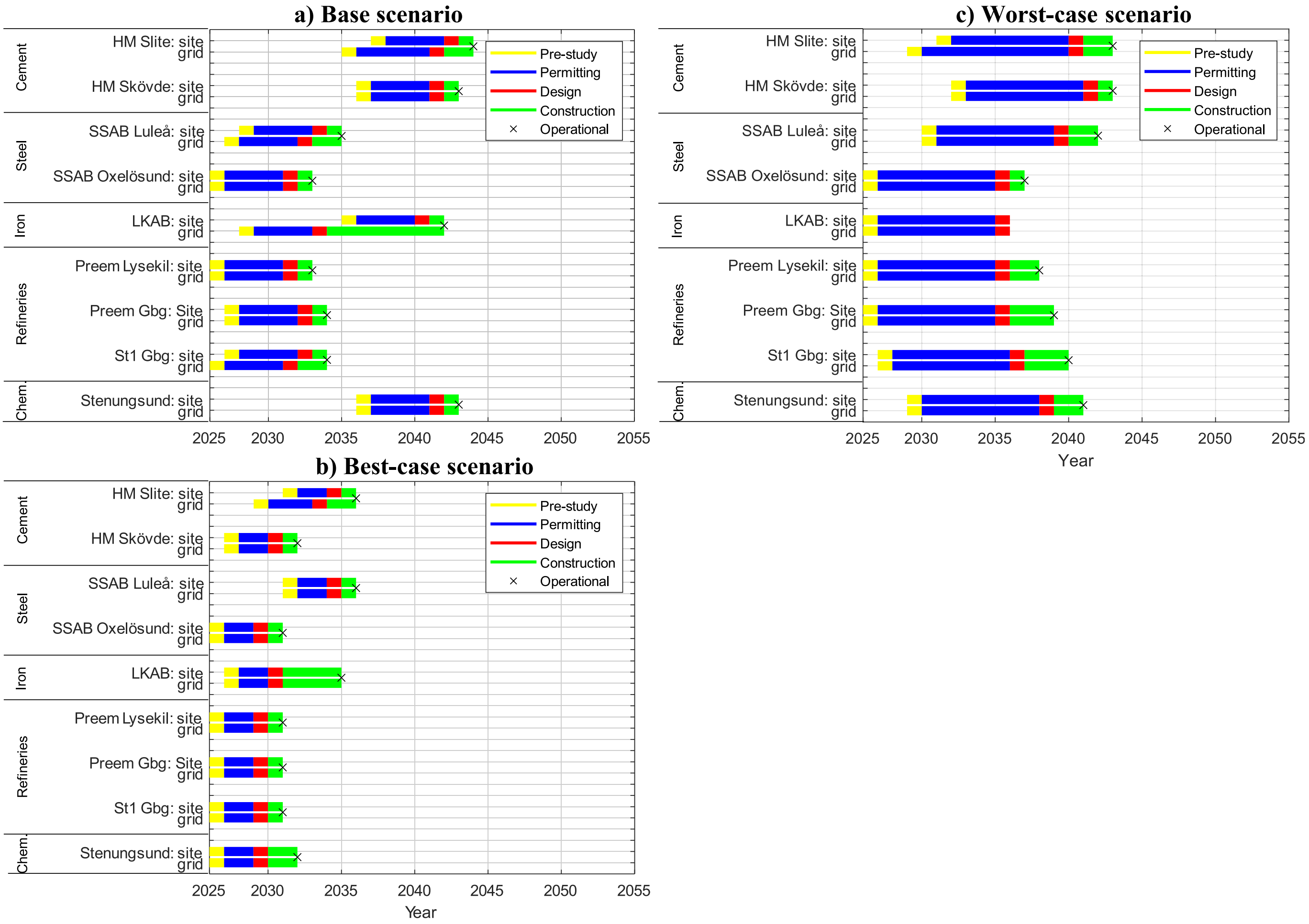

Fig. 4. Timelines for the different project steps applied in the modeling for the electricity grid and site-related electrification activities for the a) Base, b) Best-case, and c) Worst-case scenarios at the modeled plant locations.

electrified after Year 2040 in the *Base* scenario.

