Is Green Steel Socially Beneficial?

A Cost-Benefit Analysis of SSAB’s Green Steel Investment

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Abstract

This article aims to undertake a comprehensive cost-benefit analysis of SSAB's investment in green steel production under the HYBRIT initiative, focusing on the implications of operating within the EU Emission Trade System and an illustrative scenario employing a carbon tax. The study evaluates profitability and social benefits, utilizing time series models to forecast electricity prices in different regions of Sweden, accounting for energy inputs from wind, hydropower, and nuclear sources. The analysis finds that expanded wind power generation could significantly bolsters the project's viability due to its lowering of electricity costs. Under the current EU Emission Trade System framework, the project's success appears to result in a social loss if the permit cap is considered exogenous. In the illustrative carbon tax scenario, with escalating social costs of carbon factored in, the economic attractiveness of SSAB's green steel increases, promoting alignment with broader environmental objectives. The study highlights crucial regulatory shifts, such as the elimination of free carbon permit allowances and the introduction of the EU's carbon border adjustment mechanism, which are pivotal in determining the future landscape of the steel industry. These changes encourage a transition toward sustainable production practices, positioning proactive companies for competitive advantage in a low-carbon economy.

Key words: Cost-Benefit Analysis, EU Emission Trade System, Green Steel, Hydro-Based Steel, Sustainability

LIST OF ACRONYMS

ADF	Augmented Dickey Fuller
AIC	Akaike Information Criteria
ASEAN	The Association of Southeast Asian Nations
BIC	Bayesian Information Criterion
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BOF	Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture, Utilization, and Storage
CO2 emission	Carbon Dioxide emission
DICE	Dynamic Integrated Climate and Economy
DR Pellet	Direct reduced Pellet
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
ETS	Emissions Trading System
FaIR	Finite Amplitude Impulse Response
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution
GDIP	Green Deal Industrial Plan
H2GS	H2 Green Steel
IAM	Integrated Assessment Model
IEA	International Energy Agency
K-H	Kaldor-Hicks
PAGE	Policy Analysis of the Greenhouse Gas Effect
NPV	Net Present Value
SCC	Social Cost of Carbon
WACC	Weighted Average Cost of Capital

The following terms are used interchangeably:

Direct Reduced Iron, Sponge Iron

SE1, Bidding area 1

SE3, Bidding area 3

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1. INTRODUCTION

Aiming to become the world's first climate-neutral continent by 2050, the European Commission published a roadmap in 2011. This plan targets a reduction of at least 80 percent in domestic greenhouse gas emissions by 2050 compared to 1990 levels (European Commission, 2011). To achieve this ambitious goal, substantial investments and a comprehensive set of climate and energy policies are necessary. Notably, the Emission Trade System has been implemented to promote a carbon-neutral economy (European Commission, 2011, 2023). Currently, the steel industry is frequently discussed within the context of decarbonizing industries. It is responsible for approximately 8 percent of the world's energy-related CO2 emissions (Quader et al., 2015; IEA, 2023; Worldsteel Association, 2023). However, the International Energy Agency (IEA) in 2023 reported that the steel industry is not on track to achieve a carbon-neutral economy. This shortfall is primarily due to the inadequate development of necessary technologies. Specifically, the existing hydro-based technology for producing green steel is insufficient.

The global effort to make a sustainable transition to a carbon-free economy, driven by the implementation of EU policies, and especially the emission trade system, has compelled firms to quickly adapt to a changing environment. In response, SSAB, together with LKAB and Vattenfall, has initiated the HYBRIT project 2016 (SSAB, 2024). This groundbreaking effort aims to establish the first steps toward a green steel supply chain, promoting fossil-free and zero-emission steels (ibid). Despite the potential of this initiative to foster a greener future, the energy-intensive nature of hydro-based steel production has attracted skepticism. Critics like Johansson & Kriström (2022) and Sundén (2023, 2024) have raised concerns about the viability of HYBRIT under the Emissions Trading System. They argue that while consumers may pay a green premium to reduce emissions, the permits could simply be transferred to other industries, negating the environmental benefits. Furthermore, an investigation into SSAB showed that when their plants and other energy-intensive industries in the region are operational, they account for 50 percent of Sweden's total electricity consumption. Sundén criticizes LKAB's investment in hydro-based production, highlighting the potential for significant increases in electricity prices that could challenge the profitability of such investments. He emphasizes that these investments carry high risks both in the short and long term and points out that 25 percent of the funding for these projects comes from taxpayer money. This raises concerns about the financial burden on the public and the economic feasibility of relying heavily on hydro-powered solutions in the steel industry. According to the Swedish Energy Agency (2022), the future annual electricity demand from industry giants in the north could reach up to 370 TWh by 2045. However, estimates vary, with Holm et al. (2023) predicting 330 TWh and Vattenfall (2024) forecasting 300 TWh. However, Vattenfall, as a part of this initiative is confident in fulfill the demand and stated that this demand will require reliable delivery, economic efficiency, timely feasibility, and broad societal and political support. It is a fully realistic goal but necessitates political decisions, broad cooperation, and a forward-moving plan.

Hence, our research question states as:

"Is SSAB's investments in transitioning to green steel socially beneficial?"

To answering that question, this study aims to investigate SSAB's investment in green steel from a social benefit perspective, examining the broader implications of transitioning towards sustainable and environmentally friendly production processes. By utilizing the lens of cost-benefit analysis, this study incorporates electricity prices from two different Swedish bidding areas, northmost Bidding area 1 and the middle part of Sweden Bidding area 2, to predict future prices without an increased demand and later, predict the potential demand increase of electricity prices. It further adapts four different scenarios to evaluate variations in electricity supply. Importantly, the analysis includes the social cost of carbon and an increased permit price, providing a comprehensive view of the economic and environmental dynamics in the green steel industry.

Our results highlight the critical role of integrating wind power to reduce the costs of green production. Additionally, the gradual phasing out of free carbon permit allowances is expected to increase the demand for these permits, thereby raising the social cost of carbon. By incorporating these increased costs into our scenario analysis for conventional steel producers, we demonstrate that these factors significantly enhance the viability of SSAB's investment. This, in turn, encourages the steel industry to adapt to evolving environmental regulations. Over the long term, this adaptation is likely to be beneficial, contingent upon electricity suppliers fulfilling their commitments. SSAB's initiative marks the first attempt globally to establish a green steel supply chain, an area still largely unexplored and often viewed negatively in existing research. Through our study, we aim to provide clarity to all stakeholders on whether such investments are socially beneficial. By analyzing scenarios both within and outside the emissions trading system, our research offers a comprehensive view of how EU climate interventions impact the steel industry and society. Additionally, our study enhances the methodology of the cost-benefit analysis by incorporating predicted electricity prices using time series models. This approach provides a more robust foundation for evaluating the economic aspects of the initiative.

The remaining sections of this study are organized as follows: First, this study provide a review of cost-benefit analysis principles, followed by information regarding the appraisal of SSAB. This includes a deeper understanding of the electricity market, how green steel differs from conventional steel, and further discussions on policy interventions and the social cost of carbon. Later, a section explaining our model is presented with a brief description of the data selection. Continuing with presentation of our results as well as analysis, and discussion of the implications. The essay's limitations, future recommendations and conclusions are presented at the end.

2. THEORETICAL FRAMEWORK

This chapter presents the foundation of this study. First, it introduces the fundamentals of the Cost-benefit Analysis, then further provides readers a deeper understanding with SSAB's appraisal, along with the collaborators. The chapter continues with describing the electricity market and then explains the comparison of conventional and green steel from different perspectives. Additionally, this chapter will introduce European Union policy interventions to reduce CO2 emissions. Lastly, followed by a discussion on how to estimate the social cost of carbon emissions.

2.1 CBA Principles

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Cost-benefit analysis (CBA) is a systematic process used to evaluate the overall value of an investment or project by comparing its anticipated benefits, which are quantified in monetary terms, to facilitate a straightforward comparison with costs. (Johansson & Kriström, 2018; Campbell & Brown, 2022). It is particularly useful in assessing the implications of climate change when designing regulatory policies (Van Den Bergh & Botzen, 2015). The groundwork for CBA is often attributed to 19th-century engineer and economist Jules Dupuit, who introduced the concept of "utility remaining to consumers," now known as consumer surplus. In the mid-1930s, the US. Congress passed a flood control act, prioritizing projects where the benefits exceeded the costs. This principle became the essence of CBA, emphasizing that projects should proceed if their benefits outweigh their costs (Johansson & Kriström, 2018).

Key principles guiding CBA have evolved over the years, including the consideration of opportunity costs, which represent the value of resources in their best alternative use, and evaluating net present value (NPV) to account for the time value of money and consumption (Campbell & Brown, 2022). NPV provides a comprehensive measure of a project's financial performance by comparing the present value of its inflows and outflows. By discounting future cash flows back to their present value using a specific discount rate, NPV allows decision-makers to evaluate financial outcomes on a common basis, regardless of when they occur. This makes NPV a vital tool for objectively comparing the comprehensive scope of a project, ensuring that a project’s costs are justified against the expected benefits, and providing a clear, numeric basis for decision-making (ibid).

During the development of its principles, several economic concepts like the Pareto criterion, Kaldor compensation principle, and Hicks's principle have guided the implementation of CBA (Johansson & Kriström, 2018). The Pareto criterion proposes that a project should proceed only if at least one person benefits without making anyone worse off (Campbell & Brown, 2022). The Kaldor principle argues that a project should be approved if those who gain could theoretically compensate those who lose. Hicks's principle presents a similar but reversed concept. Despite challenges in applying these criteria, which often lead to uneven outcomes that favor the wealthy over the disadvantaged, the Kaldor-Hicks (K-H) criterion remains crucial. CBA not only evaluates a project's efficiency but also considers how the costs and benefits are distributed among different societal groups (ibid). For instance, a public infrastructure project like building a new highway may benefit commuters by reducing travel time but negatively impact residents through increased noise or reduced property values (Johansson & Kriström, 2018; Campbell & Brown, 2022). Thus, according to the K-H criterion, a project is beneficial if those who gain could theoretically compensate those who lose, even if some are negatively affected. This means a project does not need to be a Pareto Improvement (where some benefit and no one suffers) but rather a Potential Pareto Improvement (ibid).

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In this way, CBA seeks to provide decision-makers with valuable insights for strategic choices by objectively identifying, measuring, and comparing the comprehensive scope of a project. The analysis should be proportionate to the project's scale, ensuring that its cost is justified and that it is appropriately detailed based on the expected benefits (Campbell & Brown, 2022). Ultimately, CBA objectively measures the impact of projects within a dynamic context by comparing the current state to potential future scenarios (ibid). By applying CBA to SSAB’s appraisal, this study aims to assess the viability of the project and its social benefits.

2.1.1 CBA Implications

CBA have been applied widely on environmental projects, such as building, construction and steel industry (Naturvårdsverket, 2013; Fischedick et al., 2014; Krüger et al., 2020 Sudarsan & Sridharan, 2021; Bhaskar et al., 2022; Johansson & Kriström, 2022; Biajawi et al., 2023). Although the approach is widely used to assess the welfare impacts of policies or projects, it is not without its criticisms and limitations, as noted by Naturvårdsverket in 2013. Like any evaluative method, CBA has inherent drawbacks (Naturvårdsverket, 2013; Campbell & Brown, 2022). These include subjectivity and value measurement issues, where the neutrality of the analysis may be compromised by subjective values—a concern highlighted by James Buchanan, leading to skepticism about the precision of welfare measurements and the methods used (Naturvårdsverket, 2013). A notable criticism is the monetary valuation, as CBA assumes all welfare effects can be converted into monetary terms. This critique targets both the precision of measurement methods and the unit of measurement (money), suggesting that not all valuable things can or should be priced (ibid).

There are also criticisms regarding how CBAs aggregate different types of costs and benefits, such as the challenge of quantifying intangible costs like noise nuisances. Furthermore, the practice of discounting future revenues and costs to their present value is debated. Critics argue that the choice of discount rate is arbitrary and can significantly influence the analysis, potentially favoring certain outcomes over others. The flexibility in choosing discount rates and other parameters can lead to manipulation of CBA outcomes. Critics also argue that while CBAs claim to be objective, the subjective choice of parameters undermines this objectivity. A critical perspective on CBA highlights that it may disadvantage low-income earners, as it often measures benefits based on willingness to pay, which tends to favor higher income groups (ibid). The study by Schmitz & Seckler (1970) on agricultural technology developments in California illustrated this point, showing how technological advancements benefited some but adversely affected the poorest workers, typically from Mexico. Despite the project being deemed profitable under the Kaldor-Hick's criterion, which assumes optimal income distribution, the case underscores the need for including distributional analyses in CBA to address equity concerns (Schmitz & Seckler, 1970).

2.1.2 Previous Research

Johansson and Kriström (2022) conducted a cost-benefit analysis of a general new fossil-free plant in Northern Sweden, a key influence on our study. The authors evaluated the merits of paying a premium for green steel to benefit the environment through reduced CO2 emissions by evaluating the investment by calculating the NPV. It involves comparing the production costs of conventional steel to those of green steel. The study emphasizes the significant cost of electricity, highlighting its importance given the energy-intensive nature of steel production. The analysis also considered the annual steel output, applied a social discount rate of 3 percent, and set a time horizon of 20 years. However, they concluded that, given the EU's emission cap and trade system, consumers may believe they are reducing CO2 by purchasing green steel, while they are not.

In another application of CBA to green steel, Sundén (2024) assesses LKAB (fossil-free sponge iron) and H2GS (fossil-free steel) operations in northern Norrland. The evaluation includes detailed cost assessments for hydrogen production, storage, sponge iron production, and steel production, all calculated as Levelized Cost of Production (LCOP) per unit. These costs incorporate expenses for fixed assets (CAPEX) and operational and maintenance costs (OPEX). Sundén concludes that "It is not sufficient for investments to become profitable within ten years; they need to be profitable from the outset."

