Faster decarbonization of heavy industries in low-carbon power grids: Using process flexibility for handling grid congestions[⋆,⋆⋆]

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Abstract

Industrial decarbonization requires substantial electricity and grid infrastructure. Policies are developed and significant funds are being directed to decarbonize electricity generation and incentivize investments in renewable energy. Expansion of the transmission grid, however, is lagging. Even though grid capacity limits may be critical only for a few hours annually, industries ready to make large energy-intensive decarbonization investments may be refused grid connection due to security-of-supply requirements. We demonstrate that industrial flexibility can alleviate grid congestions and increase grid reliability. In low CO_2-intensity power grids, this can increase the pace of decarbonization of heavy industries via electrification. By aligning industrial processes with grid load, peak demand can be reduced, facilitating faster sector decarbonization. Our study presents a bottom-up model of the demand-side flexibility of energy intensive processes in heavy industries (chemicals, cement and metals). Applying this to a Norwegian industry region, combined with power flow analysis, the flexibility reduces strain on transmission grids during peak demand, reducing grid overload hours by 90 %. Activating industrial flexibility incurs significant operational costs, primarily determined by the most stringent processes. We estimate a unit cost of 111–210 €/MWh for flexibility of the industry sectors considered, comparable to other grid reinforcement alternatives but with significantly reduced time for realization. In the investigated transmission grid, 339 MW of new electrification measures can be accommodated, allowing for decarbonization measures representing 16 % of the annual CO_2-emissions of the industries. Our findings emphasize the importance of encouraging more flexible processes in heavy industries to accelerate decarbonization by electrification in low-emission power grids.

1. Introduction

Decarbonizing the industry sector is critical for meeting global emission reduction targets. The sector accounts for 47 % of CO_2-emissions worldwide, out of which heavy industries are responsible for 70 %.[1,2] Emissions from heavy industries are regarded as hard to abate due to the complexity of industrial processes and the diverse range of emission sources.[3] Addressing these challenges will require a mix of decarbonization measures, including direct electrification, indirect electrification (e.g. hydrogen), and carbon capture, which all require electricity. The global industrial electricity demand is therefore expected to nearly double by 2050 in a net-zero emission scenario.[1]

The accumulated increase in electricity demand in all sectors will require rapid grid capacity extensions. Meanwhile, new renewable generation must be introduced, largely driven by solar PV and wind, which requires balancing with demand and additional increase in transmission capacity.[4] Currently, the power sector is still dominated by unabated fossil fuels, accounting for over 60 % of global electricity generation.[5] As such, the indirect emissions associated with the electrification of industrial demands can counteract the intended positive climate effect.[6] However, increasing investments in renewable generation are reducing the carbon intensity of the power sector, a trend expected to continue for decades.[7] As emissions decrease, electrifying industrial energy demand in low-carbon power grids will become increasingly important in the energy transition.[8,9]

Much attention has been directed towards stimulating investments in new generation capacities, while the critical role of the power grid in facilitating industrial decarbonization has often been overlooked.[10] In power grids with high shares of renewables, electrification of industrial demand may create new grid congestions, directly reducing the pace of decarbonization.[11] Over the last decade, investments in renewable generation have nearly doubled, while grid investments have not seen the same increase. In the EU, annual power grid investments must increase more than threefold to reach the climate targets,[12] and this has caused the International Energy Agency to warn that, unless necessary incentives are provided, grid capacity could pose a significant obstacle to the clean energy transition.[13] Expanding the power grid may take years, or even decades,[14] and finding ways to more efficiently utilize the capacity of the exist-

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ing grid will reduce the growing connection queues. The grid capacity is typically only challenged for a few hours over the year; therefore, reducing demand during these critical hours may free up space in the grid for new loads, thereby accelerating the decarbonization of industry by electrification.

Heavy industries often cluster in specific areas, enabling resource sharing, collaboration, and optimized use of limited resources. These clusters act as hubs where companies benefit from close proximity. While industry clusters have been identified as potential "gateways to change", most industry cluster decarbonization projects aim to establish shared infrastructure for blue hydrogen production as a potential revenue stream,[15] or share carbon capture, handling and intermediate storage infrastructure to reduce the cost of decarbonization.[16–18] Yet, industry decarbonization will highly impact the electrical grid and the way the capacity of this infrastructure is shared among colocated industries.[12] Even in sectors with complex processes and high operating temperatures, such as the chemical industry, direct electrification, or indirect via e.g. hydrogen, will be one of the key elements in their decarbonization.[8] However, the extent to which electrifying industrial processes will affect existing power grids and infrastructure has been little explored.

Zero-carbon energy systems require increased investments in electricity transmission capacity and more flexible resources to balance generation and demand, and for providing grid services.[19] Demand-side flexibility is one option with the potential to alleviate grid capacity challenges and support balancing the power system.[20–22] In the industry sector, some effort has been made to quantify and identify potentials for demand-side flexibility, although this typically focuses on balancing generation and demand, rather than handling grid challenges.[8] Industry has significant potential to find new ways to interact with the power grid,[23] and while energy system models often solely include simplified storage models,[19] utilizing energy or product storage in industry can be cost-effective.[24–26] However, there is still a gap between industry's ability for demand-side flexibility and the actual shifting of electricity consumption by industries, mainly due to a lack of financial incentives[27] or competence and awareness.[21]

The cited literature explores demand-side flexibility for power system balancing, typically between generation and demand. However, few studies focus on the industry's potential to provide grid services and enhance grid capacity. Otashu et al.[28] developed a model incorporating the flexibility of a chlor-alkali electrolysis process in optimal power flow calculations. They demonstrated the system-economic benefits of utilizing end-user flexibility for balancing the power system and addressing grid congestions. However, this approach requires the system operator possession of accurate load flexibility data, which industries are often reluctant to share. Manana et al.[29] investigated an industry's potential to increase production capacity without upgrading the transmission grid. They found that combining dynamic grid capacities with demand-side flexibility measures could increase the grid capacity by reducing the total grid peak load, avoiding the need for new transmission lines. This is called increasing the *grid hosting capacity* by Alturki et al.[30], defined as "the amount of new production or consumption that can be added to the grid without adversely impacting the reliability or voltage quality for other customers". Determining the available grid hosting capacity is complicated in meshed grids, as they have more complex power flow routing options than radial grids. Since power system reliability is crucial, grid redundancy is often assessed using the N-1 criterion, which ensures the system can withstand the failure of all single components, including the most crucial one.[31] To account for complex grid topologies, power flow analysis is often required to determine the grid hosting capacity unlocked through demand response.

In the industry sector, the flexibility potential of multiple actors, or clusters, has been scarcely investigated. This is particularly the case for flexibility in existing processes, as such data is often sensitive. Energy system models including several industry actors or sectors typically evaluate flexibility based on simplified assumptions or parametric input rather than the actual process flexibility.[32–37] In contrast, Golmohamadi et al.[38] modelled the flexibility potential of two heavy industries (cement and metals) in detail. However, the aggregated flexibility was used in day-ahead and balancing markets, and the potential effect in reducing grid peak load or increasing grid reliability was not evaluated. With industry representing a significant amount of final energy demand, identifying the sector's potential for flexibility in handling grid challenges is crucial.

We aim to address this gap by presenting a bottom-up flexibility model of energy-intensive processes in four heavy industries. We present a methodology to evaluate the cost of this flexibility, both on an industry-specific level and aggregated for multiple industries, with the aim of increasing the grid hosting capacity. We analyze the system reliability through a power flow analysis, and finally compare the cost of increased grid hosting capacity through industrial flexibility to the cost of building new transmission grids and the cost of alternative energy storage options. Comparing the operational costs of activating industrial flexibility to alternatives for increasing grid capacity has not previously been addressed by research. Finally, we discuss the impact of utilizing flexibility in the industry sector to accelerate decarbonization in low-carbon power grids, and its potential implications on emissions and other environmental aspects.

The remainder of the article is structured as follows: Section 2 presents the methodology used in the paper, first explaining the overall model overview, then presenting the specific case study used to demonstrate the value of the methodology. In the same section, we present the industries and their flexibility potential. Section 3 discusses the findings with regards to flexibility potential and the associated costs, both on an individual level and with regards to overall grid implications. Section 4 and Section 5 discusses the overall implications of the results and concludes the paper.

2. Material and methods

2.1. Method description

The methodology developed in this work identifies the potential for increasing grid hosting capacity in an area by accounting for the interplay between the power grid and flexible industry actors. To this end, we implement a detailed operational model of the industries to identify the potential for alleviating grid bottlenecks using industrial flexibility. The operational model evaluates the flexibility potential of multiple energy-intensive industry actors with different characteristics and flexibility potential. The model finds the cost-optimal operation of the industry actor's processes in order to avoid exceeding the transmission grid limitations. Finally, a power flow model is used to ensure the reliability of the power system through a N–1 contingency analysis. Fig. 1 presents one application of the methodology, in which an industry area and an electricity demand dominated area are on the same side of a major grid capacity limitation, while the large electricity generation capacities are on the other side. Coordinating the industrial power demand can reduce the grid peak load and thereby enable increased hosting capacity on the demand side of the transmission grid. In this study, we apply the methodology to a grid with multiple industries present at different nodes, and evaluate how flexibility may increase grid reliability.