Comparing the timelines in Fig. 4a (*Base* scenario) and Fig. 4b (*Best-case* scenario), the system goes from being constrained mainly by the yearly grid expansion capacity to a combination of both the permitting times and the grid expansion capacity. For the *Best-case* scenario (Fig. 4 b), it is clear that most, but not all, of the projects are started in the first time-step of the modeling, implying that a combination of both permitting times and grid yearly grid construction capacity is limiting the deployment. In addition, a rapid transition of the system to full electrification can be seen in the *Best* case, with the final projects completing construction in Year 2037, facilitated by the rapid permitting procedures and high expansion capacity of the grid infrastructure. In the *Best* case, the permitting times connected to the projects are 2 years (2.5 years for the installations connected to HM Slite), and there is capacity to accommodate additional industrial loads of 595 MW/year to the grid. (Note that the largest increase in Swedish industrial electricity since the 1970′s is around 300 MW/year, averaged over a 5-year period). Transitioning the industrial system in such a short period of time does indeed present some challenges. Grid expansion projects are subject to high risks of delays throughout the project, due for instance to appeals against the project during the permitting phase or the lack of an available workforce or a constrained supply of important components during construction [17]. Such risks could jeopardize the ability to transition quickly. It would also require the planning and scoping of the projects to start imminently to reduce the risk of delays.

In the *Worst-case* scenario (Fig. 4c), we observe a slow transition towards electrification, with permitting procedures for the projects being finished in Year 2035 at the earliest. In addition, in the *Worst-case* scenario, one of the nine projects, the implementation of hydrogen direct reduction at LKAB, fails to be electrified within the modeled period of 2025–2055. This means that according to the previously mentioned prioritization order followed by the model, the large potential emissions reduction from LKAB obtained through reducing currently exported iron ore in Sweden using regionally produced hydrogen, places too high a demand on the grid capacity to be prioritized, so it cannot be completed within the modeled time-horizon. If the modeling period is extended, we observe that all electrification projects can be completed up to Year 2058, which is significantly later than the Swedish net-zero target of Year 2045. It should, however, be noted that even in a system with poor conditions for electrification (such as in the modeled *Worst-case* scenario), there may be solutions, such as importing blue hydrogen or ammonia that could act as a bridging solution and thereby, reduce the demand on the grid infrastructure, which would enable a faster transition.

Fig. 5 shows the number of sites electrified (Fig. 5a) and the cumulative unabated emissions (Fig. 5b) over time for the *Base* scenario and six additional scenarios. From Fig. 5a, it is evident that the strongest individual impact on the time taken to electrify all sites is from the grid expansion capacity. Obviously, varying both the permitting times and the grid expansion capacity has the greatest impact on the time taken to electrify the system. However, looking at the cumulative unabated emissions over the period in Fig. 5b, the differences in cumulative emissions between the *Half permitting times* and *Double grid expansion capacity* scenarios, as well as between the *Double permitting times* and