An earlier study by Fischedick et al. (2014) shows that hydrogen-based steel production could become more profitable than conventional steelmaking after 2050. If electricity prices remain low, profitability might be achievable as early as the 2030s. The authors also found that hydrogen production could significantly impact the total production costs. Furthermore, a study by Vogl et al. (2018) demonstrates that hydrogen-based steel production is sensitive to electricity prices and the amount of scrap steel utilized. It only becomes competitive when the carbon price ranges between 37 to 75 dollars and the electricity price is around 44 dollars per MWh. The International Energy Agency (2020) estimated the production cost of hydrogen-based steel production to be between 550 and 750 dollars per ton, assuming electricity prices remain at 45 dollars per MWh. In comparison to conventional steel production, which does not factor in the cost of carbon, the green premium is estimated to be up to 20 to 70 percent higher. The report suggests that, with a carbon price of 100 dollars per ton, hydrogen-based production could potentially be more competitive than conventional production if electricity prices do not exceed 30 dollars per MWh. Bhaskar et al. (2021) estimated the production cost for hydro-based production to be up to 669 dollar per ton with an electricity price as 56 dollar per MWh, which amounts to a green premium up to 60 percent. Jacobasch et al. (2021) estimated the production cost for hydro-based production to up to 786 to 1000 dollar per ton with an electricity price as 86 dollar per MWh, which corresponds to a green premium of 100 to 150 percent. The authors emphasize that, even with free electricity, if the carbon price is 120 dollars per ton, the hydro-based production increases its competitiveness significantly. Lastly, another report by Hydrogen Europe (2022) estimated a production cost of hydro-based production to 774 to 897 per ton with an electricity price 88 dollar per MWh, which corresponds to a green premium of 17 to 40 percent compared to conventional steel. To be able to have a competitive advantage over conventional production the carbon price needs to be around 154 dollars per ton.

In summary, all mentioned studies illustrate a range of factors, including carbon pricing, electricity costs, and market dynamics, influence the financial feasibility of transitioning from conventional to hydrogen-based steel production.

2.2 SSAB's Appraisal and a Joint Venture HYBRIT

In 2016, SSAB, LKAB (Europe's largest iron ore producer and predominantly owned by the Swedish government), and Vattenfall (one of Europe's major energy companies) launched the HYBRIT initiative (SSAB, 2024). This venture aims to establish a completely fossil-free value chain to address carbon dioxide emissions in the Swedish steel industry. Their goal is to develop a steel production process that emits water vapor instead of carbon dioxide. The steel industry is one of the largest carbon emitters globally, accounting for about 7 percent of all emissions (ibid). The HYBRIT initiative could reduce Sweden's carbon dioxide emissions by 10 percent and Finland's by about 7 percent. Each company owns an equal third of the HYBRIT initiative, which corresponds to 75 percent, the rest 25 percent is supported by the Swedish Energy Agency through funding for a four-year research project (SSAB 2024; Vattenfall, 2024). The initiative begins with iron ore in pellet form, mined by LKAB, and is transported to SSAB's facilities in Luleå, Oxelösund, and Raahe in Finland, where the product is 'green steel'. The entire process utilizes electricity supplied by Vattenfall (SSAB, 2024).

In 2021, HYBRIT produced its first hydrogen-reduced sponge iron and delivered the world's first fossil-free steel, with Volvo as the initial customer (SSAB, 2024). As most of the production occurs at SSAB, the focus of recent studies has been on SSAB's operations. SSAB is undertaking a significant investment, projected at EUR 4.5 billion, which includes contingencies. The Luleå mill is set to produce 2.5 million tons per year using two electric arc furnaces and advanced secondary metallurgy (ibid). This initiative will use a mix of fossil-free sponge iron and recycled scrap. The company plans to fund the investment through its own cash flows, avoiding other types of investments not related to green steel. The expected benefits from this investment include an increase in EBITDA (Earnings Before Interest, Tax, Depreciation and Amortization) by more than SEK 5 billion per year based on current commodity forecasts (ibid). The new mini mill will offer lower fixed costs, higher efficiency, shorter lead times, and no CO2 costs, with a planned production increase of 0.5 million tons per year and an improvement in the mix with 1 million tons per year of special and premium steel grades. The startup of the new mill is scheduled for the end of 2028, reaching full capacity a year later (ibid).

To date, SSAB has entered 55 partnerships with leading customers for its fossil-free and zero-emission steels (SSAB, 2024). However, although this initiative appears to enhance a zero-emission steel scenario, it is highly energy-intensive (HYBRIT, 2023). The estimated electricity need will exceed 70 TWh annually, which is an extensive amount demanded by industrial giants in the north (ibid).

2.2.1 The Swedish Electricity Market

According to Vattenfall (2022), the Swedish electricity supply consists of 68 percent renewable energy, such as hydro, which is the majority, along with biopower, and a combination of wind and solar energy. During 2023, the total electricity produced amounted to 163 TWh, where 40 percent was produced by hydropower, 29 percent by nuclear power, 21 percent by wind power, 8 percent from conventional thermal power, and lastly 2 percent by solar power (Swedish Energy Agency, 2024). However, in 2011, Sweden divided the country into four different bidding areas, SE1, SE2, SE3, and SE4, where SE1 is the northernmost part of Sweden and SE4 is the southernmost part. This division aims to enhance the visibility of the electricity supply and demand in each area and to fulfill each area's demand without the need to transport electricity across the country, thereby helping to keep the electricity prices stable (ibid). Currently, SE1 produces 26 TWh of the total electricity, where 74 percent is generated by hydropower, 22 percent by wind power, and 4 percent by thermal power. SE2 produces 50 TWh, primarily using hydropower followed by wind and thermal power. Nevertheless, regarding SE3, which produces most of the total electricity supply at 76 TWh, corresponding to 47 percent, the majority of the electricity is produced by nuclear power at 61 percent, with a mix of hydro, wind, and thermal power. Lastly, SE4, which produces the least amount of electricity, primarily relies on wind power followed by a mix of hydro, solar, and thermal power (ibid). The production source of electricity is chosen based on geographical advantages: over 90 percent of the hydropower is in SE1 and SE2 due to the availability of rivers. Meanwhile, SE3 and SE4 primarily use nuclear power, which is chosen for its ability to provide stable electricity when active (Vattenfall, 2022). Figure 1 below, by Johansson & Kriström (2012), they rank electricity generation sources based on their marginal costs—the cost of producing one additional unit of electricity. In the Figure 1, different types of power plants are arranged from the lowest to the highest marginal cost.

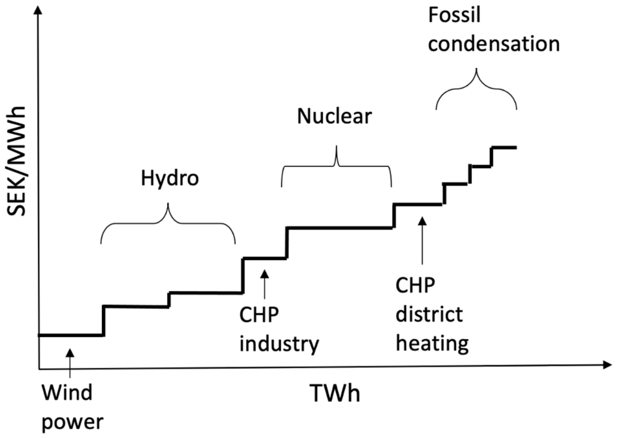

Figure 1. Electricity price market dynamics, where the price is set by the last produced unit of electricity. Figure redrawn from Johansson & Kriström (2012).

Wind power, positioned at the leftmost part of the curve, indicating very low or zero marginal costs and fossil condensation at the rightmost, implying a high and increasing marginal cost (Johansson & Kriström, 2012). Demand for electricity varies throughout the day and seasons, influencing which power plants are utilized. During low demand, cheaper sources like wind and hydro might suffice, but during peak demand, more expensive fossil-fueled plants might be necessary. At equilibrium price, the electricity supplied equals to the quantity of demand, which in the graph is set at the most expansive power plant, this equilibrium price is generated each hour from the Nord pool spot market (ibid).

With that said, the industrial giants in the north will increase the demand of future electricity, and consequently increase the electricity price, and according to the Swedish Energy Agency (2022), the annual demand for electricity in Sweden is expected to increase to 280 TWh by 2035, and to 370 TWh by 2045. Another report by Holm et al. (2023), estimated that the future electricity demand till increase to 330 TWh by 2045. Meanwhile, Vattenfall (2024) projects a lower future electricity demand of 300 TWh by 2045. As a part of the HYBRIT and the main provider of electricity to the initiative, Vattenfall is actively working to meet this demand by expanding its investment in new renewable energy plants, such as wind power plants.

Since our study focuses on SSAB's investment in Luleå, which predominantly utilizes renewable energy in the SE1 bidding zone, which our analysis will be based on. Additionally, to create a scenario depicting increased electricity demand and consequently higher prices, the SE3 bidding zone is used to model a scenario with higher electricity prices.

2.3 The comparison of Conventional and Green Steel

2.3.1 Conventional and Green Steel Production

Conventional steel production is generally executed through two primary methods: the blast furnace-basic oxygen furnace (BF-BOF) route and the electric arc furnace (EAF) route (Cheremisinoff et al., 2008). The former, a traditional and widely adopted approach, especially for producing new steel from raw materials, involves three main steps (Cheremisinoff et al., 2008; Johansson & Kriström, 2022). First step, iron ore mining extracts ore that contains iron in the form of iron oxide. This ore undergoes processing to eliminate impurities, producing a concentrated form of iron ore referred to as sinter or pellets. Subsequently, during the smelting process, these sinter or pellets are introduced into a blast furnace along with coke—a carbon-rich form of coal—and limestone (ibid). Inside the blast furnace, coke acts both as a fuel and a reducing agent to release carbon monoxide, which reacts with the iron oxide in the ore, reducing it to metallic iron. Following this, the molten iron, combined with some scrap metal, is transferred to a basic oxygen furnace (BOF). In the last step, high-purity oxygen is blown into the furnace, initiating a chemical reaction with the carbon in the molten iron, thereby reducing its carbon content and converting it into steel. This production method results in a significant environmental challenge in conventional steel production (ibid). The EAF method contrasts this by primarily utilizing recycled steel scrap. Electric currents are applied to the scrap in the furnace, melting it down with heat generated from electric arcs. This technique is generally less carbon-intensive than the previously mentioned BF-BOF method, but it depends heavily on electricity (ibid). If the energy used is renewable energy rather than coal, it will make the production carbon emission free, it has the potential to reduce emissions by 90 to 95 percent compared to BF-BOF, with only a marginal cost premium of 8 to 13 percent (World Economic Forum, 2023). This method offers a promising pathway towards near zero-emission steel at lower cost compared to other near zero-emission methods, but there are limitations surrounding the availability and the quality of recycled scrap steel, as the method uses it as its primary raw material in steel production (ibid).

In terms of green steel production, numerous innovative ideas are under development to produce environmentally sustainable 'green steel' with reduced CO2 emissions. This includes Carbon Capture, Utilization, and Storage (CCUS) and the hydrogen-based Direct Reduced Iron (DRI) - combined with the Electric Arc Furnace. According to the World Economic Forum (2023), CCUS is expected to become commercially available after 2028. This technology can integrate into conventional steel production to capture CO2 emissions, which can then be repurposed or safely stored. Despite its potential to cut emissions by up to 90 percent, the implementation of CCUS involves a significant cost increase, estimated between 65 to 120 percent over conventional methods (ibid). On the other hand, the hydrogen-based DRI-EAF process is more developed and is currently the main way to decarbonize the steel industry (Karakaya et al., 2018; World Economic Forum, 2023). It utilizes hydrogen as a reducing agent, reacting with iron ore to produce DRI (also refers to as sponge iron), and water vapor, thus eliminating carbon emissions from the reduction step. Once produced, sponge iron serves as a feedstock in EAFs, which use electricity rather than fossil fuels, enhancing compatibility with renewable energy sources (ibid). The method, employed by SSAB and its partners LKAB and Vattenfall, involves LKAB supplying DR pellets, Vattenfall providing renewable energy, and SSAB using at least 50 percent of scrap steel to produce the final product for consumers.

2.3.2 Drawbacks of Hydrogen-Based DRI-EAF Process

The Hydrogen-based DRI EAF process can potentially reduce emissions by up to 97 percent compared to conventional BF-BOF processes (World Economic Forum, 2023). However, there are two significant input issues in this type of production: the scarcity of Direct Reduced (DR) pellets and the consequences of intensive electricity use.

Regarding DR pellets, Sundén (2023) notes that while the hydrogen-based DRI-EAF process holds the greatest potential for reducing CO2 emissions, it requires DR pellets to produce Direct Reduced Iron. DR pellets[1] are a rare, high-quality type of iron ore known for their exceptional iron content and purity. Their availability is limited because the ore used for their production can only be mined in a few locations worldwide (ibid). The global supply of tradable DR pellets is even scarcer, accounting for just 4 percent of the global iron ore trade

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[1] The pellets used for iron sponge production are called DR pellets (Direct Reduction pellets) in contrast to those used in blast furnace BF pellets (Blast Furnace pellets). DR pellets must contain at least 65 percent iron and preferably 67 percent iron or more. It can be compared with BF pellets which contain less than 65 percent iron.

and 2 percent of global steel production. The restricted supply of DR pellets stems partly from the limited number of mines capable of extracting sufficiently high-quality ore and the vertical consolidation of DR pellets into specific value chains (Sundén, 2023). As a result, developing comprehensive fossil-free value chains from mining to steel, via sponge iron and EAF, remains challenging and is just one of many ways to reduce carbon dioxide emissions in the steel industry. Despite this, the limited supply creates financial opportunities for companies like LKAB with access to high-quality ore. Such ore is particularly well-suited for fossil-free steel production, while refining lower-quality ore remains cost-ineffective (ibid). Sundén (2023) argues that companies investing in the sponge iron arc furnace value chain without secure DR pellet access face significant risks due to the limited supply and rising prices. As many steel companies shift production towards these fossil-free value chains, the demand for high-quality iron ore and DR pellets is expected to increase significantly, driving up their prices (ibid). Furthermore, the potential premiums generated by fossil-free steel are expected to benefit mining companies with access to high-quality ore, resulting in a green premium of 35 to 70 percent compared to conventional BF-BOF processes (Sundén, 2023; World Economic Forum, 2023).