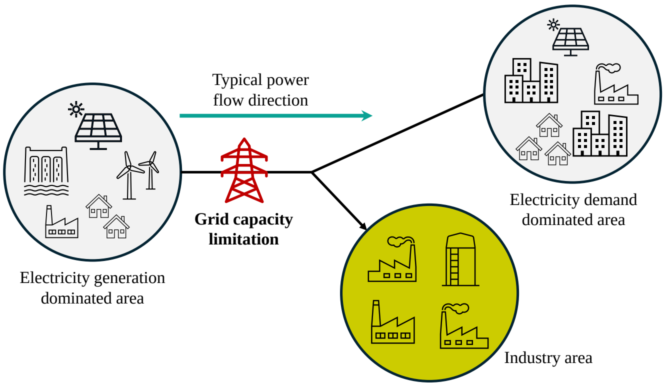

Figure 1: A generation dominated and a demand dominated area, on separate sides of a transmission grid limitation. The methodology investigates the potential for flexible operation of the industry actors on the demand dominated side to reduce overall grid peak load. Hence enabling increased electrification and decarbonization on the demand side of the grid limitation.

2.1.1. *Operational model.*

The operational model is formulated as a mixed-integer linear problem in Julia/JuMP.[39] It evaluates the cost-optimal operation of the industry processes, considering energy and emission costs, flexibility costs related to load changes, load shifting and shedding, and available process flexibility. The model is available in GitHub.[40]

The methodology considers three options for flexibility, namely fuel switching, load shedding and load shifting.[27] The cost of fuel switching is mainly accounted for by energy costs and emission costs, where fuel switching increases the cost beyond nominal operational costs. Load shedding costs are accounted for by production losses due to reduced operation and the price of the product. Load shifting is enabled by product or energy storages, allowing the processes to shift loads from one period to another without reducing production volumes. Load change costs include several parameters such as the specific cost of changing loads, and the costs of operating outside the nominal operational area of equipment and operating outside normal working hours. The flexibility potential and the associated activation cost may vary significantly between the different industry actors. This is further described in Section 2.2.1.

The available grid capacity retrieved from the power flow model is accounted for by a penalty cost in the case of insufficient grid capacity to supply all demands, known as grid deficit costs (c_t^{gd}). The grid deficit cost is calculated in Eq. (1), where the value of the actual grid deficit (p_t^{gd}) is calculated using the power balance constraint in Eq. (2). The sum of the hourly total power demand of each respective industry actor ($p_{i,t}$) minus the hourly grid deficit is constrained below the grid capacity limit ($\mathrm{P}_t^{\mathrm{lim}}$), which can either be a constant limit, or a time series of varying capacity. As described in the Introduction, the grid is often only utilized close to its full capacity for shorter periods of the year. In this work, we therefore use a grid capacity limit equal to the *available* grid capacity, set by subtracting all other static power demands from the grid capacity.

$$c_t^{\mathrm{gd}} = p_t^{\mathrm{gd}} * \mathrm{Cost}_{\mathrm{gd}} \tag{1}$$

$$\sum_i p_{i,t} - p_t^{\mathrm{gd}} \leq \mathrm{P}_t^{\mathrm{lim}} \tag{2}$$

2.1.2. *Power flow model.*

The power flow model is used to identify potential grid congestions in the area, and to determine the available grid capacity. After the operational model has optimized the industry operations accounting for prevailing grid limitations, the updated load data is used in the power flow model to ensure that all grid limitation issues are handled, and no new bottlenecks have occurred. The power flow model is also used to ensure that the N–1 criterion for transmission lines is fulfilled.

The power flow analyses are conducted using DC power flow in pandapower.[41] The analyses are conducted using net load data in each node, taking local generation and demand into account. Technical data specifications on lines and transformers are created manually using built-in pandapower functions that fit the specific case, further described in Section 2.2.2.

2.2. *Case study setup*

We present the value of the proposed modelling approach through a case study in the industry region of Grenland. This is the largest industry region in Norway, accounting for around 20 % of the total CO_2-emissions from Norwegian land-based industry. Several of the industry actors are energy intensive: some are based on electricity, while others rely heavily on fossil fuels. The total peak power demand in the area is around 700 MW, of which 450 MW is used by the industry.[42] We have analyzed four industry actors, with a total peak demand of approx. 300 MW. Several of the industries have plans for decarbonizing or expanding their processes through carbon capture and storage (CCS), electrification or hydrogen. At the same time, new industry actors have signalled their interest to establish in the industry region. Overall, these plans result in a significantly increased demand for power, and the grid company in the area has had applications for more than 2,000 MW of new power demand in total. The power grid in the area is limited both by local restrictions in the regional grid, as well as in the transmission grid level.[42] Expanding grid capacity may take decades; therefore, finding ways to increase the hosting capacity of the existing grid without challenging grid reliability is crucial to increasing the pace of the green transition of existing industry.

2.2.1. Industries.

We have based our analysis on four different industry actors, representing sectors commonly found in energy-intensive industry sites worldwide: cement production, chemical production (ammonia, nitric acid and vinyl chloride monomer [VCM] production including chlor-alkali electrolysis), and basic metals production (ferromanganese and silicomanganese). Table 1 presents which flexibility category the individual actors have the option of utilizing. While all the actors in theory have the possibility to perform load shedding by shutting down entire production lines, this would for some of them require a week of shut down and start up procedures, with accordingly huge costs. We have therefore focused on flexibility potentials in which normal operation can be re-established in reasonable time.

The data gathering and specific investigation of the actors has been performed in cooperation with the industries, and by reviewing available literature. We investigate the potential for flexibility in the existing processes, referred to as the *Base case*, and a future case, referred to as *Decarbonized*. In the Decarbonized case, we include the planned decarbonization efforts of the industry actors, which are openly available, as well as some potential decarbonization or expansion plans.

Table 1: Flexibility potentials of the different industries

Industry	Fuel switching	Load shedding	Load shifting
Ammonia & nitric acid	-	x	x
Cement	-	x	x
Ferroalloy	-	x	-
VCM	x[1]	-	x

[1] Only in the Decarbonized case

Fig. 2 presents the minimum and maximum power demand of the different industry actors, thereby highlighting the fraction of the total power demand that can be regarded as flexible. In the following sections, we provide the specific details on how the flexibility potential of the different industries is modelled, and how this affects the operational cost. The full details of the industry process operation, and the model formulation is described in the Electronic Supplementary Information⋆⋆.

Ammonia and nitric acid.. The ammonia production process can be split into two subsections: the synthesis gas production and the ammonia production, commonly using the Haber-Bosch process.[43] In Europe and North-America, hydrogen and nitrogen are primarily produced from natural gas, water and air through synthesis gas production.[44] The synthesis gas production is highly emission intensive, and one of the main pathways for decarbonizing ammonia production is to replace the synthesis gas production with green hydrogen electrolysis and air separation units.[45] Hydrogen and nitrogen is then further refined in the Haber-Bosch process. Around 90 % of ammonia worldwide is today produced from the Haber-Bosch process, where hydrogen and nitrogen are synthesized into ammonia, NH_3, in a high-pressure process.

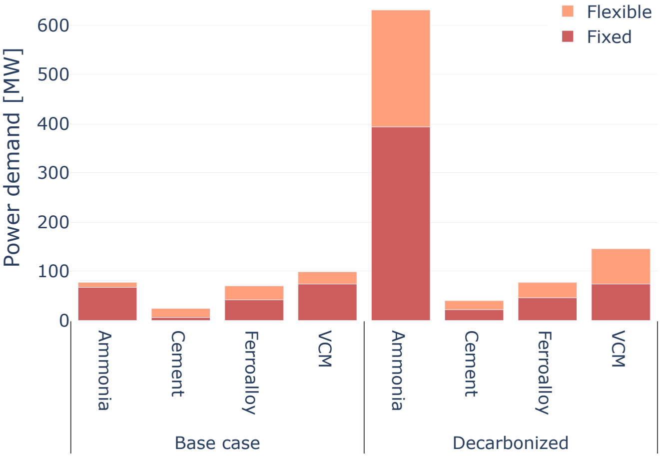

Figure 2: Overview of the industry actors, and their maximum and minimum power demand in the Base case and the Decarbonized case.

As the hydrogen and nitrogen come directly from the synthesis gas production, the flexibility of both processes is largely distinguished by the most inflexible process. The currently used Haber-Bosch process in the investigated plant is estimated to be able to ramp down to approx. 60 % of nominal operation within two hours.[46,47] However, existing process equipment is primarily designed for static operation, and thermal stress may affect the lifetime of the equipment if the process operation is changed to a more dynamic operation. The frequency of such regulations must therefore be limited.[47] The processes also require a certain settling time to respond to dynamic operation, restraining the potential for dynamic operation.[48] New, state-of-the-art equipment is able to operate in a significantly more dynamic way, with regards to the frequency of changes, minimum operational limits and ramping times, according to the producers.[49] It is anticipated that these characteristics will gain more significance in the future due to the rapid increase in variable renewable generation. The emphasis on the production of *green chemicals* has increased the importance of energy efficiency and the dynamic capabilities of the Haber-Bosch process.[50] In this work, we investigate the anticipated flexibility potential of the existing plant as described in Table 2. In the Decarbonized case, the synthesis gas production process is replaced by hydrogen production from PEM electrolysis and nitrogen production from air separation units. While the existing process design does not include any product or energy storage enabling significant load shifting, a future design could potentially become more flexible by incorporating a hydrogen storage between the electrolyzers and the Haber-Bosch process. However, after discussions with the specific industry actor, hydrogen storages beyond what is strictly necessary for process stability have not been included in the present study. This is due to safety and regulation aspects, but could be a potential for future flexibility enhancement.