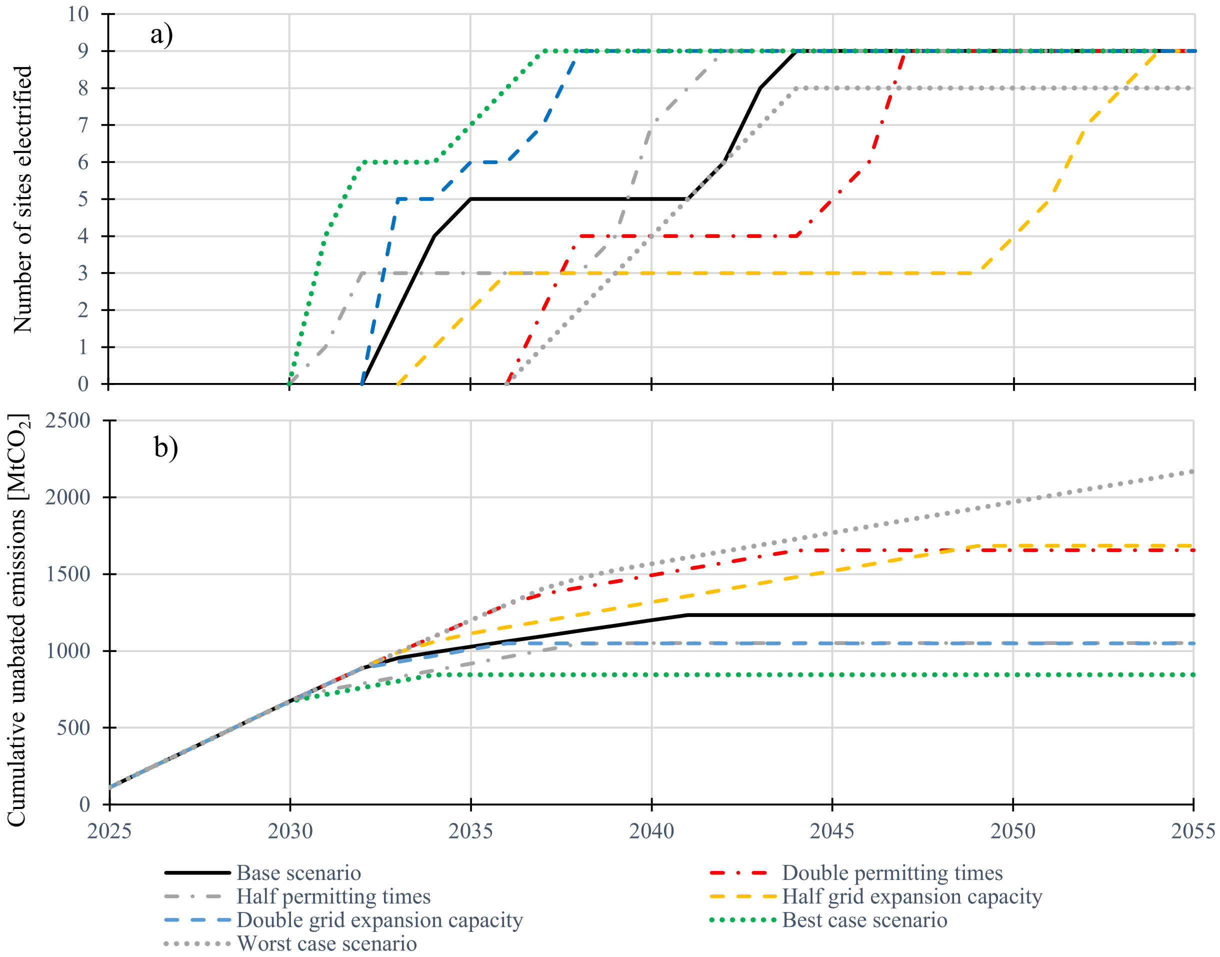

Fig. 5. Number of sites electrified (panel a) and cumulative unabated emissions (panel b) over time for the seven scenarios studied. Two scenarios modify the permitting times for electricity grid expansion (dashed-dotted lines), two scenarios modify the yearly electricity grid expansion capacity (dashed lines), and the remaining two scenarios, Best-case and Worst-case, apply a combination of both (dotted lines).

Half grid expansion capacity scenarios, are small. Furthermore, with respect to the amounts of unabated emissions, there are large differences between the *Best-case* and *Worst-case* scenarios, ranging from around 850 $MtCO_2$ over the period in the *Best-case* scenario to around 2,150 $MtCO_2$ over the period in the *Worst-case* scenario. In other words, going from short permitting times and a high capacity to expand the electricity grid towards long permitting procedures and slow pace of expansion of the grid cause the unabated system emissions to increase by a factor of about 2.5.