In the context of electricity intensity, Johansson and Kriström (2022) highlight the potential for a significant increase in electricity prices due to the high-power demand of SSAB and the new and planned electricity-intensive facilities such as LKAB, H2 Green Steel (H2GS), and Northolt. Together, these companies anticipate a total electricity demand of 85 to 90 TWh annually, which is about 50 percent of Sweden's current electricity production. This increased demand could significantly drive-up electricity market prices, negatively affecting households (ibid). In another report, Sundén (2024) examines the impact of Swedish companies LKAB, SSAB, H2GS, and Fertiberia in Norrland on electricity prices in the Nordic region, particularly in zone SE1. Their collective electricity use is projected to reach 20 TWh by 2026, 40 TWh by 2030, and up to 90 TWh by 2050. If these companies proceed with their 2026 plans without a corresponding increase in electricity production, prices are expected to rise sharply. In the Nordic region, prices could increase by 77 percent, and in Denmark, by up to 40 percent Norrbotten County in northern Norrland could see the largest hike, with increases of up to 176 percent (ibid). Zinchenko (2023) emphasis on the potential energy price increase, as the price of green steel might increase significantly if the electricity price increases more than 100 euro per MWh, which will result in a green premium of 200 to 300 euro per ton.

This escalation will result in a welfare loss, reducing the consumer surplus by SEK 92 billion annually and heavily impacting consumers in Norway and Sweden (Sundén, 2024).

Electricity producers will profit from these changes while companies investing in new facilities will face rising electricity costs. By 2026, prices are expected to be at least $80 per MWh, significantly increasing the cost of fossil-free steel production compared to conventional methods. By 2030, additional production capacity will be needed to prevent a doubling of prices across the Nordic region, but prices in zones SE1 and NO4 may still quadruple (ibid). This will have significant consequences for consumers in Finland, northern Norway, and northern Sweden. Transmission capacity to SE1 will also be strained due to increased demand, potentially making fossil fuel-based production in Finland and NO4 profitable. Meeting the projected increase in demand by 2050 will require an additional 42 TWh of production in SE1 or a 140 percent increase in transmission capacity (ibid).

2.3.3 Market Dynamics and the Green Steel Transition

The global steel industry currently contributes to 8 percent of the world's energy-related CO2 emissions (Quader et al., 2015; Worldsteel Association, 2023). This significant environmental impact is primarily due to the energy-intensive nature of steel production. Over the past decade, CO2 emissions from steel have increased annually by an average of 2.5 percent, driven by rising demand in emerging markets, particularly in India, ASEAN, and Africa (IEA, 2023; Worldsteel Association, 2023). Currently, the majority of global crude steel production is concentrated in Asia, with China accounting for 54 percent of global output, or 1080 million tons. Sweden, the 33rd largest producer, manufactured 4.4 million tons of crude steel in 2022 (Worldsteel Association, 2023). Around 78 percent of global steel is produced using conventional methods, while the remainder relies on Electric Arc Furnace processes (ibid). Regional variations in production methods are significant: 90 percent of China's steel production uses the blast furnace-basic oxygen furnace (BF-BOF) method, while North America depends on EAF for 70 percent of its steel output. Other major regions, such as India and the European Union, maintain a more balanced mix of BF-BOF and EAF techniques (ibid). Green steel, however, constitutes less than one percent of global supply, and the market's ability to absorb a 40-70 percent premium on low-emission steel remains untested (Worldsteel Association, 2023). Market dynamics suggest that regions expecting significant increases in steel consumption, particularly in emerging markets, are likely the least able to afford this premium (ibid).

World leaders today are encouraging the steel industry to reduce CO2 emissions in their production processes and firms are attempting to adapt to near-zero emission production, the industry still faces significant challenges in transitioning to near-zero emission technologies (IEA, 2023). According to the World Economic Forum (2023), this transition requires an investment of USD 372 billion by 2050. This translates to an annual need of USD 14 billion, on top of the usual USD 96 billion in capital expenditures, marking a 15 percent increase. The World Economic Forum (2023) emphasizes the need for policy measures such as carbon pricing, technology development subsidies, and public procurement commitments to attract necessary investments and enhance returns in the steel industry. It also highlights the role of large institutional investors and multilateral banks like the World Bank and Asian Development Bank in providing low-cost capital contingent on strict emission reduction targets. Investment needs differ regionally: the EU and China should expand their Electric Arc Furnace (EAF) assets for secondary steelmaking, while the U.S. and India must maintain theirs due to limited scrap availability. Although 70 percent of major publicly traded steel companies consider climate impacts in their strategy, only 12 percent are actively developing emissions management systems, with an equal percentage recognizing climate change as a relevant business issue (ibid).

To reduce CO2 emissions within the industry, various countries are implementing measures. Europe is leading the way with advanced zero-emission projects (IEA, 2023). In February 2023, the European Union released the Green Deal Industrial Plan (GDIP), and in April 2023, it introduced the Carbon Border Adjustment Mechanism (CBAM) and announced the phasing out of free Emissions Trading System (ETS) allowances for steel producers by 2034 (ibid). Notably in Sweden, SSAB is on track to become the first steel producer to offer a scrap-based steel product that could meet several near-zero emission thresholds if anticipated values are achieved. Moreover, the construction of the first two commercial H2-DRI projects, HYBRIT and H2GS, is progressing well (ibid).

Today the cheapest green steel is produced in US and China, around 980 dollar per ton (production cost 700 dollar per ton) (Technology Rethink Research, 2023), and for the conventional steel price, 761 dollar per ton (*Steel Price*, 2024), which corresponds to a premium of 28.78 percent. Some figures from Monash University in Australia, suggesting that green steel can be produced for 570 dollar per ton using renewable energy, a mix of wind, solar, battery storage and hydrogen (Reuters, 2024). What distinct Sweden from the rest of the world is access to cheap renewable energy, this can potentially increase the competitive advantages to the steel producer (Zinchenko, 2023).

In sum, Europe is leading the way with innovative zero-emission projects, and Sweden exemplifies this with HYBRIT and H2GS working towards green steel. However, achieving widespread adoption of green steel requires 372 billion in investments by 2050. the current landscape of steel production, highlighting both conventional and emerging green technologies. The traditional BF-BOF method remains dominant but is environmentally taxing due to high carbon emissions. The EAF method is less carbon-intensive but relies heavily on renewable electricity. Although CCUS might be the most efficient emissions reduction strategy, it is currently unavailable and requires significant investment. However, the hydrogen-based DRI-EAF process is the most promising emissions reduction strategy available, capable of reducing emissions by up to 97 percent compared to conventional methods. The previously mentioned two major challenges: the scarcity of high-quality DR pellets and rising electricity prices. Each have the potential to increase the price of the green steel with a green premium between 35 to 70 percent, which corresponds to a green premium 200 to 300 euro per ton (Worldsteel Association, 2023). However, the anticipated increases in electricity costs could reach up to 176 percent in some Nordic regions due to the surging demand from new green steel projects (Sundén, 2024). By 2026, prices may exceed 80 dollar per MWh, significantly raising costs for producers and consumers, and adversely impacting welfare. This underscores the importance of investing in renewable energy infrastructure to meet growing electricity demands while maintaining affordability.

2.4 Policy Interventions

As briefly mentioned in the previous section, the European Union has implemented several policies in 2023, including the Green Deal Industrial Plan (GDIP) and the Carbon Border Adjustment Mechanism (CBAM), which were implemented to reinforce with the 2005 European Union Emission Trade System (ETS), due to the risk of carbon leakage (European Panel Federation, 2023; IEA, 2023).

2.4.1 Green Deal Industrial Plan

The EU GDIP addresses global warming and aims for net-zero emissions together with policies like the Fit for 55 packages[2] and the REPowerEU Plan[3], outlines the EU's strategy to

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[2] The "Fit for 55" package is a comprehensive set of legislative proposals aimed at helping the EU achieve its climate goal of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. The package includes revisions to EU legislation on renewable energy, energy efficiency, land use, energy taxation, and emissions trading, among others. Its goal is to accelerate the decarbonization of key sectors like energy, transportation, and buildings to align with the EU's target of climate neutrality by 2050 (European Council, 2024).

[3] The "REPowerEU Plan" was launched in response to heightened energy security challenges, especially due to geopolitical tensions and the conflict in Ukraine. Its primary objective is to quickly reduce the EU's dependence

move away from fossil fuels and transition to a sustainable, net-zero economy by 2050 (European Commission, 2023). The open trade and resilient supply chains to support the global green transition and secure e EU GDIP is built on four pillars: first, a predictable and simplified regulatory environment to speed up scaling of innovative solutions like renewable energy. Second, increased access to funding to fast-track investments in sustainable production. Third, skill enhancement through upskilling and reskilling programs via initiatives like the Net-Zero Industry Academies to bridge the skills gap. Fourth, promoting essential raw materials. These pillars aim to position the EU as a leader in the clean energy market, projected to grow to Euro 600 billion annually by 2030. The strategy focuses on leading net-zero technology development, creating quality jobs, boosting industrial competitiveness, and ensuring fair trade. The goal is a unified European strategy to meet investment demands and transition smoothly to a net-zero industrial era (ibid).

2.4.2 Emission Trade System and Carbon Border Adjustment Mechanism

The European Union Emission Trading System is a cap-and-trade system introduced in 2005, aiming to reduce emissions by 62 percent by 2030. The ETS is divided into four phases, each striving to minimize the emission cap below the previous phase (International Carbon Action Partnership, 2022).

Phase one covered the three-year period from 2005 to 2007, starting with a cap of 2,096 MtCO2e, calculated using a bottom-up approach based on the aggregation of national allocation plans from each member state. Phase two spanned five years, from 2008 to 2012, using the same approach and began with a cap of 2,049 MtCO2e. Phase three, from 2013 to 2020, had its cap based on emissions monitoring, starting at 2,084 MtCO2e (International Carbon Action Partnership, 2022). This cap was reduced annually by a linear factor of 1.74 percent, corresponding to a reduction of 38 million allowances annually, resulting in a cap of 1,816 MtCO2e by the end of 2020. Lastly, phase four covers a ten-year period from 2021 to 2030. Like phase three, it includes an annual linear reduction, set at 2.2 percent per year from 2021 to 2023, increasing to 4.3 percent for 2024 to 2027, and then to 4.4 percent from 2028 to the end of phase four. In terms of emission allowances, phase four will reduce allowances in two steps: by 90 million in 2024 and by 27 million in 2026. Notably, within the power and steel

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on fossil fuel imports, particularly from Russia, by diversifying energy sources and increasing the use of renewable energy. The plan emphasizes energy efficiency, accelerating renewable energy projects, and enhancing the integration of energy markets to boost resilience and independence in the EU's energy supply (REPowerEU, 2022).

industries, free allocation of allowances is expanded from 2024 to remove barriers for the deployment of new technologies such as green hydrogen or hydrogen-based steel (ibid).

In the context of allowance allocations, the first allowance in phase one was primarily based on grandfathering, using historical emissions as the basis, while some member states opted for auctioning, others employed benchmark-based allocation (International Carbon Action Partnership, 2022). In phase two, eight member states—Germany, the United Kingdom, the Netherlands, Austria, Ireland, Hungary, Czechia, and Lithuania—conducted auctions for about 3 percent of the total allowances while approximately 90 percent, being allocated for free. In phase three, 57 percent of allowances were distributed through auctioning. Of these, 88 percent were allocated to member states based on their verified average emissions from 2005 to 2007 (International Carbon Action Partnership, 2022). Additionally, 10 percent of the allowances were shared among 16 lower-income member states as part of a solidarity provision, and the remaining 2 percent were awarded to member states that had achieved emission reductions of at least 20 percent relative to their base year under the Kyoto Protocol. Beyond this 57 percent, the rest of the allowances were distributed for free to mitigate the risk of carbon leakage, using sector-specific performance benchmarks (ibid). As demand for free allowances exceeded the available volume, each installation's free allocation was adjusted using a uniform cross-sectoral correction factor, which was revised in 2017 to reflect updated emissions data and market conditions.

In phase four, which is like phase three, the auctioning allowance will be kept on the same level, accounting for up to 57 percent of the cap. Of this portion, 90 percent are allocated to Member States based on their emissions share, while 10 percent are distributed to lower-income Member States under a solidarity provision (ibid). Free allocation continues to play a crucial role in mitigating carbon leakage, with allowances granted based on sector-specific performance benchmarks (International Carbon Action Partnership, 2022). These benchmarks were updated in 2021, and adjustments will occur yearly until 2025 to reflect technological progress, with fixed reduction rates for sectors like steel that face significant abatement costs. However, a fixed reduction rate was applied for the steel industry, as they face high abatement costs and emission leakage risks (ibid). In 2021, the European Commission introduced a buffer of over 450 million allowances, initially for auctioning, to be available if the volume of free allocations is exhausted, thus potentially avoiding the need for applying the uniform cross-sectoral correction factor, which is set at 1 for 2021 to 2025. Looking ahead, from 2026 to 2030, free allocations will be conditional on the implementation of energy efficiency measures and carbon neutrality plans for the lowest performing installations, promoting decarbonization (ibid).

Johansson and Kriström (2018) suggest that the carbon permit in this case can be interpret as the value of emission, due to fixed supply of emission permits, the number of permits is predetermined (exogenous), any new project requiring permits must purchase them, potentially driving up the price if demand is high. Therefore, the cost to society of emissions from any project is represented by the price of the permits it needs.

The latter policy, the CBAM, part of the EU's "Fit for 55" package, is a market-based policy designed to prevent carbon leakage by aligning non-EU imports with the EU's emission reduction targets (European Panel Federation, 2023; European Council, 2024). The CBAM, gradually implemented from 2023 to 2026, complements the EU ETS by phasing out free emissions allowances and eventually applying to sectors like iron, steel, cement, aluminum, fertilizers, and hydrogen, which are significant for imports (International Carbon Action Partnership, 2022; European Panel Federation, 2023; European Council, 2024). It began with a data collection phase in October 2023, focusing initially on reporting without levying charges. Targeting carbon-intensive industries, the CBAM aims to cover over 50 percent of ETS emissions, with a significant portion of the EU's steel consumption—30 percent—imported from outside the EU (Carbon Border Adjustment Mechanism, n.d.). It also strives to adhere to World Trade Organization rules by equating the carbon price of imports with that of domestic goods (ibid).