The investigated ammonia production site also produces nitric acid, using a fraction of the produced ammonia as feedstock. The major power consuming equipment are three large compressors. As there is some overcapacity in compressor capacity, it is possible to adjust when the smallest of these compressors is operated.[51]

The main cost drivers included in the objective function related to the ammonia plant are the energy costs of natural gas and electricity, emission costs related to natural gas, and the cost of lost production over the analysis period. All main cost parameters are presented in Table 6.

Cement.. Cement production accounts for around 7 % of the global CO_2-emissions, and the sector is expected to grow by up to 25 % by 2050.[18] The majority of CO_2 originates from chemical reactions during the calcination of limestone under high temperatures,[54]. Therefore, carbon capture is regarded as the most relevant option to reduce emissions from the process. In addition to calcination, cement production involves crushing, grinding and heating the limestone and other raw materials in a kiln, resulting in the formation of clinker. This clinker is then finely ground to produce the final cement product.

The flexibility of cement production has been investigated in several other works,[55,56] where the flexibility potential is found to be significant. The crushers and mills used to obtain the required granularity can be shut down at short notice, using on-site intermediate product storages, or stockpiles, to feed the continuous calcination and kiln processes. We evaluate the flexibility based on the process information provided in this case, where there are four stockpiles for intermediate products, six different mills and crushers, and a nominal cement production of 177 tons/h.[57] Some of the machinery is primarily operated during daytime, so we have assumed that operating outside normal working hours has a certain "discomfort cost", denoted $\mathrm{Cost}_{\mathrm{cem,\,lc}}$ in Table 6. In addition, energy costs and load shedding costs related to production losses are included in the calculation of total flexibility costs. In the Decarbonized case, additional power demands related to carbon capture operation is included, and regarded as a fixed demand. The main flexibility features in this process are described in Table 3.

Ferroalloy.. We have also considered a site producing silicomanganese and ferromanganese, two of the major ferroalloys produced in the world. Silicomanganese and ferromanganese are key components in steel production, and the demand has increased in line with the increasing demand for steel. Ferroalloy production is most commonly produced in electric arc furnaces, in which the raw materials are poured into a smelter and heated by electrodes until the metal oxide reacts with carbon, and liquid ferroalloys are tapped from the smelter.[58] The process is highly energy intensive, primarily requiring electricity, in addition to the carbon source used in the chemical reaction, which is typically coke.[59]

The investigated ferroalloy producer has participated in different flexibility markets for several years, primarily in reserve markets for power grid balancing. The power demand of the smelters can be reduced to approx. 60 % of the nominal load for up to four hours without affecting the quality of the product. However, as the smelters are normally operated at full load, it is not possible to use buffer product storages to catch up with lost production, and therefore, any load reduction comes at a significant loss of revenue.[60] The overall flexibility limitations are described in Table 4. Although there is ongoing research on the decarbonization of ferroalloy production, e.g. using CCS or biocarbon, we have not accounted for any specific additional power demand for decarbonization in this study. However, we have assumed a 10 % increase in the plant's production capacity in the Decarbonized case.

Vinyl chloride monomers.. VCM is a chemical product that is most commonly refined to polyvinyl chloride (PVC) and used in plastic products all over the world. The production process has been identified as a process with significant flexibility potential by several previous studies, in particular when integrated with chlor-alkali electrolysis.[61–64,25,65] Chlor-alkali electrolysis alone accounted for around 4.3 % of the total electricity consumption in Germany in 2017.[66] VCM is normally produced by chlorinating ethylene with chlorine produced by chlor-alkali electrolysis in the oxychlorination and direct chlorination process. This forms the intermediate product, ethylene dichloride, which is then cracked under high temperatures to VCM. The two main energy-intensive steps of the process are the chlor-alkali electrolysis, based on electricity, and the thermal cracking of ethylene dichloride, based primarily on natural gas combustion. Decarbonization possibilities for thermal cracking are direct electrification or replacing the natural gas, e.g. with green or blue hydrogen, for combustion. As the investigated plant is already working with the green hydrogen decarbonization alternative, we have assumed that natural gas has been completely replaced by hydrogen in the Decarbonized case.

Chlor-alkali electrolysis is highly flexible, and although the subsequent thermal cracking of VCM must operate at constant load, an intermediate product storage of ethylene dichloride enables some load shifting flexibility of the electrolysis process. As the constant-operation thermal cracking is the final production step, performing load shedding is in reality infeasible without incurring huge costs. In the Decarbonized case, we have assumed hydrogen production by PEM electrolysis, which significantly increases power demand and process flexibility, due to the ability to shift between hydrogen and natural gas combustion. Although hydrogen storage could have somewhat increased the flexibility of the processes, this has not been included in the current study. A detailed investigation of the flexibility potential of the plant can be found in Foslie et al.[25] Table 5 summarizes the major flexibility parameters of the process.

Table 2: Major flexibility parameters of the ammonia & nitric acid production process. SG: synthesis gas; H-B: Haber-Bosch

	SG[47]	H-B[52,47,48]	PEM[53]	Nitric acid[51]	Other
Min. operation	80 %	60 %	10 %	90 % [1]	100 %
Max. ramping rate (per hour)	20 %	20 %	100 %	10 %	-
Min. time between load reductions (hours)	-	150	-	24 [1]	-
Min. constant operation after change (hours)	-	24	-	-	-
Max. consecutive load changes (hours)	-	5	-	-	-

[1] Only for the smallest compressor, the two larger ones are operating at full capacity at all times.

Table 3: Major flexibility parameters of the cement production process.[56,57] C: crushers; RM: raw mills; CP: clinker production (calcination and kiln); CM: cement mills

	C	RM	CP	CM	Other
Min. operation	0 %	0 %	100 %	0 %	100 %
Operation modes	On/off	On/off	-	On/off	On/off
Max. ramping rate (per hour)	100 %	100 %	-	100 %	-

Table 4: Major flexibility parameters of the ferroalloy production process.[60] FeMn: ferromanganese; SiMn: silicomanganese

	FeMn	SiMn
Min. operation	60 %	60 %
Max. consecutive reduced load (hours)	4	4
Min. time between load reductions (hours)	12	12

2.2.2. *Power grid.*

The industry area is located between electricity generation-dominated areas in the west and electricity demand-dominated areas in the east, as the example presented in Fig. 1. However, the transmission grid in reality is more complex than the simple system presented in Fig. 1, as seen from Fig. 3 which presents details of the transmission grid in the area. The Norwegian transmission system operator has identified that additional power demand in the industry cluster (present in bus B4 and B6 in Fig. 3) will pose a new transmission grid congestion west of the region, constraining the maximum load on the sum of lines L1 and L6 to 2200 MW. This is in particular during winter, when the dominating power flow is from buses B1 and B2 towards bus B7.[68] To investigate the potential for reducing the peak grid load in lines L1 and L6, we have performed an analysis of the total load on these lines for two critical weeks in 2022; Week 5, having the highest net load in 2022 (2,113 MWh/h), and week 50, having highest mean net load (mean net load over the week of 1,271 MWh/h with a peak load of 2,003 MWh/h). We also ensure the reliability of the power system, by investigating whether the grid meets the N-1 criterion at all transmission lines, when combined with industry flexibility for handling the grid congestions in lines L1 and L6.[3]

The total grid load of L1 and L6 is a result of the generation and demand in the Grenland area, as well as further transmission to the neighbouring price zone, represented by bus B7. The technical specifications for the transmission lines are defined in dialogue with the relevant grid company in the Grenland area, supported by openly available information from the Norwegian transmission system operator.[42] The impedances were set using national transmission line data sheets.[69] The details regarding input parameters can be found in the Electronic Supplementary Information[⋆⋆].

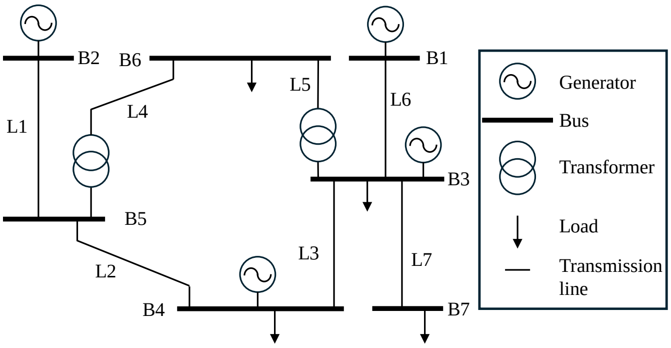

Figure 3: Presentation of the grid topology of the region. L1, L2, L3, L6 and L7 are 420 kV transmission lines, while L4 and L5 are 300 kV lines.

Fig. 4 presents the total generation and demand in the region, as well as the external demand represented by bus B7. The industries' power demand accounts for approx. 12 % of the peak load. In the following sections, we will examine the degree to which altering these 12 % of demand may enable reduced overall peak loads in congested sections of the grid and free up grid space for more decarbonization and electrification measures.