3.2. Distribution of emissions mitigation via electrification and CCS

Fig. 6 shows the amounts of CO_2 emissions that are mitigated by electrification and the levels of CO_2 that must be mitigated with CCS in the a) *Base*, b) *Worst-case*, and c) *Best-case* scenarios with a lifetime of 15 years set on CCS technology. This means that once it is in place, CCS cannot be replaced by electrification within 15 years of initial implementation. The emissions allowed from the system in Fig. 6 are the most-stringent possible that still yield a feasible solution for each scenario. A strict limitation on emissions forces the model to maximize the use of CCS, so as to avoid emissions during the transition towards complete electrification. The emissions mitigation is implemented in steps rather than in a continuous upward gradient, as the model focuses all of the grid construction capacity into one or a few projects at a time, to get them into operation as quickly as possible.

Implementing CCS also requires additional grid capacity, due to the conditioning of CO_2. However, this electricity demand is small compared to the electrification of the site, and it will not present significant competition for new grid infrastructure capacity. However, the lock-in effect caused by the imposed lifetime on CCS technology does have an impact on the system-build up. For instance, in the *Base* scenario, the time to complete electrification of the system is increased by four years when CCS is forced into the solution. The four-year increase in time taken to electrify the system observed here will be extended the longer the assumed lifetime on CCS equipment. Since industrial operators are likely to want to use any equipment for as long as possible to minimize the specific cost of their investment, this presents an interesting tradeoff between rapid emissions reductions, and rapid electrification of the system. Namely, if the aim is to minimize emissions as soon as possible, the reliance on bridging technologies will be larger, thus delaying the transition to a fully electrified system.

In addition to electrification taking longer, and the large reliance on CCS, the model re-prioritizes electrification projects when strict emissions limitations are enforced. This re-prioritization can be observed in the *Worst-case* scenario, where the ironmaking process at LKAB is not electrified before 2055 without an emissions limitation that forces the model to rely heavily on CCS. However, due to the strict emissions limitation and the 15-year lifetime for CCS installations applied for results shown in Fig. 6, other projects rely on CCS for longer, and grid construction is focused on the LKAB project instead. This results in the LKAB project being electrified in 2053, while projects in cement, steelmaking and chemical manufacturing rely on CCS until later in the period.