In summary, as the free allocation of allowances is set to be phased out in 2026, and costs for the steel industry are expected to rise accordingly, the carbon permit price is expected to increase substantially, SSAB (2023) estimates that a cost of EURO 100 per ton of CO2 (SEK 1160) will correspond to an additional expense of SEK 10 billion, while Cai et al. (2023) found that the permit price will reach 811 dollar per ton of carbon by 2050. This change is anticipated to increase the value of fossil-free steel.

2.5 Social Cost of Carbon Emission

The Social Cost of Carbon (SCC) plays a pivotal role in this study, as it represents the global impacts over time of CO2 emissions, regardless of their geographic origin, highlighting that these emissions create a worldwide externality (Van Den Bergh & Botzen, 2015). A higher SCC indicates that greater damages can be turned aside by reducing greenhouse gas emissions, thus it is beneficial to invest more in such efforts. According to social cost-benefit analysis, if the SCC is determined to be SEK 150 per ton of CO2, it is economically justified to invest no more than SEK 150 to prevent each ton of emission (ibid). If the costs to prevent emissions exceed SEK 150, it becomes more cost-effective to endure the emissions, following the economic efficiency or utilitarian social welfare principles. As such, determining an appropriate level for carbon tax is crucial as it shapes climate policy decisions significantly (ibid). An appropriate carbon tax promotes the adoption of low-carbon energy sources and shifts consumer behavior towards low-carbon goods by incorporating the SCC into all economic prices through the production and consumption lifecycle (Van Den Bergh & Botzen, 2015). Additionally, the SCC is instrumental in assigning monetary values to ecological services like carbon capture by natural environments.

The SCC is rather complex to calculate than what it seemed in theory and is often determined by using Integrated Assessment Models (IAMs), utilizing climate data and economy analysis to estimate the damages from greenhouse gas emissions over lengthy periods, such as 100 or 200 years (Van Den Bergh & Botzen, 2015; Environmental Protection Agency, 2023). Further, the future damages are transformed into a present-day SCC value with an applied social discount rate, which significantly affects the SCC and is contentious due to its dependence on projected economic growth and ethical considerations of how to equitably consider future generations' welfare (ibid). Beside the social discount rate, another factor that can influence the SCC is how IAMs account for both tangible and intangible climate impacts, handle uncertainties, and integrate scenarios that are extreme but plausible. These factors are crucial for a comprehensive economic assessment of climate issues, as emphasized by Weitzman in multiple studies (ibid). Additionally, the influence of individual risk aversion to uncertain climate impacts on the SCC is a critical aspect that has not been adequately addressed in empirical analyses (ibid).

Van Den Bergh and Botzen (2015) present three primary Integrated Assessment Models (IAMs) used in climate economics: Dynamic Integrated Climate and Economy (DICE), Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), and Policy Analysis of the Greenhouse Gas Effect (PAGE). The DICE model employs a global approach without regional differentiation and uses average parameter values to estimate climate damages, expressed through a damage function that impacts various sectors. In contrast, FUND accounts for regional variations and calculates damages across several sectors, incorporating both explicit and implicit adaptation measures. Similarly, PAGE considers regional effects and bases damage estimates on probability distributions, including explicit modeling of adaptation measures that mitigate economic and non-economic damages under certain temperature increases. These models are crucial for quantifying and presenting the economic damages from climate change in present value terms, based on various assumptions about economic growth, technological development, and adaptation strategies. However, despite providing clear policy guidance, they face significant scrutiny due to the simplification of the complex dynamics between climate and the economy, and their common use as 'black box' tools in policy analysis (ibid).

To enhance the accuracy of estimating the social cost of carbon (SCC), the U.S. EPA has transitioned to a new methodology from the previously mentioned models (Environmental Protection Agency, 2023). This modern approach adopts a modular framework to address the limitations inherent in the Integrated Assessment Models (IAMs). It divides the estimation process into distinct components, each specializing in a different aspect of the analysis (Environmental Protection Agency, 2023). This includes a socioeconomic and emissions module that utilizes updated probabilistic projections, a climate module employing the Finite Amplitude Impulse Response (FaIR) model for detailed climate dynamics, and a damage module that uses varied damage functions to provide a more comprehensive assessment of potential impacts. Additionally, the discounting module introduces dynamic discount rates to better reflect real-world uncertainties and economic realities, incorporating near-term rates that help align the economic evaluations with the near-term policy-making framework. This shift not only increases the accuracy and transparency of the estimates but also enhances the U.S. EPA's ability to integrate the latest scientific and economic insights, thereby improving the reliability of policy guidance based on these estimates (U.S. EPA, 2023).

Table 1. Social cost of carbon estimated by the U.S. EPA (2023) using the Near-Term Ramsey discount rate in 2020 USD.

Emission	Near-term rate		
Year	2.5%	2.0%	1.5%
2020	120	190	340
2030	140	230	380
2040	170	270	430
2050	200	310	480
2060	230	350	530
2070	260	380	570
2080	280	410	600

In summary, although various methods have been used to evaluate the social cost of carbon (SCC), the U.S. EPA has adopted a new approach: a modular framework. Table 1 displays the estimated social cost of carbon using this methodology with three different discount rates –2.5 percent, 2.0 percent, and 1.5 percent– they found that the SCC will range from 139 to 228 dollars per ton, 224 to 338 dollars per ton, and 375 to 519 dollars per ton of CO2, respectively, between 2028 and 2058 (Environmental Protection Agency, 2023).

3. METHODOLOGY

In this chapter, we first describe the methodology used to assess the feasibility of SSAB's appraisal. We then introduce our forecast model for future electricity prices, including the motivation behind the chosen variables and our data collection methods.

3.1 CBA and Net Present Value Estimations

To determine if SSAB's green steel investment is superior to conventional steel, the NPV of the project will be analyzed and compared to that of continuing conventional steel production. The method utilized in this thesis to calculate the NPV of green steel builds upon the method used by Johansson & Kriström (2015, 2022) when they performed a cost benefit analysis of the investment in green steel production by H2GS in Boden. It is assumed that prices are equal to costs and that the project with highest NPV should be undertaken. Additionally, conventional steel is assumed to be produced in a traditional blast furnace. In the calculations of NPV, this study does not only consider private costs and benefits, but also aims to capture the cost and benefits to society, meaning to incorporate the social costs caused by the negative externalities of CO2 emitted during production.

Since Sweden is part of the EU ETS, total emissions are set to a fixed cap within the EU. This cap could be considered exogenous since it is not determined by the market but set by policymakers (Johansson & Kriström 2022; Johansson & Kriström 2018, p.16; European Commission 2014, p.211). Consequently, the trading of permits in theory creates a net zero change in CO2 emissions when the cap is reached, since if SSAB would reduce its CO2 emissions, other steel manufacturers would purchase permits to increase their emissions. The exception is if SSAB would be a large enough producer to lower the cap on emissions on its own, which the study does not assume. Furthermore, this would mean that the CO2 emitted remains the same regardless of green or conventional steel is produced Ibid). Thus, the social cost created by the long-term damage of carbon emissions is the same whether SSAB switches to green steel or not, which means that if green steel is more expensive to produce, consumers are paying a price premium without any decrease in carbon emissions (Ibid).

Considering the nuances regarding accounting for the social cost of carbon and how the existence of a cap-and-trade system can impact the NPV, 3 different cases have been considered in this article and are listed below:

1. The current EU ETS is kept in place and the permit cap is considered exogenous.
2. The EU ETS is abolished and replaced by a carbon tax, where companies are taxed equal to the permit price suggested by SSAB.
3. The EU ETS is abolished, and the SCC is set according to the U.S. EPA's recent estimates.

Starting with Case 1, which is the same case considered by Johansson & Kriström 2022, an appraisal of the NPV can be estimated according to:

$$NPV = \sum_{t=1}^{31}((C_c - C_g) \cdot tonnes\ produced + (FC_c - FC_g)) \cdot (1 + SDR)^{-t} \tag{1}$$

C_c denotes the cost of producing a ton of conventional steel, which is equal to the price of conventional steel, C_g denotes the production cost of green steel per ton, FC_c is the fixed cost of conventional steel and FC_g is the fixed cost of green steel. SDR^{-t} is the social discount rate to the power of the number of time periods from the starting period, 2028. SSAB is stating that the time horizon of their new steel mill investment is at least 30-40 years according to Hillström P. (personal communication, 13 May 2024), which is the reason chosen to calculate the NPV for the period 2028 to 2058, that is 31 years. The cost of green steel is compiled according to the below equation (Sundén, 2024):

$$C_g = hydrogen\ production\ costs + iron\ reduction\ costs + DR\ pellet\ costs + steel\ scrap\ costs + plant\ operating\ costs + electricity\ usage\ per\ ton \cdot electricity\ price\ /\ MWh \tag{2}$$

Meanwhile, C_c requires a much smaller amount of electricity (Cheremisinoff et al., 2008) and is set to be constant when excluding the SCC. The social discount rate, SDR, was chosen to be 3 percent, which is a commonly used rate when calculating the NPV (European Commission, 2014).

Moving on to Case 2, the equation for NPV is modified by adding the cost of paying a tax equal to a commonly assumed permit price of SEK 1160 per ton of carbon emitted equation

(3). This price is based on the EUR 100 per ton price used by SSAB (2023). It is now assumed that when SSAB reduces their emission that does not enable another steel manufacturer to increase its emissions, thus if the SSAB's predicted cost of permits is equal to the social costs

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$$NPV = \sum_{t=1}^{31}((C_c + permit\ price \cdot CO2\ emissions\ per\ ton - C_g) \cdot tons\ produced + (FC_c - FC_g)) \cdot (1 + SDR)^{-t} \tag{3}$$

Subsequently, the Case 3 equation (4) is almost the same as Case 2 equation apart from the price of carbon being set to the SCC estimated by the U.S. EPA (2023). Their estimations are not constant but show an increasing SCC as displayed in Table 1 in section 2.5. Furthermore, these estimations vary depending on which SDR used to calculate the NPV of the SCC. Since there are no permits in this case, the CO2 level will decrease as one producer decreases their emissions leading to reduced emissions, increasing the social NPV of green steel. If a carbon tax was set to follow the SCC set by the EPA this would also factor into the NPV calculations of the firms.

$$NPV = \sum_{t=1}^{31}((C_c + SCC \cdot CO2\ emissions\ per\ ton - C_g) \cdot tons\ produced + (FC_c - FC_g)) \cdot (1 + SDR)^{-t} \tag{4}$$

Several of the variable costs of the production of green steel were based on the estimations in Sundén's (2024) report, including the cost of hydrogen production maintenance costs that are set to SEK 460, iron reduction maintenance costs are SEK 215, DR pellet costs are SEK 1905, steel scrap costs are SEK 1017, and the sum of various plant operating cost is SEK 910. The amount of electricity needed per ton of green steel produced is also taken from Sundén's estimation and is set to 3.505 MWh. Electricity costs will be forecasted using the method described in section 3.2. Moreover, the cost of producing a ton of conventional steel is set to SEK 5211 (Ibid). The fixed costs of green steel are from SSAB's (2024) estimated investments into building the new steel mill in Luleå and amounts to SEK 52.2 billion, while the fixed costs of conventional steel are set to SEK 23.2 billion, which are costs SSAB has stated it will require to maintain the existent plant and its equipment. Conventional steel is assumed to emit 1,4 tons of CO2 per ton of steel (IEA, 2023). The exchange rates used when converting prices into SEK are 11.6 SEK/EUR and 10.7 SEK/USD. The steel mill is assumed to produce at full capacity, meaning that quantity of steel produced is estimated to be 2.5 million tons (ibid), regardless of if it is green or conventional steel.

The motivation for including Case 2 and 3, other than to theoretically observe how permits and different estimations of SCC affects the NPV, is that SSAB is manufacturing steel in Iowa in the United States, where there is no cap-and-trade system. If it is assumed that the fixed costs of building a steel mill is the same in Iowa, the results of this article could be of interest if SSAB plans to construct a fossil-free steel plant in America in the future. However, the electricity market in the US is quite different than in Sweden and electricity prices are generally more expensive.

Lastly, a sensitivity analysis of the results will be performed, where electricity prices, DR pellet prices, the SDR and the SCC will be varied to see how it could change the NPV of SSAB's green steel investment in the Luleå steel mill.

3.2 Forecasting of Electricity Prices

The evolution of electricity prices is a large determinant of the future cost of green steel (Choi & Kang, 2023; Johansson & Kriström, 2022; Henrekson & Sandström, 2023). Therefore, an effort has been made to forecast possible scenarios of future electricity market prices to be used in the appraisal of SSABs green steel production. The method utilized to forecast future electricity prices is time series forecasting. A method which has been used to forecast electricity prices before (Weron, 2014; Raviv, Bouwman & Van Dijk, 2013). This study utilizes autoregressive integrated moving average (ARIMAX) and seasonal autoregressive integrated moving average (SARIMAX) models, where the X denotes exogenous, for the exogenous variables that are added in the model. ARIMAX and SARIMAX models have previously been used on several occasions in the context of electricity prices (Elamin & Fukushige, 2018; Liu et al, 2023). Even with more complicated models such as Neural Network models, there is high uncertainty when forecasting the long-term electricity prices (Weron, 2014). ARIMAX models use past information to predict future time periods in combination with observations of one or several exogenous X-variables. Since the future observations of these exogenous variables also are unknown, they too must be forecasted. Hence, depending on the variable, ARIMA and SARIMA based forecasts of the multiple exogenous variables were performed. The exogenous variables later used in the SARIMAX forecast of electricity prices were several likely predictors of electricity prices and will be further described in section 3.2.1.

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$$y_t = a_0 + \beta X_t + \sum_{n=1}^{p} a_n\, y_{t-n} + \sum_{n=1}^{q} \theta_n\, \varepsilon_{t-n} + \sum_{n-1}^{P} \phi_n\, y_{t-sn} + \sum_{n-1}^{Q} \eta_n\, \varepsilon_{t-sn} + \varepsilon_t \qquad (5)$$

The shape of a SARIMAX model fitted on the dependent variable y_t is displayed in equation (5) (Korstanje, 2021) and it comprises of a constant a_0, a coefficient of the effect of the exogenous variables β multiplied by their observed values X_t, an autoregressive (AR) component $\sum_{n=1}^{p} a_n y_{t-n}$ where a_n denotes the effect of the $\mathrm{n_{th}}$ lag of y_t with p number of lags, a moving average (MA) component $\sum_{n=1}^{q} \theta_n \varepsilon_{t-n}$, where the θ_n is the coefficient that captures the effects of previous effect of previous error terms ε_{t-n} , summed to q number of lags (Ibid). The $\sum_{n=1}^{P} \phi_n y_{t-sn}$ and $\sum_{n=1}^{Q} \eta_n \varepsilon_{t-sn}$ terms are the respective seasonal autoregressive and moving average terms, meaning that they capture the effects of the previous season, up to P and Q lags respectively (Ibid). The model is then written as a $\mathrm{SARIMA(p,d,q)x(P,D,Q)_S}$, denoting the order of lags included in the model in addition to the inclusion of D orders of first differencing and D orders of seasonal differencing, as well as the number of seasons s. The number of seasons, s, utilized in the forecast where a SARIMA or SARIMAX model was appropriate was chosen to be 12, since our data is monthly.