2.3. *Cost parameters*

Table 6 presents the major cost parameters and assumptions used in the study that affect the cost of flexibility. The cost of energy ($\mathrm{Cost}_{\mathrm{el}}$ and $\mathrm{Cost}_{\mathrm{ng}}$) and emissions ($\mathrm{Cost}_{\mathrm{em}}$) are based on the long-term foresight of the Norwegian Water Resource and Energy Directorate for 2040.[70] Grid deficit costs ($\mathrm{Cost}_{\mathrm{gd}}$) are set to an artificially high level, which are sufficiently high enough to be the last resort after utilizing all other flexibility options first. The load shedding costs of ammonia ($\mathrm{Cost}_{\mathrm{ls,\ amm}}$), cement ($\mathrm{Cost}_{\mathrm{ls,\ cem}}$) and ferroalloys ($\mathrm{Cost}_{\mathrm{ls,\ mn,\ FeMn}}$

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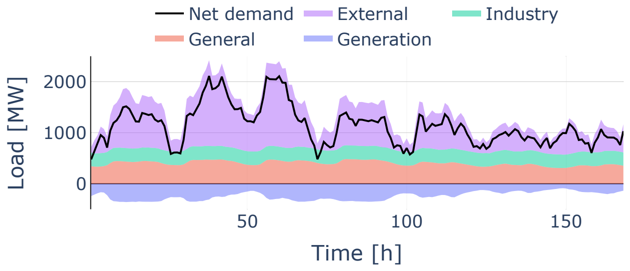
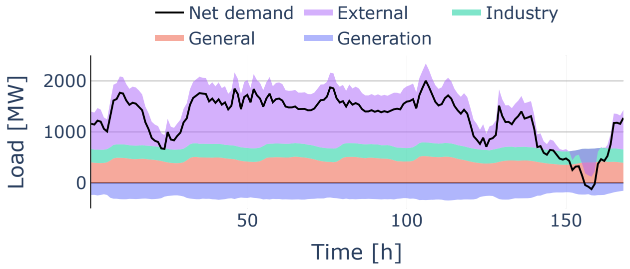
[3] Bus B7 is covered from another part of the transmission grid and line L7 is hence not relevant in this contingency analysis.

Table 5: Major flexibility parameters of the vcm production process.[67,53] CAE: chlor-alkali electrolysis; OXC: oxychlorination; DC: direct chlorination; TC: thermal cracker

	CAE	OXC	DC	TC	PEM
Min. operation	66 %	100 %	75 %	100 %	10 %
Max. operation	105 %	100 %	105 %	100 %	100 %
Max. ramping rate (per hour)	100 %	-	100 %	-	100 %



(a) Week 5.



(b) Week 50.

Figure 4: Regional generation and demand during weeks 5 and 50, showing how much of the total demand which is used by the industry actors, and how much is other general or external demand.

Table 6: Major cost parameters of the optimization model. el: electricity; ng: natural gas; em: emissions; gd: grid deficit; amm: ammonia & nitric acid; ls: load shedding; cem: cement; lc: load change; mn: ferroalloy; FeMn: ferromanganese; SiMn: silicomanganese

	Unit	Value
Cost_{el}	€/MWh	49.0
Cost_{ng}	€/MWh	52.0
Cost_{em}	€/ton_{CO_2}	164.0
Cost_{gd}	k€/MW	100.0
$\text{Cost}_{\text{ls, amm}}$	€/$\text{ton}_{\text{ammonia}}$	1,000.0
$\text{Cost}_{\text{ls, cem}}$	€/$\text{ton}_{\text{cement}}$	150.0
$\text{Cost}_{\text{ls, mn, FeMn}}$	€/ton_{FeMn}	1,250.0
$\text{Cost}_{\text{ls, mn, SiMn}}$	€/ton_{SiMn}	1,400.0
$\text{Cost}_{\text{lc, cem}}$	€/hour	1,000.0
$\text{Cost}_{\text{lc, vcm}}$	€	5,000

and $\text{Cost}_{\text{ls, mn, SiMn}}$) are based on a combination of discussions with the industry actors and the available market price of the final products. Load change costs of cement ($\text{Cost}_{\text{lc, cem}}$) are based on information from the industry actor and estimates of additional costs from operating outside regular working hours, while load change costs of VCM ($\text{Cost}_{\text{lc, vcm}}$) are based on estimations of increased degradation of electrolysis cells of the chlor-alkali electrolysis.[63]

3. Results

In this section, we present the results of the optimization model, and how industrial flexibility affects the overall transmission capacity into the area, as well as how the reliability of the transmission grid is affected. In Section 3.1, study the Base case, and how flexibility can decrease the grid peak load into the area (lines L1 and L6), thereby increasing the grid hosting capacity. In Section 3.2, we investigate how flexibility is affected by introducing the increased demands of the Decarbonized case, both on an aggregated level, and for the individual industry actors and the grid. Section 3.3 presents the impact on N-1 contingencies for all lines, and the further grid development. In the Base case, the industries have a mean nominal power demand of 266 MW, and a total weekly electricity consumption of 44,688 MWh. In the Decarbonized case, the mean nominal power demand increases to 890 MW, with a total weekly consumption of 149,520 MWh.

3.1. *Current process flexibility*

3.1.1. *Technical flexibility potential of the industries with existing processes.*

Fig. 5 presents the industries' aggregated deviation from the mean power demand of 266 MW in the Base case over a week. This is presented in two hypothetical flexibility cases, which require a shift of an equivalent amount of total energy. The first case represents a four-hour reduction of 25 % of the mean power demand, approaching the maximum flexibility that could be achieved by the industries, while the second is a 48-hour reduction of 2.1 % of the mean power demand. While the four industries are able to meet the flexibility request, there is a difference in which actor provides the required flexibility, as well as the following rebound effect. To meet the high 25 % capacity reduction request, the flexibility assets of all actors are activated, including both load shifting and load shedding. However, in the long, low-capacity case, the ferroalloy producer is able to continue regular operation and avoid expensive production losses. While the ammonia and the cement producer have sufficient load shifting capacities to handle both the long and short case without incurring significant additional costs, the VCM producer receives a load shifting cost from their chlor-alkali electrolysis cells. The majority of the reduction in power demand is handled by load shifting in the long duration case, resulting in a larger rebound effect after the activation, due to VCM and cement actors aiming to catch up with lost production volumes. However, the total flexibility cost is lower in the long, low-capacity reduction, as it avoids costly production losses.

3.1.2. *Potential for increased grid hosting capacity by reducing peak load of the grid.*

To increase the potential for adding new power demands, and by extension, increased decarbonization, the overall grid load in the area must be accounted for. This may enable the total load during peak hours of lines L1 and L6 to be shifted to other periods with excess capacity in the grid, thereby increasing the transmission grid hosting capacity into the area. In Fig. 6a, we present the number of hours with *grid overload* when adding a static demand on top of the existing grid load, including the industry load. Grid overload occurs when the total grid load of L1 and L6 is above the grid limit set by the transmission system operator, namely 2200 MW in total.[68] In week 5, only 80 MW of static demand can be added before the first hour of grid overload. However, when factoring in the flexibility of the industries in the existing grid load, we can add up to 150 MW of static demand before encountering grid limitations. The same trend holds for week 50: in the non-flexible case, 190 MW of static demand can be added, but by leveraging the industry flexibility, an additional 80 MW of static demand can also be accommodated. Implementation of the planned decarbonization measures would increase the industries' mean power demand by 624 MW. If all this is regarded static, we can see that the grid limit would be breached in approx. 20–40 hours per week.

In Fig. 6b, the total cost of activating the flexibility is presented, showing the cost of increasing the grid hosting capacity by reducing total grid peak load by 10 MW to 80 MW. Up to approx. 60-70 MW, the main cost is related to the loss of production of the ferroalloy producer, and when increased beyond that, the ammonia producer must reduce it's production. This incurs a significant cost increase, considering that the Haber-Bosch process requires steady operation at reduced load for an extended time period. Therefore, even a short reduction could incur significant production losses.

3.2. *Flexibility of decarbonization measures*

3.2.1. *Impact of accounting for flexibility in the added demand from process decarbonization.*

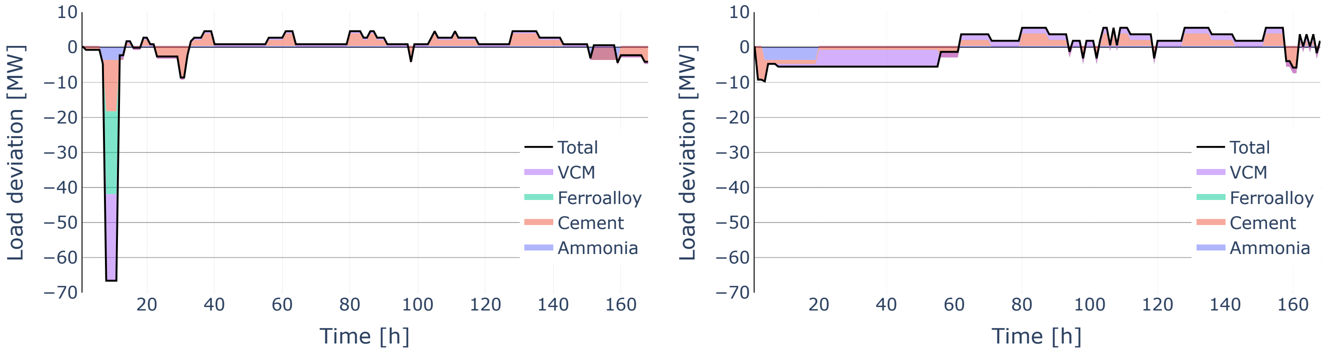
In the previous section, we demonstrated that by considering the flexibility potential of current industrial processes (Base case), we can decrease the overall peak load of the grid. This in turn increases the grid's hosting capacity for new, static demand by 70–80 MW. However, given that most requests for new power demand in the grid are tied to industry decarbonization efforts, it is necessary to explore the flexibility potential of this new demand as well (Decarbonized case). If it is possible to shift these loads away from peak hours to other time slots, it may be feasible to further increase the hosting capacity beyond the initial 70–80 MW.