In terms of emissions mitigation in the system, in the *Base* and *Best*-

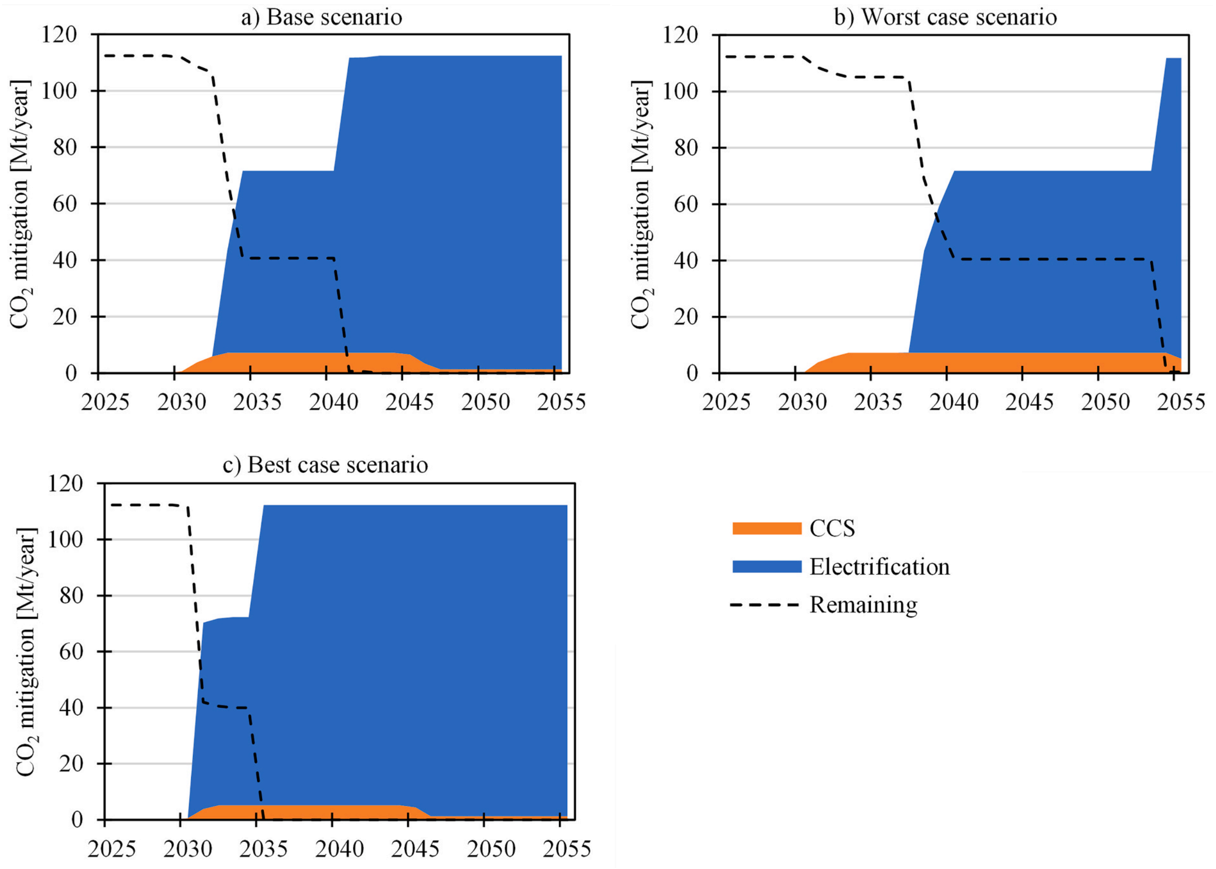

Fig. 6. Annual levels of CO_2 mitigation from electrification and CCS in the Base, Best-case and Worst-case scenarios, together with the remaining emissions (dashed line). A lifetime on CCS technology is set, limiting the minimum utilization time of the technology to 15 years.

case scenarios, the total use of CCS over the period of 2025–2055 is in the range of 90–120 $MtCO_2$, which is approximately equivalent to 2–3 times Sweden's current yearly GHG emissions. In the *Worst-case* scenario, the system is reliant on CCS for a longer period, due to the long permitting times and the slow pace of grid capacity expansion, mitigating around 174 $MtCO_2$ over the period. This implies that in a highly emissions-constrained economy, CCS can have an important role to play in reducing site emissions. An equal per-capita distribution of the global emissions budget that yields a 67 % probability of reaching the 1.5 °C target would give Sweden a total fossil emissions budget of 475 $MtCO_2$ from Year 2020 [39]. Thus, in a context where permitting times are slow and the pace of grid expansion is slow, the impact of and mitigating an additional 174 $MtCO_2$ using CCS can be considered substantial.

It should be noted, that there are uncertainties as to whether all of the industries considered in this work will still operate in the future and whether their production outputs will remain constant, which is