In order to determine the appropriate order of the $\mathrm{SARIMA(p,d,q)x(P,D,Q)_S}$ components of each prediction model, the time series of the variables was observed, in addition to analyzing the autocorrelation and partial autocorrelation function. The benefits of a SARIMAX model over an ARIMAX model is that several of the variables used in the forecast, including electricity price, exhibit seasonal cyclical activity that appears as unit roots in several of the variables. These effects are better captured with a SARIMAX model (Ibid). Several variables also showed signs of non-stationarity or time trends. Additionally, some of them showed signs of conditional heteroscedasticity. Since the goal of the forecast was only to predict the general future mean trend of electricity prices given the past values, it was decided not to fit an ARCH or GARCH component to the models.

Augmented Dickey Fuller (ADF) tests of up to 12 lags were then performed on each variable to test for the existence of a unit root (Endres 2010, p. 233). The non-stationary variables were then seasonally differenced of order D=1 to remove the seasonal unit root and then tested again to ensure stationarity. If the variable still displayed signs of a unit root, first-differencing was utilized since this can eliminate the unit root process (Ibid, p. 212).

After transforming all variables including the electricity price and the exogenous variables into showing no sign of a unit root, the information criteria (IC) were checked in order to determine the optimal order of p and q. For a model with p lags, $IC(p) = ln(T^{-1} \cdot$

$SSR(p)) + penalty$, where T is the number of time periods and SSR is the sum of squared residuals of the model. The Schwarz Bayesian Information Criterion (BIC) was selected as the determining information criteria since it has a stricter penalty term = $(p + 1)\ ln(T)/T$ compared to the Akaike Information Criteria (AIC) = $(2(p + 1)/T$ when including higher order lags, thus preventing overfitting of the model. STATA commands assisted in finding the lowest BIC as well as manually testing multiple orders of the P and Q.

Furthermore, the 3 best models in terms of BIC were selected and tested by their predictive power in an in-sample forecast of the observed data. This was done by selecting 75 percent of the dataset to train the model on and then collecting the Mean Squared Forecast Errors (MSFE) of the forecast compared to the last 25 percent of the observations. Lastly, the model with the lowest MSFE was trained on the whole dataset and used to predict the years 2024 to 2058, monthly. After repeating this process for all variables, future electricity prices were predicted using the forecasted exogenous variables.

3.2.1 Variable Selection

The first dependent variables to be forecasted was the electricity price for electricity bidding area 1 (SE1), which is the northernmost bidding area in Sweden, and includes Luleå where SSAB plans to build their new steel mill. Additionally, the price for bidding area 3 (SE3) was later forecasted, to serve as an example of an area where electricity demand is higher. Regarding the exogenous variables used, several potential determinants of electricity prices were considered. As mentioned in section 2.2.1 electricity price is determined by the final produced energy source for that period, however since data on the last produced electricity source was not available, the GWh amount of power generated from different energy sources was used instead. These variables include the amount of power generation from hydro, solar, nuclear and wind sources. Vattenfall aims to sustain a 100 percent sustainable energy mix, which makes sustainable energy sources particularly interesting. Additionally, electricity demand, electricity exports and electricity supply were considered since they most likely will affect the price, however since the correlation between these variables are very high, electricity demand was chosen.

Several weather-related exogenous variables that in theory could impact electricity prices were also considered. These variables included, monthly average wind speed, monthly rain levels and monthly average daily high temperature recorded in the Luleå area, which acted as a proxy for the regional average. Lastly, monthly average hydro plant reservoir volume and mineral industry electricity usage was collected. In order to determine which variables to ultimately include in the SARIMAX model, OLS regressions were used to observe which variables had any statistically significant correlation with electricity prices. Since wind speed, hydro plant reservoir, rain and mineral industry were not statistically significant in any regression, these were excluded from the model (see Table A3 in appendix). Solar power was not significant in the SE1 price case; however, it was significant in the case of SE3 price. Therefore, solar power was kept and later forecasted.

It is unlikely that all the variables included in the model are exogenous. Electricity demand for instance is affected by the electricity prices. Nonetheless, since the X in SARIMAX denotes exogenous, these explanatory variables are at times referred to as exogenous variables, when used to predict future electricity prices.

The final variables utilized in our predictions are summarized in Table 2. Hydro, wind, solar and nuclear power are denoted in GWh, as well as electricity demand. Solar power is a relatively new component of Sweden's energy grid and was recorded to be zero until January 2019 according to our data, although it has constantly increased. The maximum price in both SE1 and SE3 was observed during December 2022 and was due to the gas shortage supply shock caused by the Russian invasion of Ukraine.

Table 2. Summary statistics of all included variables.

Variable	**Obs.**	**Mean**	**Std. dev.**	**Min**	**Max**
Price SE1	339	319.1	187.2	55.83	2060
Hydropower	338	5572	1034	2645	8101
Electricity demand	338	13710	2048	9671	18300
Nuclear power	338	5126	1147	2000	7375
Solar power	338	22.39	73.04	0	579.0
Wind power	338	789.3	991.5	0	4674
Temperature	339	2.848	9.136	-15.80	20.30
Price SE3	339	363.0	289.9	66.26	2690

3.2.2 Data Collection

Since the objective is to forecast electricity prices, the timespan of the collected dataset was adapted to the longest available timespan that data for electricity prices was available. The most extensive dataset found was from Nord Pool (2024), i.e. the pan-European power exchange where electricity spot prices are determined. Since Sweden’s energy market was deregulated and replaced by Nord Pool in 1996, the dataset starts in 1996 and ends in March 2024. It included the monthly historical prices for bidding area 1 and 3. The final time series was compiled of monthly data in order to train the models to more observations and further accurately capture the relationship between price and the exogenous variables.

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Data for wind speed, rain levels and temperature, of which only temperature was included in the model, were collected from the Swedish Meteorological and Hydrological Institute (SMHI, 2024). Additionally, data for hydro, wind, solar, nuclear power and electricity demand was downloaded from the Swedish Statistical Central Bureau (SCB, 2024). The variables collected from the SCB only had observations until February 2024, which is why these variables have 338 observations and not 339 as observed in Table 2.

4. EMPIRICAL RESULTS

This chapter presents and describes the results of this study. Initially, this study introduces the descriptive statistics of the forecast predictions and then the result of the predictions, which is subsequently applied in the cost-benefit analysis. Later, move on to present the sensitivity analysis, highlighting the robustness of this study.

4.1 Electricity Price Prediction

4.1.1 Descriptive statistics

As previously mentioned, Augmented Dickey Fuller (ADF) tests were performed in order to make sure that the variables used in the forecast were stationary. The null hypothesis of the ADF test could not be rejected at the 5 percent level for any of the variables used except hydropower generation and temperature level, meaning that the existence of a unit root could not be rejected. P-values were generally higher around the 11th and 12th lags. This is most likely due to the seasonal components and trends in the data. To deal with this seasonal differencing of order D=1 was employed on the non-stationary variables. The ADF results when including 12 lags are displayed in Table 3 and shows that all seasonally difference variables are stationary apart from solar power. This was addressed by utilizing first differencing of order d=1.

Lastly, as detailed in Table 4 the BIC of multiple combinations of lag orders was analyzed to select the models with the lowest BIC. The data was then trained on the 3 first quartiles of the data to predict the final quartile, after which the MSFE was recorded.

Table 3. Augmented Dickey Fuller (ADF) test results.

ADF without seasonal- and first-differencing			ADF inc. first order seasonal differencing		
Variable	**Test statistic**	**P-value**	**Variable**	**Test statistic**	**P-value**
Price SE1	-2.632	0.0536	Price SE1	-5.162	0.0001
Hydropower	-4.008	0.0086	Electricity demand	-6.568	0
Electricity demand	-3.319	0.0631	Nuclear power	-5.587	0
Nuclear power	-3.385	0.0534	Wind power	-7.546	0
Wind power	-0.692	0.9736	Solar power	2.676	1
Solar power	12.45	1	Price SE3	-6.125	0
Temperature	-3.827	0.0152	First-differenced solar power	-9.135	0
Price SE3	-3.469	0.0428			

The critical values for the Augmented Dickey Fuller (ADF) test, where the test statistic values are -3.987, -3.427, and -3.13 for significance levels of 1%, 5%, and 10%, respectively.

The model with the lowest MSFE, as displayed in Table 4, was selected for performing a SARIMA prediction of each respective variable using the entire time period. The future SE1 and SE3 price was then forecasted, including the predictions of the exogenous variables.

Table 4. The lowest MSFE model for each variable and the corresponding BIC and MSFE

Variable	**Model**	**BIC**	**MSFE**
Price SE1	SARIMA(2,0,2)x(1,1,1)$_{12}$	4131	64209
Hydropower	ARIMA(8,0,6)	5369	485510
Electricity demand	SARIMA (4,0,11)x(0,1,0)$_{12}$	5118	528490
Nuclear	SARIMA(2,0,2)x(1,1,1)$_{12}$	5070	591640
Solar power	SARIMA(11,1,9)x(0,1,0)$_{12}$	2713	22489
Wind power	SARIMA(2,0,2)x(1,1,1)$_{12}$	4639	691550
Temperature	ARIMA(4,0,11)	1628	83
Price SE3	SARIMA(2,0,2)x(1,1,1)$_{12}$	4338	228250

4.1.2 Prediction of the exogenous variables

When forecasting our exogenous variables, they are heavily influenced by the past trend, which can be observed in Figures A1 to A9 in the appendix. Graphs of the predicted yearly total of energy per energy source can also be found in the appendix. Because of this historical trend, wind power is projected to increase, as it has been in the recent decades. Our prediction has wind power increasing from around 38 TWh in 2024 to 118 TWh in 2058, which would require a substantial expansion of wind power. In contrast, hydropower is predicted to remain at a similar level to today at around 70 MWh per year, while nuclear power is forecasted to slowly decrease, as has been the recent trend, from 49 TWh to 30 TWh. Solar power was projected to drastically expand since it was zero until 2019, this led to predictions being unreliable since such an expansion of solar power would lead to decreasing electricity prices which is not credible, especially in SE1. On account of this and the lack of significance in the regression of SE1 prices as shown in Table A3 (in appendix) solar power was ultimately not used in the SARIMAX prediction of electricity prices.

Lastly, the forecast for energy demand shows an increase from 170 TWh in 2023 to 240TWh in 2024. This is noticeably less of an increase than the 82 TWh increase in electricity demand that is predicted when all the HYBRIT companies and H2GS reach their full operating capacity. This is in part why SE3 prices was included as an example of what prices could look like if electricity prices increase due to the upcoming demand shock. Nonetheless, it is unlikely that these companies will operate at full capacity until after a couple of years and in line with Swedish electricity production expanding to supply the new investments.

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4.1.3 Final Electricity Price Prediction

Figures 2 and 3 illustrate the historical and predicted electricity prices for Electricity Bidding Area 1, denominated in SEK, from the year 1996 extending beyond 2058. The actual prices, depicted in red, show considerable volatility over the years with a prominent spike around 2022, attributed to the Russo-Ukrainian War. In contrast, the predicted prices, using the SARIMAX model and represented in blue, vary across the figures.

Specifically, in the case of Figure 2 a) below, the predictions align closely with historical data until 2023 but fail to capture the peak and subsequent price variations. Post-2023, the model forecasts a relatively stable price trajectory with minor fluctuations, trending between SEK 497 to SEK 802 per MWh between 2028 to 2058. This indicates a challenge in predicting future volatilities or impacts from unforeseen global events, such as wars, which are difficult to include in standard predictive models.

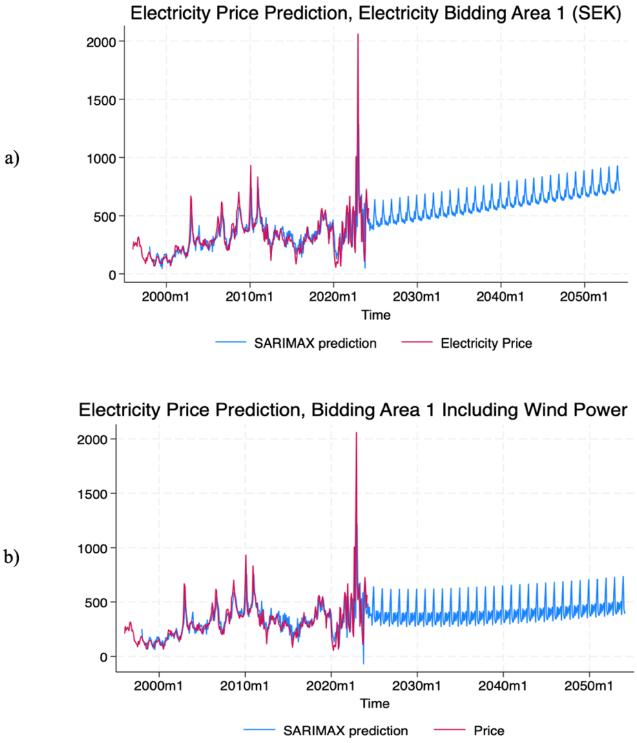

Figure 2. SE1 Electricity Price Prediction (a) SARIMAX(2,0,2)x(1,1,1)$_{12}$ prediction excluding wind power as an exogenous variable. This model will be referred to as Scenario 1. b) SARIMAX(2,0,2)x(1,1,1)$_{12}$ prediction including the wind power prediction as an exogenous variable. This model will be referred to as Scenario 2.