Fig. 7a and Fig. 7b illustrate the total grid load for the base case and the new decarbonization demands, with and without flexible operation of the industry actors. Table 7 presents how operational costs and grid load are affected by flexible operation of the industry processes in the Decarbonized case. This shows that the total peak load in L1 and L6 is reduced by around 339–355 MW, which is equivalent to 38 %–40 % of the nominal power demand of the industries, thereby reducing the number of hours with grid overload significantly. In week 50, overload hours are reduced from 48 hours to only 1 hour. The accumulated energy overload, i.e. electricity that would have to be curtailed to avoid violation of grid limits, is reduced by 5,213 MWh (80 % reduction) in week 5 and 5,614 MWh (99 % reduction) in week 50. The total operational cost of activating this flexibility is 436 k€ in week 5, and 1,211 k€ in week 50, giving a mean unit cost of the activated flexibility of 84 €/MWh and 216 €/MWh, respectively.

3.2.2. *Various types of industries face distinct flexibility challenges.*

The unit cost of flexibility exhibits a significant difference between weeks 5 and 50 as evident from Table 7. The reason for this gap can be seen when comparing Fig. 7c and Fig. 7d, which illustrate how the industry actors adapt their power demand in response to flexibility requests. Among the industries, three demonstrate an ability to adjust their production frequently. However, the ammonia producer faces significant limitations in its regulating capabilities. Although the main power demand of the ammonia actor is hydrogen electrolysis, a process known for its flexibility, the produced hydrogen directly feeds into the Haber-Bosch process, which is significantly less flexible. Without any potential for intermediate storage between these processes, the overall flexibility is determined by the most rigid process step. While frequent production adjustments may incur costs across all industries, the ammonia producer is the primary cost driver. To maintain process stability and mitigate material stress, the ammonia producer must consistently operate at a reduced load for a specified duration. Interestingly, the valuable part of demand reduction, occurring during the 19 hours of grid overload in week 5 or the 48 hours in week 50, constitutes only a fraction of the total reduction in power demand attributed to the ammonia producer. In week 50, the demand for flexibility from the industry actors is spread out over an extended time period, causing the ammonia producer to operate at reduced capacity for more than half of the entire week, while the other actors reduce their demand when needed, considering their individual load change or production loss costs.

Fig. 8 presents how the different actors respond to the demand for flexibility in weeks 5 and 50, as measures by key metrics. In Fig. 8a the flexibility provided during the hours of grid overload is presented, which shows that the ammonia producer represents the majority of the flexibility provided. However, due to the significant restrictions in flexible operation of the processes, Fig. 8b also shows that the reduction in total electricity use of the ammonia producer is very large, and greatly exceeds the actual "valuable" flexibility, which is presented in Fig. 8a. However , the cement producer demonstrates the opposite pattern, where the flexibility provided is higher than the total reduction in electricity consumption, due to the potential for load shifting and ability to catch up with lost production. The ferroalloy producer and the VCM producer have no or limited



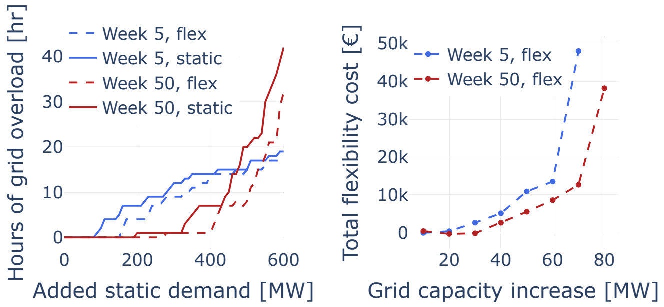
(a) Short, high capacity reduction.

(b) Long, low capacity reduction.

Figure 5: Deviation of the optimized power demand compared to the mean power demand of the processes in normal operation for two cases of equal energy shifted. This is further divided into the deviation of each industry actor from their mean power demand.

Table 7: Comparison of the effect of activating industry flexibility in the grid in weeks 5 and 50 in the decarbonized case

	Week 5		Week 50	
	Static	Flexible	Static	Flexible
Grid peak load [MW]	2,737	2,398	2,628	2,273
Hours of grid overload [h]	19	11	48	1
Total energy overload [MWh]	6,487	1,275	5,687	73
Total cost of flexibility [k€]	-	436	-	1,211
Mean unit cost of flexibility [€/MWh]	-	84	-	216



(a)

(b)

Figure 6: Fig. 6a presents the number of hours during week 5 and 50 in which the grid peak load is above the total grid capacity for increasing amounts of added static capacity. This is evaluated both with and without flexibility in the existing industry demand. Fig. 6b presents the total flexibility cost of increasing the grid hosting capacity by activating industrial flexibility in the same weeks.

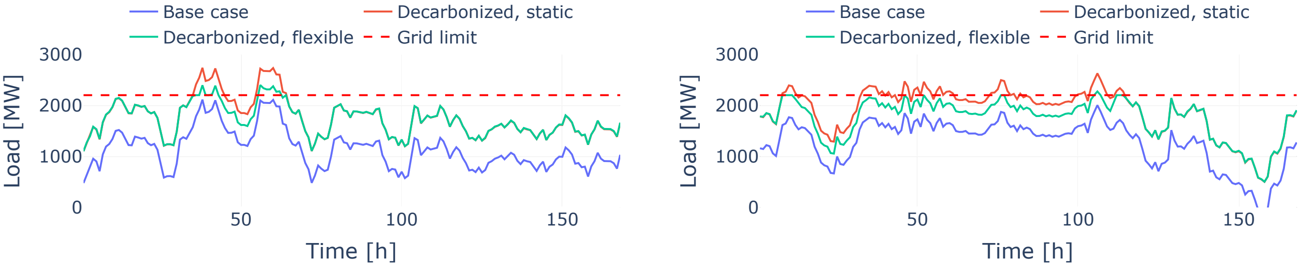
potential for load shifting, but can vary their load frequently to a larger degree, and therefore the flexibility provided is in the same range as the total reduction in electricity use. These characteristics are of high importance when considering the flexibility potential of an industry dominated area. While actors with load shifting potential may reduce their demand at a lower cost, the flexibility comes with a rebound effect after activation. Conversely, actors with load shedding potential avoid the rebound effect, but may incur significant costs due to lost production volumes.

The consequence of lost production is also seen in Fig. 8c, which presents the unit cost per flexibility provided. The ammonia producer sees significantly higher unit cost in week 50 than in week 5, due to significant production losses in periods with no grid capacity issues, as seen in Fig. 7. However, the ferroalloy producer has the highest unit cost of flexibility, as they only have the option of reducing the production volumes, at significant costs of production losses. The total effect of flexibility activation on operational cost, presented in Fig. 8d, reflects the product of unit cost and the total flexibility provided, where again, the ammonia producer dominates the overall cost due to their large load reduction volumes.

3.2.3. Unit cost of flexibility.

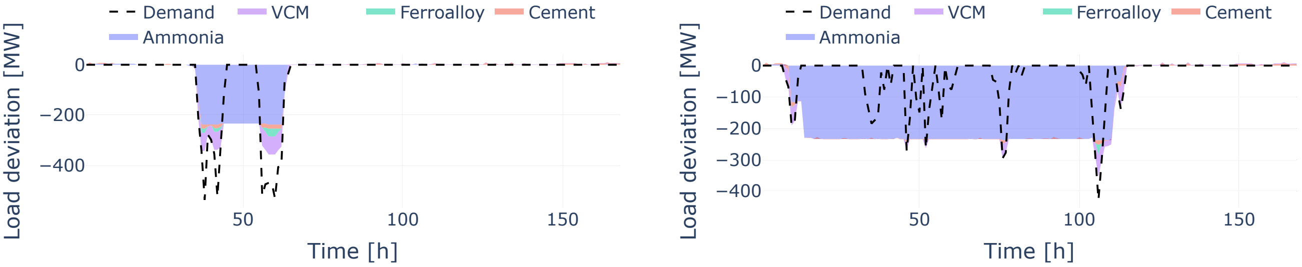
As presented in Fig. 5, the activated flexibility assets differ depending on the duration of a flexibility demand and the capacity requested. As such, the mean unit cost of activating flexibility will vary significantly, which is also seen in Table 7 and Fig. 8c. The key factors influencing the total unit cost of flexibility of the industry actors in this case are the innate restrictions of the Haber-Bosch process in the ammonia production plant, and the cost of lost production, which is related to the product price. The flexibility offered will differ among the chemical industries, and the product price is subject to significant market uncertainty. We therefore investigate the effect of variations in these parameters on the unit cost of flexibility in Fig. 9. The variations in process flexibility of the Haber-Bosch process, and in product prices are presented in Table 8. The high flexibility scenario is based on the expected state-of-the-art dynamic abilities of the Haber-Bosch process.[71,52,49]

The most significant difference is related to the flexibility potential of the chemical ammonia production, as seen in Fig. 9.