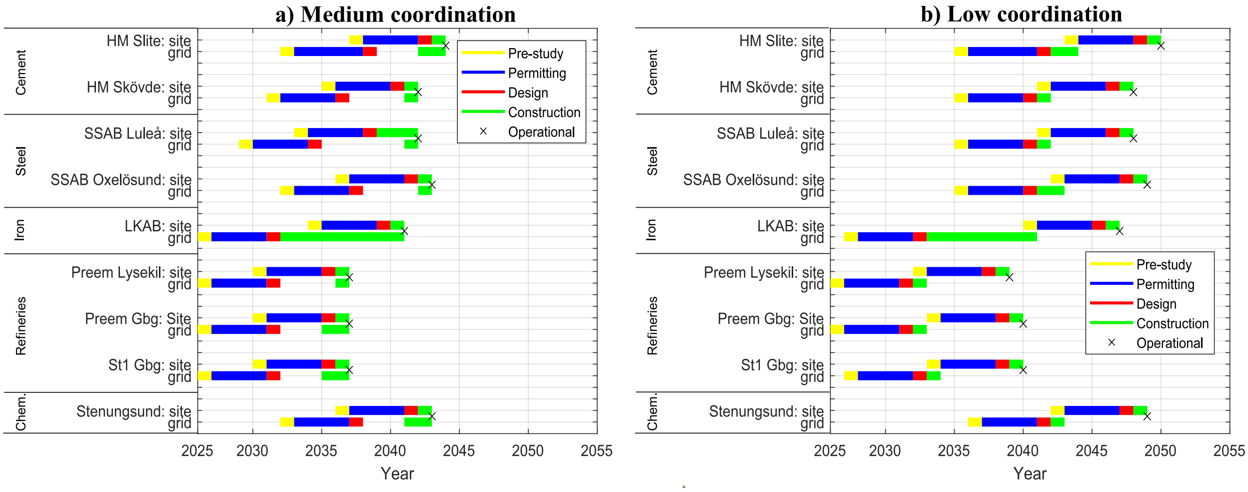

Fig. 7. Timelines of the different project steps applied in the modeling for the electricity grid and site-related electrification at the studied plant locations, showing: a) the Medium coordination scenario, in which the sites do not initiate their pre-study procedures until the relevant grid permitting is completed; and b) the Low coordination scenario, in which the sites do not start their pre-study procedures until the relevant grid construction is completed.

assumed in the calculation of emissions mitigation in this work. Furthermore, it should be noted that expansion of the grid infrastructure as a result of the plans for electrification in multiple sectors will require substantial investments. A recent report has estimated that the investment needed in the Swedish electricity grid up to Year 2045 is upwards of 1,000 billion SEK (roughly 87 billion €), including maintenance of the existing grid and expansion to meet the future demand [38]. This is a substantial increase compared to recent decades, during which time the electricity grid has essentially been in maintenance mode.

3.3. Impact of coordination between site and infrastructure

Fig. 7 shows the timeline for electrification at the investigated sites for two cases that apply lower levels of coordination between the sites and infrastructure. In Fig. 7a, the *Medium coordination* scenario, the sites start their pre-studies first after the associated grid permitting is completed. In similarity to the *Base* scenario (see Fig. 4a), all of the considered industries can electrify their operations before Year 2045, i.e., the system is still constrained mainly by the grid expansion rate and not by the time needed for permitting, pre-studies and design studies. Thus, when applying *Medium coordination* between industrial sites and infrastructure, construction does not significantly impact the transition from a system perspective. It does, however, result in a 20 % increase in the cumulative unabated emissions compared to the *Base* scenario, showing that a lack of coordination between the industrial actors and infrastructure development may increase CO_2 emissions. Furthermore, some industries may not meet their internal targets for climate-neutral operation when avoiding risks related to infrastructure development.

In Fig. 7b, the sites start their planning and permitting processes first after grid installation, which has a considerable impact on the timeline compared to the *Base* scenario (see Fig. 4a). The industrial system reaches full electrification first in Year 2050, as compared to Year 2043 in the *Base* scenario, leading to an increase in the cumulative emissions from the system of around 55 % compared to the *Base* scenario. This dramatic increase in emissions from the system happens because the Scope 3 emissions remain unabated for a relatively long time, which causes large increases in system emissions. Since most sites are not electrified until after Year 2045, a severe lack of coordination between infrastructure deployment and development at the industrial site level jeopardizes the Swedish target of reaching net-zero emissions by Year 2045, as well as the targets of the individual companies, such as Preem's target of establishing a climate-neutral value chain by Year 2035 [27].

3.4. Sensitivity analysis

Fig. 8 shows the time required to electrify the considered industries with respect to the sensitivity analysis shown in Table 3, i.e., broadening the range of combined effects of permitting times, grid expansion capacity and coordination between actors. The analysis is performed in addition to the other scenarios in Table 3, to identify trends that are difficult to observe with fewer points of comparison. Each combination of grid expansion capacity and permitting times is run with either high or low levels of coordination between the industrial sites and infrastructure actors, to yield a range of outcomes.