Figure 2 b) includes the predicted increase in wind power in the analysis. Notably, including wind power as an exogenous variable leads to generally lower predicted electricity prices than observed in Figure 2 a), the decrease in electricity price fluctuated around SEK 376 to SEK 443 per MWh, which is substantially lower than in Figure 2 a). This suggests that wind power plays a significant role in reducing overall electricity prices according to the predictive model.

Furthermore, one can observe in Figure 2 b) that the fluctuations in the predicted electricity prices are more volatile compared to those in Figure 2 a), fluctuating around SEK 676 to SEK 969 per MWh. The increase in volatility is attributable to seasonal effects; during periods of higher wind availability, more wind power is generated, thereby influencing the variability of the predicted prices. This detail underscores the dynamic impact of renewable energy sources like wind on electricity prices.

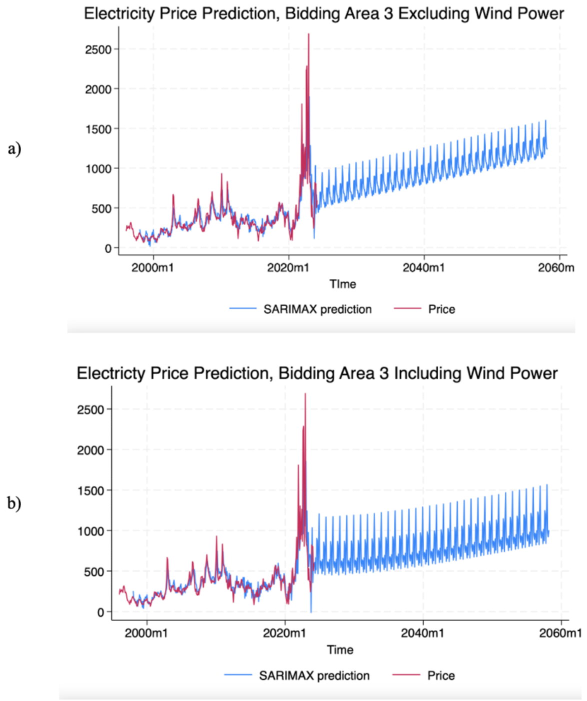

Figure 3. SE3 Electricity Price Prediction a) SARIMAX(2,0,2)x(1,1,1)$_{12}$ *prediction excluding wind power as an exogenous variable, i.e. scenario 1, using Bidding Area 3 prices. b) SARIMAX(2,0,2)x(1,1,1)*$_{12}$ *prediction including wind power as an exogenous variable, i.e. scenario 2, using Bidding Area 3 prices.*

In Figure 3 a) above, electricity prices in Bidding Area 3 are analyzed, with wind power excluded from the model. Due to the limited availability of renewable energy sources in Bidding Area 3, the usual electricity prices are generally higher. The predictive model closely follows the actual price trends up to 2023. Beyond this point, it forecasts a consistent uptrend in electricity prices with minor fluctuations, where the electricity price fluctuates around SEK 718 to SEK 1268 per MWh, from 2028 to 2058.

Moving forward to Figure 3 b), the analysis uses electricity prices in Bidding Area 3, but this time includes wind power in the model. Compared to Figure 3 a), the predictions post-2023 show a slight decrease in the upward trend of electricity prices, highlighting the significant role of wind power in moderating costs. The electricity price in this case fluctuated around SEK 676 to SEK 969 per MWh. However, similar to Figure 3 a), the inclusion of wind power introduces greater volatility in the predictions post-2023, attributable to seasonal variations in wind availability. This illustrates the dynamic impact of renewable energy sources on price stability in the energy market.

In summary, the analysis across Figures 2 and 2 demonstrates the complexities and challenges in predicting electricity prices with and without the inclusion of wind power, and further using different Bidding areas. While wind power tends to reduce overall electricity price and contributes to price fluctuations due to its seasonal nature, external factors such as geopolitical events can disrupt predictions significantly.

Two more scenarios of future electricity price were modeled as well. Scenario 3 excluded the predictions of both nuclear and wind power as exogenous variables and Scenario 4 excluded nuclear power from the model but included wind power. These results are found in Figure A10 to A13 in the appendix since the inclusion and omission of the nuclear power prediction did not substantially alter the electricity price forecast. Instead, the inclusion and omission of wind power changed the forecast the most.

4.2 Cost Benefit Analysis

Our estimation of the CBA is divided into different scenarios, with Scenario 1 and Scenario two as our primary results, the former one incorporates wind power as an exogenous variable while the latter one excludes wind power. More Scenarios are included in the sensitivity test to ensure its robustness, with Scenario 3 excluding both wind and nuclear power; and Scenario 4 excluding nuclear power. The CBA also applies the electricity prices from Bidding Area 1 and compares the NPV to when the electricity in Bidding Area 3 is used.

Regarding Case 1, under the current emission trading system permits are considered exogenous and the NPV is calculated using equation 2. Starting with Bidding Area 1 under Scenario 1, the present value cost of producing green steel is approximately SEK 387 billion, or SEK 4999 per ton. This contrasts with conventional steel’s total present value production costs of SEK 279 billion, or SEK 3597 per ton. Electricity prices in Bidding Area 1 are expected to fluctuate between SEK 497 and SEK 802 per MWh from 2028 to 2058. As depicted in the accompanying table, the NPV is a loss of SEK 108,6 billion, necessitating a 39 percent green premium for the company to break even.

In Scenario 2, shown in Table 5, which incorporates wind power, the cost of producing green steel in Bidding Area 1 drops to SEK 350 billion, or SEK 4515 per ton, when discounting for 31 years and including a SDR of 3 percent. Additionally, electricity prices in this scenario are expected to fluctuate between SEK 376 and SEK 443 per MWh. The NPV shows a reduced loss of SEK 37,5 billion, although increasing the required green premium to 53 percent to breakeven.

Table 5. NPV Results. All Scenarios illustrate electricity prices from 2028 to 2058. As before, Scenario 1 excludes wind power and Scenario 2 includes wind power. Case 1, with ETS, Case 2, without ETS, Case 3, using social cost of carbon from U.S. EPA.

Case	Scenario 1	Scenario 2
Case 1 (SE1)	−109	−71
Case 1 (SE3)	−167	−148
Case 2 (SE1)	−26	11
Case 2 (SE3)	-32	-14
Case 3 (SE1 SDR 2,5%)	43	81
Case 3 (SE1 SDR 2,0%)	123	161
Case 3 (SE1 SDR 1,5%)	262	299

Conversely, in Bidding Area 3 under Scenario 1, the electricity prices are significantly higher, expected to fluctuate between SEK 718 and SEK 1268 per MWh. This substantial increase in electricity cost impacts green steel production, leading to a total cost of SEK 445 billion, or SEK 5749 per ton, corresponding to a 59 percent green premium. The NPV shows a significant loss of SEK 166,7 billion. Under Scenario 2 in Bidding Area 3, electricity prices are expected to fluctuate between SEK 676 and SEK 969 per MWh. The loss in this scenario decreases to SEK 148,1 billion, which is still considerably higher than in Bidding Area 1 yet reflects a more manageable energy cost compared to Scenario 1. From society's standpoint, SSAB’s investment generally appears non-profitable when applying the assumptions of Case 1 due to high electricity costs of producing green steel, in addition to the carbon emissions remaining at the same level. requiring a 46 percent price premium to break even. However, from a financial standpoint of a firm there might yet exist a disincentive to not switching to green steel since the conventional steel producer needs to purchase their permits. From a firm standpoint the NPV of the investment will be calculated similarly to the NPV to society in Case 2 (see equation 3), where there is no longer a fixed cap on emissions.

Moving on to Case 2, a case without the ETS is considered, where there is no exogenously set cap, a carbon tax equaling the fixed carbon permit price of SEK 1160 per ton CO2 proposed by SSAB is assumed. When calculating the NPV for Case 2, using equation 3—the picture changes compared to the previous case. In this case the results using electricity prices from

Bidding Area 1, Scenario 1, shows a reduced loss in NPV compared to Case 1. The NPV increased by SEK 82,3 billion to a NPV of -26,3 billion. In Scenario 2, the NPV turns positive at SEK 11,3 billion, indicating the profitability of SSAB's green steel investment as conventional steel production incurs additional costs for carbon emissions and highlighting the important role of electricity prices. However, if future prices resemble Bidding area 3 prices, the NPV would be negative in both scenarios.

Reflecting on the result in Case 1, from a firm perspective the NPV comparison between conventional and green steel would be more similar to the social NPV in Case 2, since conventional steelmakers still need to pay the permit cost under Case 1 even though the emission levels stay the same.

Lastly, Case 3 considers utilizing a carbon tax equaling the Social Cost of Carbon estimates provided by the U.S. EPA rather than using the cost estimated by SSAB as Case 2. The EPA estimates show an increased SCC from 2028 to 2058 as seen in Table 5. The agency applied three different discount rates when calculating the SCC: 2.5 percent, 2.0 percent, and 1.5 percent. This approach resulted in a carbon price range from SEK 1487 to SEK 2439 per ton of CO2 at a 2.5 percent rate, from SEK 2386 to SEK 3616 per ton of CO2 at a 2.0 percent rate, and from SEK 4012 to SEK 5553 per ton of CO2 at a 1.5 percent rate. These SCC figures are substantially higher than the carbon permit price of SEK 1160 per ton of CO2 suggested by SSAB. With the implementation of the higher SCC estimates from the EPA, SSAB's investments become more profitable as the SCC price increases. This is because conventional steel producers are compelled to account for and pay higher costs related to the externalities they generate during production. Additionally, we could also see a negative correlation between the SDR and the NPV, as SDR decreases to 1.5 percent, the NPV increases substantially in both Scenario 1 and 2. Lower SDR implies a higher valuation of future cost and benefits, putting a higher cost on the SCC, which increases the present value SSC created by conventional steel production emissions. In contrast, a high SDR implies a lower present value of future cost and benefits, consequently resulting in a lower SCC, making green steel less favorable in terms of NPV. From a financial standpoint of the firm, green steel will not be preferred unless conventional steelmakers must compensate for the SCC and in Case 3 this occurs through setting a carbon tax equal to the EPA's estimated SCC.

Furthermore, a comparison between Scenarios 1 and 2 yet again illustrates the advantageous role of continuing the expansion of wind power according to the predicted future trend in terms of the feasibility of green steel. Overall, this analysis demonstrates that while the high electricity prices negatively impact SSAB's investments, including the social cost of carbon makes the investment more feasible and potentially profitable in the long run.

4.2.1 Sensitivity Analysis

In terms of sensitivity analysis, we included two more scenarios, Scenario 3 excluding both wind and nuclear power and Scenario 4 excluding nuclear power. Across all scenarios, SE 1 consistently presents a less negative NPV compared to SE3, suggesting that the electricity cost conditions in SE 1 are more favorable for green steel production due to the renewable energy. The exclusion of solely nuclear power, as seen in Scenario 4, results in improved NPV figures across both areas, indicating that wind power potentially reduces costs and enhances revenues. Notably, all scenarios yield negative NPV values, highlighting that green steel production is currently not financially sustainable nor socially beneficial under the EU ETS, necessitating either a change in policy intervention, technological advancements, or economic changes to become viable.

Table 6. Sensitivity Analysis, illustrate electricity prices from 2028 to 2058. Scenario 3, excluding both wind and nuclear power, Scenario 4, excluding nuclear power.

Case	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Case 1 (SE1)			−109	−78
Case 1 (SE3)			−180	−150
Case 3 SE3 (2,5% SDR)	−15	4		
Case 3 SE3 (2,0% SDR)	65	84		
Case 3 SE3 (1,5 % SDR)	204	222		
Case 1 (SE1 SDR 6%)	−86	−61		
Case 1 (SE3 SDR 6%)	−124	−113		
Case 2 (SE1 SDR 6%)	−29	−4		
Case 1 DR Pellet (SE1 SEK 1000)	−71	−33		
Case 1 DR Pellet (SE1 SEK 2500)	−138	−101		

Table 6 illustrates the sensitivity analysis of the NPV of green steel production in the SE1 and SE3 regions under two scenarios, calculated using discount rates of 2.5 percent, 2.0 percent, and 1.5 percent. A key observation is that the NPV increases as the discount rate decreases and vice versa, which financially emphasizes the enhanced attractiveness of long-term investments at lower rates. However, from a societal benefit perspective, a lower discount rate implies a higher valuation of future costs and benefits, thus placing a higher price on the SCC. This increase in cost is disadvantageous for conventional steel producers but beneficial for green steel producers. In contrast, a higher discount rate implies a lower valuation of future costs and benefits, which reduces the SCC cost and consequently makes conventional steel production more profitable than green steel production. Furthermore, Scenario 2 consistently outperforms Scenario 1, suggesting the inclusion of wind power is a more economically advantageous strategy and also more socially beneficial. Notably, in SE1, all scenarios and rates yield positive NPVs, encouraging the financial viability of investments and social benefit. Conversely, in SE3, using a higher electricity price, the highest discount rate under Scenario 1 resulted in a loss of SEK 15 billion, suggesting the negative effect of high electricity price and the poor inclusion of wind power.

Furthermore, the last sensitivity analysis presented in Table 6 clearly demonstrates the significant impact that DR pellet pricing has on the NPV of green steel production under two distinct operational scenarios. As pellet prices increase from SEK 1,000 to SEK 2,500, there is a marked deterioration in NPV for both scenarios, emphasizing the critical importance of raw material costs to the economic viability of green steel. Scenario 1 is particularly sensitive to these cost increases, experiencing a more pronounced negative effect, whereas Scenario 2 shows less fluctuation in NPV. This suggests that Scenario 2, including wind power can mitigate the financial impact of rising raw material costs. Additionally, this analysis implies that maintaining low or stable electricity prices could mitigate the losses associated with higher raw material prices, emphasizing the importance of strategic management of both energy and material inputs in the green steel industry.

5. DISCUSSION

From the scenario 1 and 2 comparisons, it is evident that including wind power significantly affects the predicted electricity prices. However, this comes with increased volatility compared to scenarios without wind power, highlighting its seasonal nature and dependency on weather conditions. While wind power can be the least expensive method of electricity generation when conditions are favorable, it also poses a high risk due to its dependence on wind availability and other meteorological factors (Johansson & Kriström, 2012). Furthermore, we observed higher electricity prices in SE3 compared to SE1. The variation in prices can be attributed to differences in supply and demand, as well as the types of electricity generation available in each area. In SE1, located in the north, most electricity is generated by hydropower, which not only tends to be cheaper but also often results in a surplus of electricity (Vattenfall, 2022). In contrast, SE3 primarily relies on nuclear power, which is a more expensive alternative.