(a) Total grid load, Week 5.

(b) Total grid load, week 50.



(c) Flexibility, week 5.

(d) Flexibility, week 50.

Figure 7: Total grid load, with base case, decarbonized, static case and the decarbonized, flexible case as well as a presentation of the deviation from static operation for the different actors in the decarbonized, flexible case, including the demand for flexibility to avoid grid overload.

Table 8: Investigated variations in flexibility properties of the Haber-Bosch process and variations in cost of lost production reflecting market uncertainty

		Low	Baseline	High
Flexibility (Of Haber-Bosch process)	Minimum operation	90 %	60 %	30 %
	Minimum hours between load reductions	150	150	8
	Minimum hours of constant operation	72	24	4
Cost (Due to market uncertainty)	Product price multiplier	80 %	100 %	120 %

In the high flexibility scenario, it is possible to reduce the power demand by 450–500 MW, depending on the duration, while the low flexibility scenario is limited to a maximum of 100–150 MW. This emphasizes the importance of determining the achievable process flexibility of large-scale chemical processes. While the traditional operation of chemical processes has proven reliable and beneficial over several decades, the potential for increased flexibility may prove very important in a future scenario with more stringent grid capacity limitations. The unit cost decreases with increasing duration, due to the minimum duration of a load reduction of the chemical process. All cases exhibit significant load reduction potentials up to 100 MW at a unit cost below approx. 100 €/MWh, with the high flexibility scenario providing unit costs as low as 13–30 €/MWh. In the baseline flexibility scenario, the unit cost of flexibility up to 300 MW for e.g. 24 hours is between 28–63 €/MWh, while a shorter reduction for e.g. 6 hours has a significantly higher unit cost of 98–199 €/MWh depending on the cost scenario.

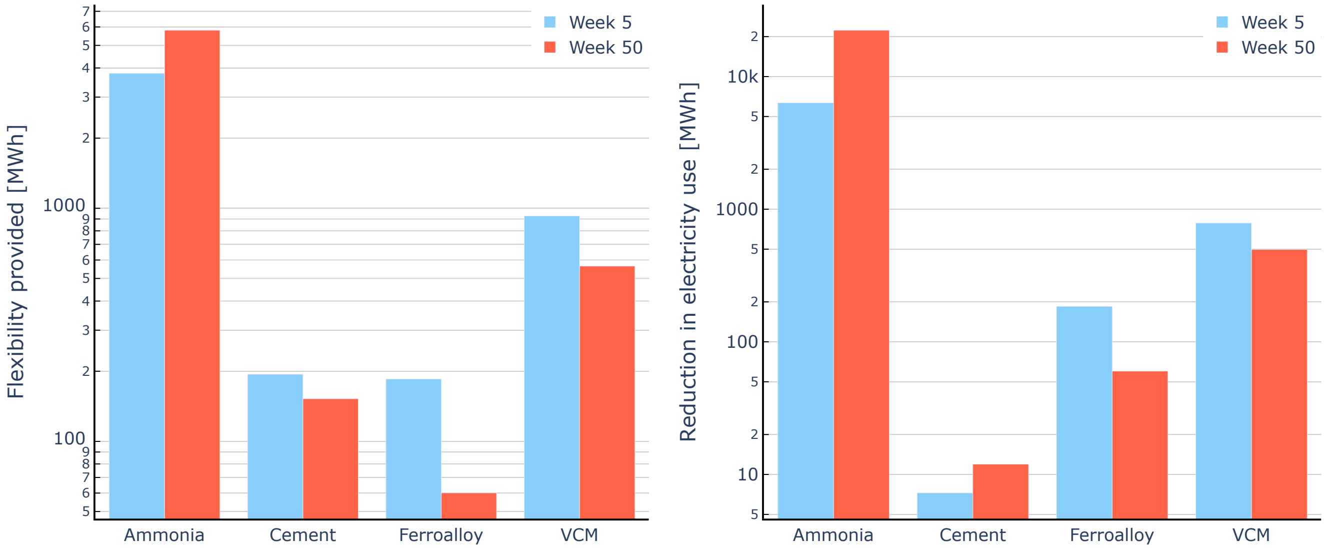
As the unit costs are sensitive to the flexibility potential of the most rigid process, in this case the Haber-Bosch process, this emphasizes the importance of increasing the flexibility potential of energy intensive chemical processes. As state-of-the-art process equipment has flexibility potential in the range of the high flexibility scenario, providing the right incentives could encourage chemical industries to invest in additional process flexibility. Other alternatives for decoupling the instantaneous power demand from rigid process steps could be to increase storage capacity for intermediates, such as hydrogen and nitrogen in the case of ammonia production.

3.3. Grid implications

3.3.1. Process flexibility ensures redundancy in the transmission grid.

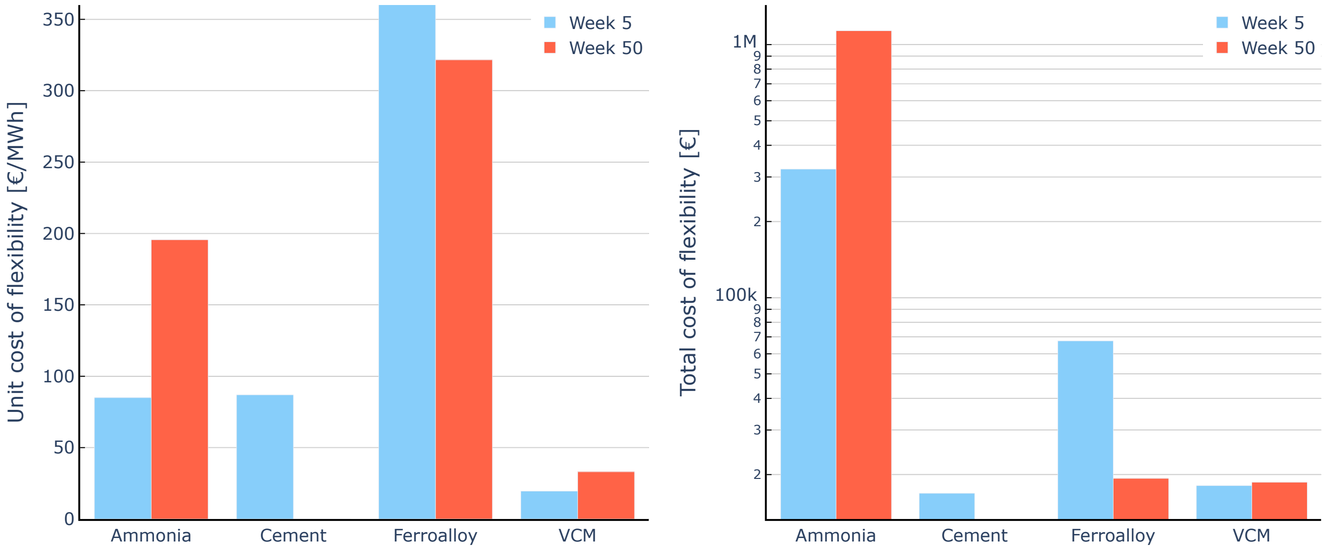
While Table 7 and Fig. 7 have shown that nearly all violations of the total transmission line capacity into the region (L1 and L6) can be handled by process flexibility, the redundancy requirement for the remainder of the transmission lines may still not be fulfilled.

A contingency analysis is conducted by studying line tripping consequences for all lines in the system using power flow analysis. Besides the previously studied lines L1 and L6, L2 is identified as the most critical of the remainder of the transmission lines. Fig. 10 presents the line peak load, both in the case of full transmission line availability and tripping of line L2. As seen, L1, L3, L4 and L6 are all significantly affected. However, L4 is the only line facing the risk of violating its maximum capacity. Analyzing the hourly load of L4 with and without L2



(a) Total flexibility activated during hours with grid overload.

(b) Total change in electricity use over the week.



(c) Unit cost of flexibility activated during grid overload.

(d) Total cost of flexibility over the week.

Figure 8: The effect of activating industrial flexibility in the weeks 5 and 50 to reduce grid overload.

tripping in Fig. 11, as well as static and flexible industry demands, it is evident that the average load of the line increases significantly. In the case of static industry demands, the grid capacity limit will be violated, risking further tripping of L4. When demand flexibility of the industry cluster is used to handle the constrained capacity of L1 and L6, the load on L4 is reduced and the breach of the capacity limitation prevented. This demonstrates that activation of industry flexibility can increase transmission grid reliability, and in this case is required to avoid further capacity violations.

3.3.2. *Alternative approaches for increasing grid hosting capacity.*

Full implementation of the planned decarbonization measures of the investigated industry actors is projected to increase the mean power demand by 624 MW. Using 2022 as reference, a total of 143 hours were identified in which the grid capacity limit of 2,200 MW would be exceeded if these measures were realized. These hours would result in a total 20,267 MWh of electricity overload. 47 % of the hours with overload happened during weeks 5 and 50, which are investigated in detail in this work.