The first thing to point out is that there is an effect of diminishing returns in terms of the impact on the speed of the transition as a function of increased grid expansion capacity. Once around 300 MW/year of grid expansion capacity is achieved, the time taken for the system to transition is only marginally decreased with further increases in capacity (1–2 years per 100 MW/year capacity). On the other hand, below 300 MW/year, each addition of 100 MW/year yields a significant reduction in the time taken to electrify the system. This non-linear behavior shows that it is very important to ensure sufficient expansion capacity of the grid to avoid outcomes that could result in the transition taking decades longer than what is aimed for with the climate targets. The modeled scenarios with low grid expansion capacity could also be seen as other activities that are outside the modeled industrial system and competing for grid infrastructure capacity. Such activities could include the establishment of new industrial sites and the reinforcement of the grid infrastructure necessary for accommodating new power generation or for electrifying the transportation sector. Thus, the greater the competition that there is for infrastructure expansion, the more important it will be to ensure a large construction capacity in order to get the projects, and thereby the CO_2 mitigation, deployed. For the system to be able to electrify fully before Year 2050 for all of the investigated permitting times with high coordination, there needs to be the possibility to accommodate at least 300 MW/year of additional industrial demand to the grid. If a grid expansion pace of 200 MW/year is applied, only permitting times of up to 3 years allow full electrification before Year 2050.

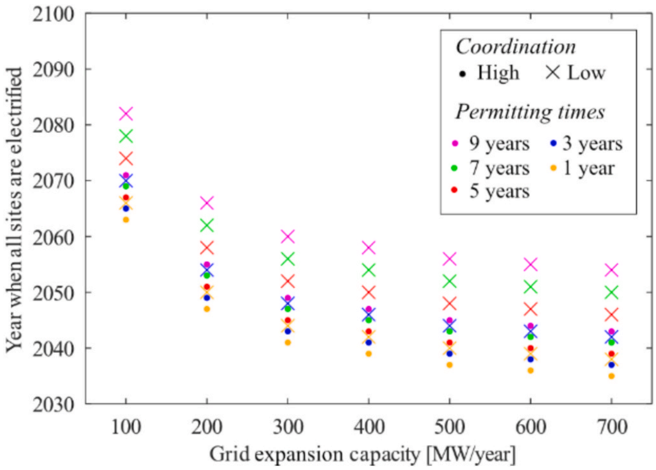

Fig. 8. Sensitivity analysis. Permitting times of between 1 and 9 years (color-coded) are assessed for grid expansion capacities in the range of 100–700 MW/year. In addition, each combination of permitting times and grid expansion capacity is run with either the High coordination (same as in the Base case, marked by dots) or low coordination (same as in the Low coordination case, marked with x) between industrial sites and infrastructure development.

Furthermore, with a low level of coordination between the sites and infrastructure development, it is clear that only permitting times of up to 3 years would allow for the system to be fully electrified by Year 2050 at a grid expansion pace of 300 MW/year. If the grid expansion pace is increased further, to 400 MW/year or more, it will still be possible to electrify the system before Year 2050 with permitting times of up to 5 years. In addition, the impact of low-level coordination between actors has a stronger effect when the permitting times are long (compare the dots and crosses of the same color in Fig. 8). This is due to the way in which low coordination is modeled, such that the permitting procedures on the site and infrastructure levels cannot be run in parallel. This in turn means that, in order for a project to become operational, two long permitting procedures need to be run consecutively.