Additionally, despite some wind power contributions, there is generally a deficit of electricity in SE3 (ibid). This in sum illustrates the potential competitive advantage for the steel producer SSAB has in Luleå also as suggested by Zinchenko (2023), where Sweden has access to cheap renewable energy. This alone increases their first mover advantage, as the first in line to generate a green supply chain of green steel.

Moving on to our CBA results, we firstly illustrated scenarios excluding the social cost of carbon while using different electricity prices from Bidding Area 1 and Area 3. The NPV reveals significant losses—SEK 109 billion and SEK 167 billion respectively—suggesting that, despite the high availability of cheaper renewable energy, investments in green steel are not currently profitable when not accounting for the cost of carbon emissions or if people are willing to pay for a price premium of 39 percent. Including wind power does help reduce production costs and minimize investment losses; however, the losses remain substantial, which also emphasize the importance of wind power supply. Our findings suggest that, in the absence of any social cost of carbon, the breakeven point for electricity prices, in our Case 1, SE1, would be SEK 8 per MWh, which is extremely low and unrealistic. This highlights the critical role of electricity production in the economic viability of green steel, how NPV is affected by having an exogenous emission cap and how making the number of emissions endogenous to the market by switching from the ETS system have large implications on the NPV of SSAB's project. This builds upon the assumption that the cap is exogenous as assumed by Johansson & Kriström (2022) and the European Commission (2014). Interestingly, Johansson & Kriström estimate the NPV to be a loss of SEK 191 billion which is a larger loss than the SEK 109 billion and SEK 167 billion loss estimated in Scenario 1 using the predicted SE1 and SE3 prices respectively in Case 1. This is probably largely due to their usage of a fixed electricity price of SEK 943 per MWh.

Additionally, the exclusion of the social cost of carbon removes a financial incentive for conventional producers to transition to greener production methods, as it is strategically unreasonable to incur losses.

When incorporating a fixed tax of carbon based on the SSABs estimated permit price in Case 2, this illustrates an environment without a cap-and-trade system, where total social cost of carbon emission is assumed to decrease when SSAB lowers its emissions. The NPV indicates a substantial difference, particularly notable when wind power is included in the prediction. For instance, the SSAB project turns profitable, achieving break-even with electricity priced at SEK 480 per MWh and a carbon price of SEK 1160 per ton of CO2. This result is somewhat in line with previous studies, in the context of electricity price, such as Vogl et al. (2018)[4], which suggested that to remain competitive, electricity should cost around SEK 437 per MWh, with carbon priced between SEK 275 and SEK 588 per ton of CO2 or Johansson & Kriström (2022) which requires the prices to be SEK 390 per MWh and SEK1044 per ton of CO2. Our findings on electricity prices are plausible given variations in how the social cost of carbon is calculated and, in our case, we have a higher SCC. Furthermore, the International Energy Agency (2020)[5] posits that green steel could become competitive at an electricity price of SEK 304 per MWh and a carbon price of SEK 1015 per ton of CO2, aligning with our carbon price but highlighting our higher electricity cost. Contrastingly, Jacobasch et al. (2021)[6] argue that green steel would compete at a carbon price of SEK 979 per ton with zero electricity cost. However, our analysis suggests that to reach break-even with no electricity costs, the significance of the carbon price disappears, emphasizing the significant role of electricity costs during green steel production. Hydrogen Europe (2022)[7] further suggests that hydro-based production could become competitive at a carbon price of SEK 1738 per ton of CO2. In our research, keeping electricity prices from SE1 constant at SEK 376 and SEK 443 per MWh, a carbon price of SEK 850 per ton CO2 is necessary for competitiveness.

However, SSAB's proposal to adhere to a static carbon permit price of SEK 1160 per ton of CO2, coupled with an expectation of overall low electricity prices, is not ideal. This stance is challenged by forecasts from several organizations, including the Swedish Energy Agency (2022), Holm et al. (2023), and Vattenfall (2024), which predict an increase in electricity prices in the near future. Additionally, the global steel demand is expected to rise, as noted by the Worldsteel Association (2023), and the phasing out of free carbon permit allowances by 2026. These factors together will create a complex environment, compelling the steel industry to transform and adapt quickly to the rapidly changing market dynamics. Nevertheless, Vattenfall (2024) as a part of the HYBRIT initiative has stated on the increase of wind power with approximately 20 TWh per year in the close future.

A more realistic approach is the EPA's model of an escalating social cost of carbon, which more accurately reflects the increasing environmental and societal impacts of carbon emissions over time. By adopting this model, we see a notable shift in the NPV, with the SSAB investment becoming profitable across various discount rate scenarios. A lower SDR results in a higher

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[4] Initially USD 44 per MWh and a carbon price between USD 35-75 per ton, used exchange rate from 2018, USD 0,1275 and inflation tool.

[5] Initially USD 30 per MWh and a carbon price USD 100 per ton, used exchange rate from 2020, USD 0,122 and inflation tool.

[6] Initially Carbon price USD 129 per ton, used exchange rate from 2021, USD 0,1226 and inflation tool.

[7] Initially Carbon price USD 154 per ton, used exchange rate from 2022, USD 0,0992 and inflation tool.

NPV, indicating a greater societal cost but also increasing the viability of the SSAB investment, as future costs and benefits are valued more highly. This adjustment also implies a greater social cost for conventional steel producers, further enhancing the competitive advantage of SSAB. This result underscores the crucial role of the social cost of carbon; with an accurately estimated SCC using a reasonable SDR, the costs to prevent emissions become more economically justified compared to the costs of enduring them, as suggested by Van Den Bergh and Botzen (2015).

The sensitivity analysis reveals a particularly striking result: when we change the SDR to 6 percent in our Case 2, using the SE3 electricity price, compared to an SDR of 3 percent, the NPV shifts from positive to negative. This is a logical outcome, as a higher SDR implies a lower valuation of future costs and benefits. This scenario tends to favor conventional steel producers by de-emphasizing the economic impact of future environmental costs, making it less beneficial for SSAB, which focuses on more sustainable production methods. However, as mentioned by Naturvårdsverket (2013), the choice of the discount rate is arbitrary and can sees as a manipulative tool to affect the analysis and the outcome if the CBA in the researchers' own beneficial way, our study adapts 3 percent according to European Commission (2014), which is a widely adapted SDR.

There are several limitations when doing a long-term forecast of electricity prices, since the degree of accuracy of the prediction decreases as predicted time periods increase. Therefore, several scenarios have been analyzed in order to give an accurate insight into what could happen, given the absence of unforeseen shocks such as another energy supply shock similar to the one in 2022. In a SARIMAX model typically, the X-variables are exogenous, meaning that there is no endogeneity or simultaneity bias between these variables and the dependent variable, in this case price. However, since few of the truly exogenous variables observed had a significant effect as regressors of price (see Table A3 in appendix), it was decided to use explanatory variables where there could be the risk of such bias such as electricity demand and the various power sources generated. Nevertheless, since the objective was to obtain a forecast of electricity prices and capture the general trend, rather than to establish causality, these variables were still included in the SARIMAX predictions of electricity prices. Therefore, a suggestion for future research would be to attempt to find exogenous variables that significantly impact electricity prices. One difficulty in finding weather related variables to use, is that it is hard to obtain aggregated regional weather data, which requires one to choose a specific location to collect the weather data from.

An improvement to this analysis would have been to incorporate the future demand shock that is expected in SE1, and Sweden at large, in the prediction of electricity prices. There are various ways to attempt this such as utilizing a neural network model or a Nash-Cournot framework (Weron, 2014). Lastly, if SSAB makes more data available regarding the different variable costs during green steel production in future, that would provide a better estimation of the cost of green steel.

6. CONCLUSION

Our cost-benefit analysis (CBA) of SSAB's investment in green steel, as part of the HYBRIT initiative, evaluated the profitability and social benefits of this energy-intensive project under different regulatory frameworks. The analysis indicated that the viability of the SSAB project is critically dependent on the inclusion of wind power. Wind power offers a significant cost advantage as it is not fuel-dependent and tends to have lower marginal costs compared to other energy sources. The economic analysis showed that the financial success is sensitive to fluctuations in the cost of electricity as well as the price of carbon permits. Under the current EU Emission Trade System (ETS) the project will result in a large loss in terms of NPV if the permit cap is considered exogenous.

Commented [DBK7]: Jag förstår inte meningen. Kan tas bort?

In the scenario where the EU ETS is replaced by a direct pricing of carbon, two distinct frameworks for carbon costing were considered. When using carbon permit cost as suggested by SSAB, coupled with the inclusion of wind power in the energy mix, a positive NPV at a SDR of 3 percent was obtained. This indicates not only a potentially financial viability of the SSAB investment, but also a higher valuation of future costs and benefits, suggesting a promising outlook for the project under these specific conditions.

Commented [DBK8]: Oklart för mig som lekman...

To further enhance the realism of our model, a scenario where the social cost of carbon escalates over time was considered. For this, we referenced estimates from the US Environmental Protection Agency, which are significantly higher than those initially used. Under this scenario, the relationship between the NPV and the SDR demonstrated a negative correlation: as the SDR decreases, the NPV increases. This implies that a lower SDR, which assigns greater weight to future costs and benefits, leads to higher costs for conventional steel producers who do not incorporate green technologies. Conversely, for SSAB’s green steel initiative, the increasing social cost of carbon enhances the project's economic appeal, as these costs do not impact it in the same way.

Commented [DBK9]: Syftra detta på den tidigare analysen som står här ovan i conlusion?

As indicated above, the economic viability of green steel, such as that produced by SSAB under the HYBRIT initiative, faces several market and regulatory challenges. However, the prospects for profitability can be significantly enhanced if companies like Vattenfall increase their supply of wind-generated electricity. This would not only reduce the energy costs associated with green steel production but also align with broader environmental goals by leveraging renewable energy sources.

Commented [DBK10]: Det här stycket skulle kunna tas bort, om du vill korta. Sagt ovan

A crucial factor that will influence the steel industry within the EU is the phasing out of free carbon permit allowances scheduled for 2026. As these allowances diminish, the demand for carbon permits is expected to rise, leading to an increase in their prices. This change will impose additional costs on conventional steel producers, compelling them to accelerate their transition towards greener steel production methods. This transition is not just a regulatory requirement but also a strategic imperative to remain competitive under changing market conditions.

Furthermore, the introduction of the EU's carbon border adjustment mechanism aims to level the playing field between EU steel producers and international counterparts. By setting a carbon tariff, the EU intends to equalize the price of steel produced within the union and that imported from outside, accounting for the environmental costs of production. As the cost of steel produced within the EU may increase due to investments in environmentally friendly technologies, this could influence the structure of the carbon tariffs. International steel producers will need to consider these developments seriously, as their access to the EU market will be affected by how well they align with its increasing environmental standards.

Overall, there is no straight forward answer to our research question, as the viability of SSAB's green steel plant depends on the estimation of social cost of carbon, the policies used to reduce carbon emissions, and future electricity costs, which are influenced by the amount and source of the energy generated. In the short run, the investment will face challenges such as high input material costs, but when weighed against the social cost of carbon and the vision of a greener future, the investment appears more favorable in the long run. A green transition is necessary, but excessive policy intervention may have a negative effect, if greener technologies are not keeping up with the pace of policy changes.

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Appendix

Table A1. Variable cost in hydrogen production and reduction to sponge iron

Year	Electricity MWh/ton	Electricity price (SEK/MWh)	Tot electricity (SEK)	DR pellet (SEK)	Installation cost (SEK)	Scrap steel(SEK)
2028	2,955	497	1468,635	1904,6	674,1	1016,5
2029	2,955	507	1498,185	1904,6	674,1	1016,5
2030	2,955	518	1530,69	1904,6	674,1	1016,5
2031	2,955	528	1560,24	1904,6	674,1	1016,5
2032	2,955	538	1589,79	1904,6	674,1	1016,5
2033	2,955	549	1622,295	1904,6	674,1	1016,5
2034	2,955	559	1651,845	1904,6	674,1	1016,5
2035	2,955	569	1681,395	1904,6	674,1	1016,5
2036	2,955	580	1713,9	1904,6	674,1	1016,5
2037	2,955	590	1743,45	1904,6	674,1	1016,5

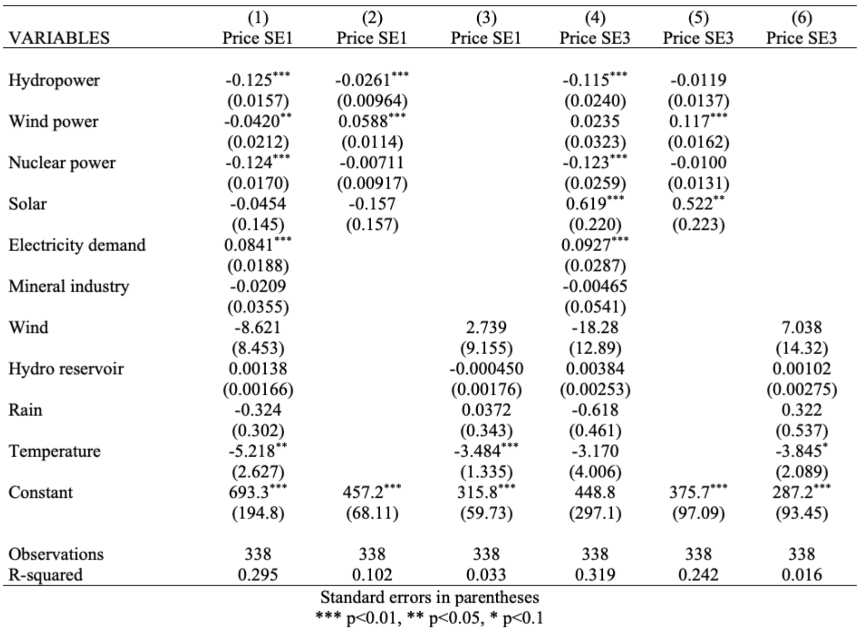
2038	2,955	600	1773	1904,6	674,1	1016,5
2039	2,955	611	1805,505	1904,6	674,1	1016,5
2040	2,955	621	1835,055	1904,6	674,1	1016,5
2041	2,955	631	1864,605	1904,6	674,1	1016,5
2042	2,955	641	1894,155	1904,6	674,1	1016,5
2043	2,955	652	1926,66	1904,6	674,1	1016,5
2044	2,955	662	1956,21	1904,6	674,1	1016,5
2045	2,955	672	1985,76	1904,6	674,1	1016,5
2046	2,955	683	2018,265	1904,6	674,1	1016,5
2047	2,955	693	2047,815	1904,6	674,1	1016,5
2048	2,955	703	2077,365	1904,6	674,1	1016,5
2049	2,955	714	2109,87	1904,6	674,1	1016,5
2050	2,955	724	2139,42	1904,6	674,1	1016,5
2051	2,955	734	2168,97	1904,6	674,1	1016,5
2052	2,955	745	2201,475	1904,6	674,1	1016,5
2053	2,955	755	2231,025	1904,6	674,1	1016,5
2054	2,955	765	2260,575	1904,6	674,1	1016,5
2055	2,955	776	2293,08	1904,6	674,1	1016,5
2056	2,955	786	2322,63	1904,6	674,1	1016,5
2057	2,955	796	2352,18	1904,6	674,1	1016,5
2058	2,955	802	2369,91	1904,6	674,1	1016,5

Table A2. Variable costs in crude steel production from sponge iron and total variable costs (Fixed costs of $4.5 billion are then added.)