The average continuous grid overload duration was 3.5 hours, with an associated average overload of 142 MW. To investigate the total yearly cost of handling the bottleneck situations with industrial flexibility, we have calculated the unit cost of flexibility for an overload period with a duration of 3 hours and a capacity of 142 MW. Table 9 presents the unit costs in the different cost and flexibility scenarios, for the mean overload duration and capacity over a year. The results show that increas-

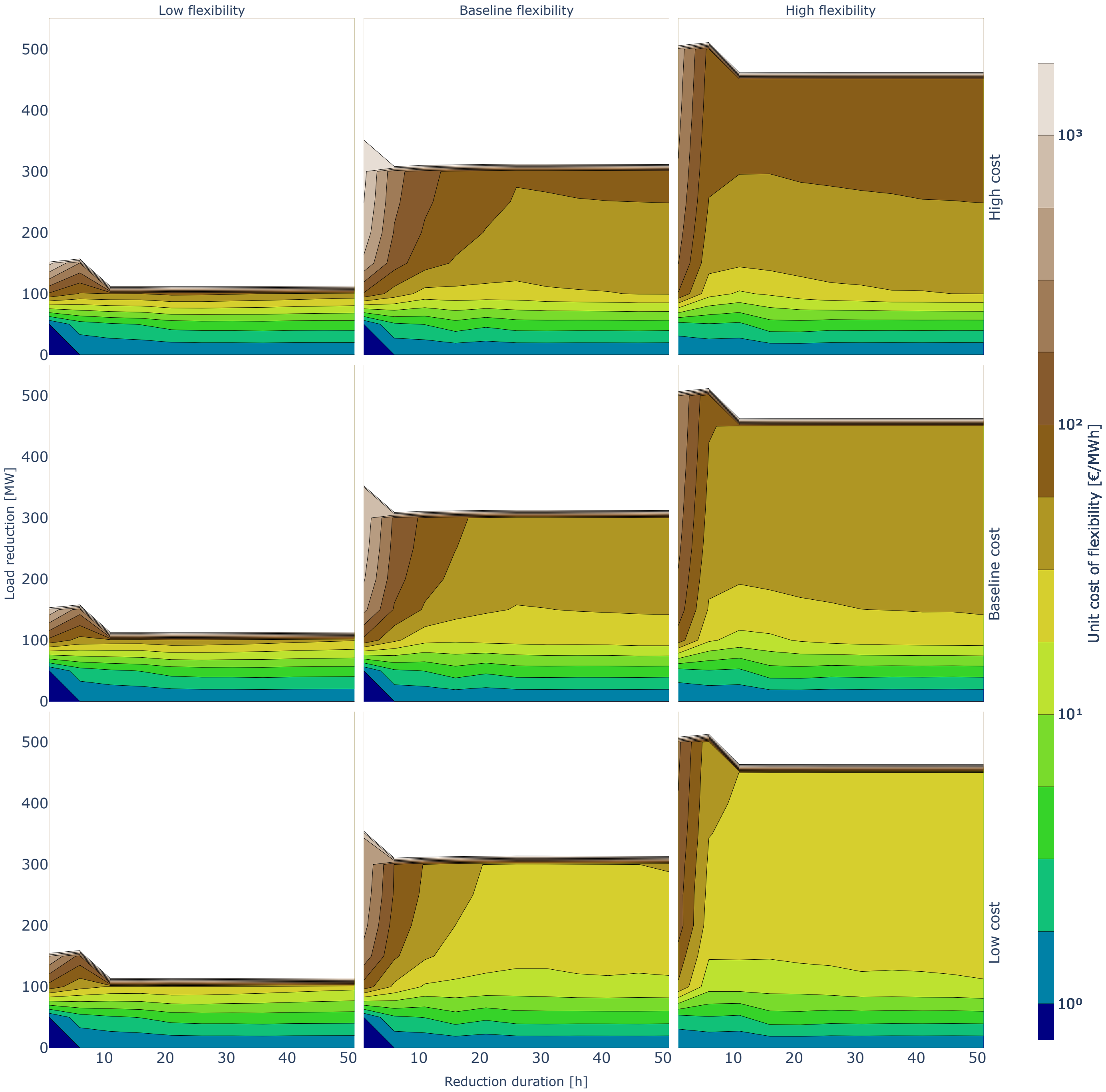


Figure 9: Mean unit cost of activated flexibility in the decarbonized case, for variations in load reduction and duration of load reduction. The white areas are outside the operational limits of stable operation of the processes. The mean unit cost is evaluated for low, medium and high flexibility, and low, medium and high cost of lost production as specified in Table 8.

ing process flexibility is of crucial importance to reduce the unit cost of flexibility. Throughout the year, industrial flexibility is able to reduce the peak demand by 339 MW, thereby reducing the number of hours with grid overload from 143 hours down to just 14 hours. For the remaining 14 hours, other measures for reducing demand would be required, such as involuntary load shedding. By applying the calculated unit cost in the baseline flexibility scenario to all the activated flexibility, the total cost of increasing the grid hosting capacity by 339 MW and reducing total accumulated grid overload from 20,267 MWh to 1,475 MWh would be 2,086–3,946 k€ for the entire year.

We compare the yearly discounted cost of two alternative approaches to increase the grid hosting capacity by 339 MW, namely transmission grid expansion and utility-scale batteries. Interestingly, the cost associated with industrial flexibility falls within the same range as that of expanding the transmission

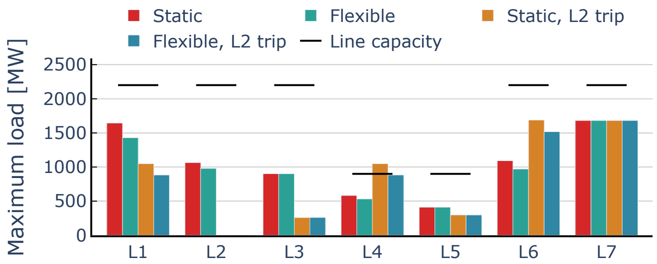


Figure 10: Maximum hourly load on all lines in the case of line tripping of L2, identified as the most critical line for the regional transmission grid.

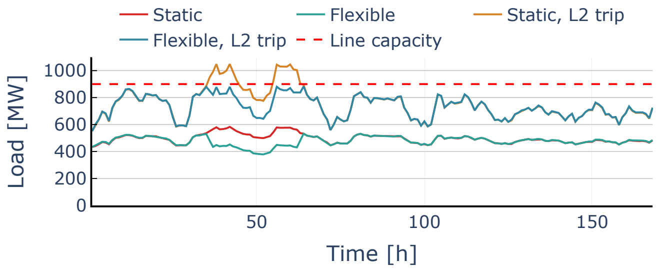


Figure 11: Hourly load of L4 with and without L2 tripping, and static and flexible industry demands.

Table 9: Unit cost of flexibility (€/MWh) for a 3 hour, 178 MW power demand reduction

	Low flex.	Baseline flex.	High flex.
High cost	380	210	60
Baseline cost	281	156	45
Low cost	191	111	27

grid, as seen in Table 10. Determining the exact cost of transmission grid investments depends on many uncertain factors, which is why a cost range was derived using a variety of references. In reality, the actual cost relies on terrain type, cost of land, conflicting area interests etc. Both the low and medium assumptions on transmission costs are lower than the industry flexibility option, while the high transmission grid cost assumption is between the low and high flexibility cost assumption. It should be noted that the high cost assumption is the one provided by the Norwegian TSO in the relevant case study area, implying that the low flexibility cost assumption is cheaper than the most realistic grid cost assumption in our case study. The highest cost assumptions for transmission grids are still cheaper than the highest cost case of industrial flexibility. However, the transmission grid versus industrial flexibility comparison is challenging for several reasons: 1) the transmission grid will be available all the time and reduce network losses, while industrial flexibility only frees up capacity when activated, 2) the transmission grid reinforcements are expected to take a decade or more to construct, meaning that the the lost value creation of new industry during the construction time is not considered, and 3) the cost estimates for industrial flexibility only includes operational costs, thereby assuming that realizing the flexibility potential does not require additional investments. Further research is required to fully grasp the trade-offs between these two solutions. However, the industrial flexibility will most likely be available several years before any new grid reinforcements may be realized.

The battery alternative is almost two orders of magnitude more expensive than the other options, and estimates on future battery costs will not significantly change the outcome of this simplified comparison. The battery required to match the flexibility of the industrial actors is equivalent to a 339 MW, ˜8 hour battery. This results in a significant 2,766 MWh battery, which is further associated with very high annualized costs. The most optimistic assumption about battery costs still results in an annualized cost of 197 k€ per MW per year, which is almost 18 times more expensive than the most expensive industrial flexibility case. However, this assumes that the battery is only used for peak shaving, which is a significant simplification. The battery could realistically stack value from multiple services, such as electricity arbitrage and balancing services. As grid congestion issues are normally predictable based on weather and load forecasts, this opens up for providing other services in between.[78] Previous studies have also shown that in order to be economically viable, grid-scale batteries need to operate in multiple markets to generate sufficient revenue streams. In the work by Yamujala et al.[74], a large grid scale battery of 120 MW is found able to generate net revenues in the range of 40–130 k€/MW/yr, depending on the price scenario and the available markets. As seen in Table 10, accounting for these potential revenues would significantly reduce the gap between batteries and the other alternatives, however, they still represent the more expensive alternative of the three.

4. Discussion

This section is separated into three sub-sections. Section 4.1 discusses the potential implications for the environment of the findings. Section 4.2 explores the requirements for enhancing the utilization of industrial flexibility, while Section 4.3 considers the generalizability and transferability of the results.