4. Conclusions

An optimization model has been developed and applied to study the timeline of the industrial transition towards electrification under varying conditions for permitting times and grid expansion capacity. The modeling approach is based on minimizing emissions by implementing electrification, applying constraints on how rapidly grid infrastructure can be expanded. We apply the model using the electrification of existing Swedish cement, iron and steel, chemical and refining industries as a case study, investigating the period between Years 2025 and 2055. In the modeling we do not account for new industrial establishments and it is assumed that the studied sites will continue to operate in the future. Since the modeling is not based on cost minimization, it does not consider decision-making based on cost tradeoffs. However, since major barriers relating to the expansion of the grid relate to long permitting times contributing to the slow expansion of the grid, the approach taken in this work aims to complement studies that investigate the costs and investment needs for new infrastructure.

Our results highlight two important aspects regarding the transition towards an electrified industry. First, our results show that to enable timely electrification, short permitting times and high capacity to build out the electricity grid are of the utmost importance. In a modeled *Best-case* scenario with short permitting times and high expansion capacity for grid infrastructure, the average time for the considered industrial sites to be fully electrified is reduced by about 5 years compared to the modeled *Base* scenario. The results also confirm that long permitting times and low expansion capacity of grid infrastructure risk jeopardizing climate goals by causing long delays in the transition, and in most of the modeled scenarios, the expansion capacity of grid infrastructure is the factor that is mostly limiting the speed of electrification. In the modeled *Worst-case* scenario (with long permitting times and low grid expansion capacity), the last electrification project is not completed until Year 2058, long after the Swedish national target of climate neutrality by Year 2045 and the EU target of Year 2050. Furthermore, the results show that for the considered sites to be able to undergo electrification before Year 2050 with permitting times of up to 9 years, the pace of grid expansion needs to be able to accommodate at least 300 MW/year of industrial demand and the coordination between the industries and supporting infrastructure development needs to be strong. In the case that the pace of electrification is low, it is shown that bridging technologies (CCS in this work) can be used to reduce excess emissions from the system. However, this comes at the cost of delaying electrification further, presenting a trade-off between rapid emissions reduction and rapid electrification.

Second, our work highlights and quantifies the effects of a lack of coordination between industrial sites and infrastructure deployment. When applying low coordination between industry and infrastructure, modeled so that the industrial actors wait for infrastructure projects to be completed before they initiate their own pre-studies, we see an increase of almost 8 years in the average time taken for sites to be electrified, as compared to the *Base* case. This, in turn, leads to low utilization of the infrastructure, presenting high opportunity costs for the grid operators from the missed potential for value generation. In terms of emissions, a *Low coordination* situation would drastically increase the cumulative system emissions by roughly 55 %, due to the amounts of emissions that are unabated during the transitional phase. In addition, if the coordination between actors is weak, permitting times of no more than 5 years, in combination with a grid expansion pace of 400 MW/year, would be needed to reach full electrification before Year 2050 (in contrast to permitting times of up to 9 years and grid expansion rate of 300 MW/year with *High coordination*).

In summary, the results presented in this paper show that long permitting times and a lack of expansion capacity of the electricity grid risk undermining the timely transition towards a fully electrified industry. The average time taken to transition the sites to electrified operation is prolonged by around 8 years if the coordination between developments on the site and infrastructure levels is weak. In practice, this implies that processes that enable strong coordination between industrial sites and the development of supporting infrastructure are important for reducing the delays in the transition of the entire system caused by long permitting times in the development of the grid infrastructure, as well as for reducing the overall demand on the infrastructure deployment capacity. Furthermore, based on the findings from this paper, we recommend that sufficient funding is allocated to grid expansion projects to avoid the outcomes where electrification projects are significantly delayed (corresponding to a grid expansion pace $>$ 300 MW/year for the studied system). Additionally, we suggest that in selecting which grid expansion projects to prioritize, projects that can achieve high emissions reductions while requiring relatively low additional grid capacity (e.g., projects relating to hydrogen production for refineries in the present work) are prioritized, to maximize emissions mitigation over time.

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CRediT authorship contribution statement

Sebastian Karlsson: Writing – original draft, Methodology, Formal analysis. **Johanna Beiron:** Writing – review & editing, Supervision, Methodology. **Fredrik Normann:** Writing – review & editing, Supervision, Conceptualization. **Filip Johnsson:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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