4.1. Environmental implications

The results of this study gave a potential for reducing peak loads by 339 MW. Assuming the 339 MW of increased grid hosting capacity is utilized to enable additional electrolysis-based hydrogen production, this could replace 212 MW$_{LHV}$ of natural gas, responsible for 376 kton CO_2 per year. In a low-carbon grid like in Norway, this substitution could mitigate up to 319 kton CO_2 annually, representing 16 % of the total emissions of the investigated industries in 2022.[79] If the alternative is waiting a decade for a new transmission grid, the cumulative CO_2-emission mitigation effect becomes substantial. While the immediate climate impact of decarbonizing heavy industries by connecting to the power grid may be questionable in a European context, given the EU's CO_2-emission intensity of electricity of 251 g/kWh in 2022, the projected decline to 110–118 g/kWh by 2030 changes this perspective.[80] Our findings underscore

Table 10: Comparison of industrial flexibility as an alternative to battery and transmission grid investment alternatives. Assuming 5 % discount rate, 70 years lifetime of transmission grids and 15 years lifetime of batteries

Solution	**Case**	**Specification**	**Annualised costs [k€/yr]**	**Annualised cost per MW [k€/MW/yr]**	**Reference**
Industrial flexibility	Low	339 MW / 2766 MWh	2,086	6.15	This work
	High	339 MW / 2766 MWh	3,949	11.64	This work
Battery	Low	339 MW / 2766 MWh	66,620	196.52	[72]
	High	339 MW / 2766 MWh	119,917	353.74	[73]
Battery w/value stacking	Low	339 MW / 2766 MWh	22,550–53,060	66.52–156.52	[72,74]
	High	339 MW / 2766 MWh	75,848–106,357	223.74–313.74	[73,74]
Transmission grid investments	Low	420 kV / 1300 MW	2,873	2.21	[75]
	Mid	420 kV / 1300 MW	5,183	3.99	[76]
	High	420 kV / 1300 MW	8,156	6.27	[42]
	Highest	420 kV / 1300 MW	10,097	7.77	[77]

that increasing the grid hosting capacity through industrial flexibility can significantly reduce CO_2-emissions in low-carbon power grids.

While electrification and increased variable renewable generation is crucial for decarbonizing the energy system, these measures also increase pressure on nature and biodiversity from their land occupation. Renewable electricity generation needs to be located in areas with favourable weather or physical conditions, be it wind, solar, or precipitation and river conditions, to warrant high energy return and profit margin on the investments. The required grid capacity expansions to enable broad electrification will be amplified by the distance between generation and demand, and the additional capacity required to handle the increased variability of intermittent renewables. Minimizing the need for new grid infrastructure can thus relieve the already significant impact on material resource depletion and land use associated with the green transition of power systems.[81,4] This study demonstrates that identifying flexibility in demand can optimize the use of existing grid capacity for electrification, thereby mitigating these environmental consequences by reducing or postponing new grid investments. In addition to reducing industrial CO_2-emissions through direct or indirect electrification, enabling more flexible industries can therefore also contribute to a more sustainable energy transition in a broader sense.

4.2. What is needed for unlocking the potential of industrial flexibility?

Advanced electricity markets accommodate flexible assets on both the supply and demand side. Yet, industrial flexibility remains underutilized. Lack of revenues, non-compatible grid fee regulations, risks related to production targets and technical limitations of the installations have been identified as main obstacles to leveraging the full potential of industrial flexibility.[27] Energy-intensive industries often also have fixed price power purchase agreements (PPAs) for a major share of their electricity consumption. Combined with grid tariffs that encourage flat consumption profiles, the incentives for flexible operation are significantly reduced. During this study, our discussions with the industry actors have indicated that while some find reserve markets of the system operator beneficial, others lack competence and fear economic consequences. These challenges also highlight that aggregators with higher power system knowledge could have an important role in facilitating industrial demand response, confirming the findings of Stede et al.[21]. With more variable renewables in the energy mix, fluctuations in spot prices will increase, enhancing the economic potential of load shifting. This may open up business potentials for aggregators, power producers or other third-party actors operating between flexible end-users and power producers. If an end-user is able to prove load-following capabilities based on the production profile of variable renewables, arguments when negotiating power prices in a PPA will be improved.

Although existing electricity markets may be sufficient to activate current flexibility assets, governmental subsidies might be necessary to encourage further investments in flexible assets or storages that exceed the economic benefits for the individual end-users but are socio-economic beneficial. This can allow grid operators to incorporate flexibility considerations when assessing new connection requests. Evaluating the total value of increasing the power grid's utilization, in terms of both emission reductions and value and job creation, could contribute to pricing flexibility correctly.

4.3. Transferability beyond system boundaries

The demand for flexibility in the power system is to a large degree determined by the topology of the power grid, the share of intermittent renewables in the power mix, and the capacities and condition of the power system in the area. While this study used a Norwegian regional case as basis, there are multiple examples worldwide where the majority of the power generation is separated from large demand centres by grid congestions. Another prominent example is Germany where transmission grid congestion between power production in northern Germany challenges decarbonization of the industry sector in southern Germany.[11] Finding ways to alleviate the stress of such congestions will become crucial in the coming years to enable a faster decarbonization of energy demand.

This study has covered four large industry actors representing the sectors basic metals, chemical and cement. Including additional sectors or subsectors in future studies, e.g. steel and refineries, using a similar bottom-up modeling approach would help identify process-specific opportunities and challenges for enhancing power system flexibility. Yet, our study have included decarbonization technologies for high-temperature heat, carbon capture, and green hydrogen production - the two latter identified as crucial measures for industry decarbonization.[9] By including the main decarbonization routes for the industry sector, we anticipate that the average flexibility potential of the industry sector as a whole is in the same range as identified in this study. Direct electrification of chemical processes is also central in several future decarbonization pathways, generally leading to less flexible processes.[8] This may be compensated for by installation of storages, either hydrogen or other product or energy storages, which may increase the flexibility beyond the quantification made in this study.

The cost of activating flexibility is dominated by product prices, as well as energy and carbon tax prices. While energy prices are set by the market in different price zones throughout both Europe and the world, both product prices and European carbon emission prices are set by an international market. Different regulations may therefore to some degree affect the cost of flexibility, but as the main cost driver of flexibility in this study was found to be the loss of revenue from production losses, the flexibility cost is likely to be primarily linked to the product price, giving similar flexibility costs throughout the market.

5. Conclusion

Decarbonization of industrial energy demands will require significant electrification efforts, further straining power grids that are already close to their capacity limits. Enabling energy-intensive industry sites with decarbonization plans to connect to these strained grids through joint flexibility efforts is an important measure to minimize delayed or cancelled industry decarbonization. Heavy-industry sites often include plants from various industry subsectors. While their flexibility capabilities differ, together they have a significant potential to reduce or shift loads in capacity and time.

To provide insights on the potential of co-located heavy industries to offer sizable load flexibility, we developed a bottom-up model of inherent process capacities and constraints. We found significant differences in the operational constraints and costs of activating flexibility in the different industries. Yet, their diversity of flexibility potential is, to some degree, complementary and can be an advantage for the industry region in offering grid flexibility. Some industry types, such as cement and certain chemical processes, have significant load shifting potentials, while metallurgical industries can only perform load shedding with resulting high losses of revenue. Other industry sectors, such as ammonia production, have limited operational flexibility if not equipped with sufficient intermediate storage (such as the case in this study), causing the total costs of flexibility to be dominated by an inability to handle rapid changes in production. In the case of persistent flexibility needs from the power grid, the inertia and process requirement of chemical industries constrains cost-efficient flexibility. Adding future decarbonization measures to the industrial loads was shown to increase the flexibility potential significantly, particularly through hydrogen production from electrolysis. However, the realizable flexibility was significantly limited by subsequent process steps. Decoupling flexible and rigid processes can therefore provide additional flexibility.

When coordinating industry processes with the overall transmission grid load, industry flexibility has been demonstrated capable of significantly reducing the number of hours with grid overload. In addition, the power flow analysis demonstrated that the reliability of the transmission grid is improved by enabling a higher degree of redundancy in case of line tripping. This reduces the need for other flexibility measures for providing flexibility, such as involuntary load shedding or CO_2-intensive re-dispatch. The unit cost of flexibility provided by the industry is comparable to that of other alternatives for increasing grid capacity. This may increase the grid hosting capacity, allowing other electrification measures to utilize the power grid and prevent the need to wait for grid capacity extensions. Industry flexibility is in the same cost range as, for example, building new transmission grids, but without the need for building additional grid infrastructure, which can take years or decades. As such, the cumulative CO_2-emission mitigation effect of accelerating new connections can be significant.

Finally, while significant private funding is being channeled into new renewable energy production, the transmission infrastructure is predominantly state-owned. The increase in renewable electricity generation is not matched by necessary grid investments. Consequently, identifying the adequate incentives to encourage industrial investment in flexibility could accelerate the decarbonization of both the industrial sector and the entire energy system.

Author Contributions

Sverre Stefanussen Foslie: Conceptualization, Data Curation, Investigation, Methodology, Software, Visualization, Writing – original draft. **Brage Rugstad Knudsen:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Sigurd Bjarghov:** Conceptualization, Investigation, Methodology, Software, Visualization, Writing – review & editing. **Magnus Korpås:** Conceptualization, Supervision, Writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

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