Electricity usage (MWh/ton)	Electricity cost (SEK)	Other (SEK)	Total variable cost	SDR	Discounted variable cost
0,55	273,35	909,5	6246,685	1,03	6064,742718
0,55	278,85	909,5	6281,735	1,03	5921,137713
0,55	284,9	909,5	6320,29	1,03	5783,960678
0,55	290,4	909,5	6355,34	1,03	5646,637275
0,55	295,9	909,5	6390,39	1,03	5512,40655
0,55	301,95	909,5	6428,945	1,03	5384,140225
0,55	307,45	909,5	6463,995	1,03	5255,819464
0,55	312,95	909,5	6499,045	1,03	5130,406137
0,55	319	909,5	6537,6	1,03	5010,526029
0,55	324,5	909,5	6572,65	1,03	4890,66887

0,55	330	909,5	6607,7	1,03	4773,543069
0,55	336,05	909,5	6646,255	1,03	4661,549536
0,55	341,55	909,5	6681,305	1,03	4549,643593
0,55	347,05	909,5	6716,355	1,03	4440,301881
0,55	352,55	909,5	6751,405	1,03	4333,469961
0,55	358,6	909,5	6789,96	1,03	4231,278591
0,55	364,1	909,5	6825,01	1,03	4129,243293
0,55	369,6	909,5	6860,06	1,03	4029,562252
0,55	375,65	909,5	6898,615	1,03	3934,183739
0,55	381,15	909,5	6933,665	1,03	3839,002198
0,55	386,65	909,5	6968,715	1,03	3746,027702
0,55	392,7	909,5	7007,27	1,03	3657,041665
0,55	398,2	909,5	7042,32	1,03	3568,285434
0,55	403,7	909,5	7077,37	1,03	3481,597068
0,55	409,75	909,5	7115,925	1,03	3398,60541
0,55	415,25	909,5	7150,975	1,03	3315,869404
0,55	420,75	909,5	7186,025	1,03	3235,069809
0,55	426,8	909,5	7224,58	1,03	3157,695969
0,55	432,3	909,5	7259,63	1,03	3080,597582
0,55	437,8	909,5	7294,68	1,03	3005,311575
0,55	441,1	909,5	7315,71	1,03	2926,189958

Table A3. Exogenous Variables Regression



VARIABLES	(1) Price SE1	(2) Price SE1	(3) Price SE1	(4) Price SE3	(5) Price SE3	(6) Price SE3
Hydropower	-0.125***	-0.0261***		-0.115***	-0.0119	
	(0.0157)	(0.00964)		(0.0240)	(0.0137)	
Wind power	-0.0420**	0.0588***		0.0235	0.117***	
	(0.0212)	(0.0114)		(0.0323)	(0.0162)	
Nuclear power	-0.124***	-0.00711		-0.123***	-0.0100	
	(0.0170)	(0.00917)		(0.0259)	(0.0131)	
Solar	-0.0454	-0.157		0.619***	0.522**	
	(0.145)	(0.157)		(0.220)	(0.223)	
Electricity demand	0.0841***			0.0927***		
	(0.0188)			(0.0287)		
Mineral industry	-0.0209			-0.00465		
	(0.0355)			(0.0541)		
Wind	-8.621		2.739	-18.28		7.038
	(8.453)		(9.155)	(12.89)		(14.32)
Hydro reservoir	0.00138		-0.000450	0.00384		0.00102
	(0.00166)		(0.00176)	(0.00253)		(0.00275)
Rain	-0.324		0.0372	-0.618		0.322
	(0.302)		(0.343)	(0.461)		(0.537)
Temperature	-5.218**		-3.484***	-3.170		-3.845*
	(2.627)		(1.335)	(4.006)		(2.089)
Constant	693.3***	457.2***	315.8***	448.8	375.7***	287.2***
	(194.8)	(68.11)	(59.73)	(297.1)	(97.09)	(93.45)
Observations	338	338	338	338	338	338
R-squared	0.295	0.102	0.033	0.319	0.242	0.016

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

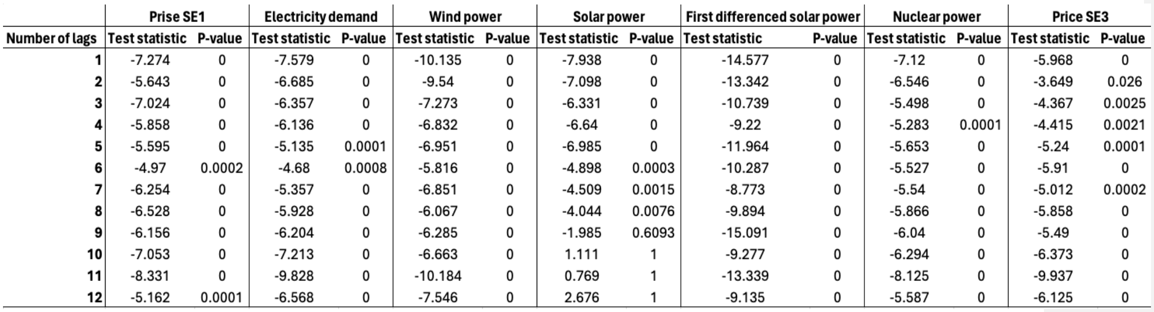
Table A4. Correlation between the variables

	Price SE1	**Hydro power**	**Electricity demand**	**Nuclear power**	**Solar power**	**Wind power**	**Tem-perature**	**Price SE3**
Price SE1	1							
Hydropower	-0.113	1						
Electricity demand	0.147	0.639	1					
Nuclear	-0.127	0.133	0.580	1				
Solar power	0.112	-0.082	-0.055	-0.340	1			
Wind power	0.280	0.104	0.368	-0.274	0.472	1		
Temperature	-0.180	-0.510	-0.881	-0.617	0.181	-0.138	1	
Price SE3	0.791	-0.017	0.181	-0.200	0.338	0.470	-0.110	1

Table A5. ADF 11 lags

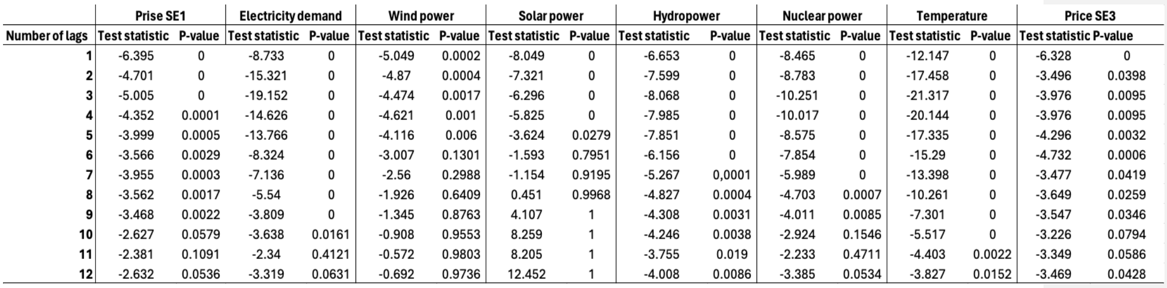
ADF of all variables, including 11 lags.			**ADF of all variables, including 11 lags and seasonal differencing.**		
Variable	**Test statistic**	**P-value**	**Variable**	**Test statistic**	**P-value**
Price SE1	-2.381	0.1091	Price SE1	-8.331	0
Hydropower	-3.755	0.019	Electricity demand	-9.828	0
Electricity demand	-2.34	0.4121	Nuclear power	-8.125	0
Nuclear power	-2.233	0.4711	Wind power	-10.184	0
Wind power	-0.572	0.9803	Solar power	0.769	1
Solar power	8.205	1	Price SE3	-9.937	0
Temperature	-4.403	0.0022	First-differenced Solar power	-13.339	0
Price SE3	-3.349	0.0586			

Table A6. Dickey fuller test results, including all lags



	Prise SE1		**Electricity demand**		**Wind power**		**Solar power**		**First differenced solar power**		**Nuclear power**		**Price SE3**	
Number of lags	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**
1	-7.274	0	-7.579	0	-10.135	0	-7.938	0	-14.577	0	-7.12	0	-5.968	0
2	-5.643	0	-6.685	0	-9.54	0	-7.098	0	-13.342	0	-6.546	0	-3.649	0.026
3	-7.024	0	-6.357	0	-7.273	0	-6.331	0	-10.739	0	-5.498	0	-4.367	0.0025
4	-5.858	0	-6.136	0	-6.832	0	-6.64	0	-9.22	0	-5.283	0.0001	-4.415	0.0021
5	-5.595	0	-5.135	0.0001	-6.951	0	-6.985	0	-11.964	0	-5.653	0	-5.24	0.0001
6	-4.97	0.0002	-4.68	0.0008	-5.816	0	-4.898	0.0003	-10.287	0	-5.527	0	-5.91	0
7	-6.254	0	-5.357	0	-6.851	0	-4.509	0.0015	-8.773	0	-5.54	0	-5.012	0.0002
8	-6.528	0	-5.928	0	-6.067	0	-4.044	0.0076	-9.894	0	-5.866	0	-5.858	0
9	-6.156	0	-6.204	0	-6.285	0	-1.985	0.6093	-15.091	0	-6.04	0	-5.49	0
10	-7.053	0	-7.213	0	-6.663	0	1.111	1	-9.277	0	-6.294	0	-6.373	0
11	-8.331	0	-9.828	0	-10.184	0	0.769	1	-13.339	0	-8.125	0	-9.937	0
12	-5.162	0.0001	-6.568	0	-7.546	0	2.676	1	-9.135	0	-5.587	0	-6.125	0

Table A7. Dickey fuller test result after seasonally differencing, including all lags



	Prise SE1		**Electricity demand**		**Wind power**		**Solar power**		**Hydropower**		**Nuclear power**		**Temperature**		**Price SE3**	
Number of lags	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**	**Test statistic**	**P-value**
1	-6.395	0	-8.733	0	-5.049	0.0002	-8.049	0	-6.653	0	-8.465	0	-12.147	0	-6.328	0
2	-4.701	0	-15.321	0	-4.87	0.0004	-7.321	0	-7.599	0	-8.783	0	-17.458	0	-3.496	0.0398
3	-5.005	0	-19.152	0	-4.474	0.0017	-6.296	0	-8.068	0	-10.251	0	-21.317	0	-3.976	0.0095
4	-4.352	0.0001	-14.626	0	-4.621	0.001	-5.825	0	-7.985	0	-10.017	0	-20.144	0	-3.976	0.0095
5	-3.999	0.0005	-13.766	0	-4.116	0.006	-3.624	0.0279	-7.851	0	-8.575	0	-17.335	0	-4.296	0.0032
6	-3.566	0.0029	-8.324	0	-3.007	0.1301	-1.593	0.7951	-6.156	0	-7.854	0	-15.29	0	-4.732	0.0006
7	-3.955	0.0003	-7.136	0	-2.56	0.2988	-1.154	0.9195	-5.267	0,0001	-5.989	0	-13.398	0	-3.477	0.0419
8	-3.562	0.0017	-5.54	0	-1.926	0.6409	0.451	0.9968	-4.827	0.0004	-4.703	0.0007	-10.261	0	-3.649	0.0259
9	-3.468	0.0022	-3.809	0	-1.345	0.8763	4.107	1	-4.308	0.0031	-4.011	0.0085	-7.301	0	-3.547	0.0346
10	-2.627	0.0579	-3.638	0.0161	-0.908	0.9553	8.259	1	-4.246	0.0038	-2.924	0.1546	-5.517	0	-3.226	0.0794
11	-2.381	0.1091	-2.34	0.4121	-0.572	0.9803	8.205	1	-3.755	0.019	-2.233	0.4711	-4.403	0.0022	-3.349	0.0586
12	-2.632	0.0536	-3.319	0.0631	-0.692	0.9736	12.452	1	-4.008	0.0086	-3.385	0.0534	-3.827	0.0152	-3.469	0.0428

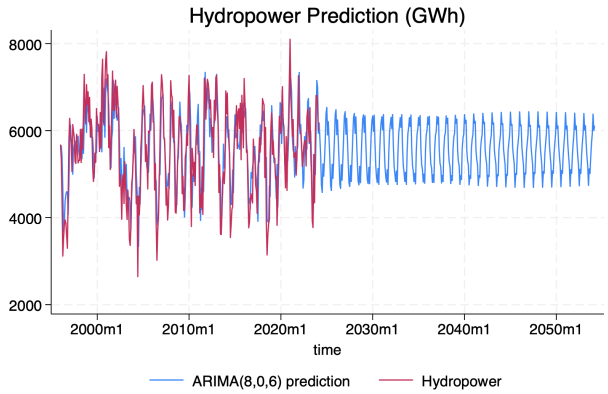


Figure A1. Predicted hydropower

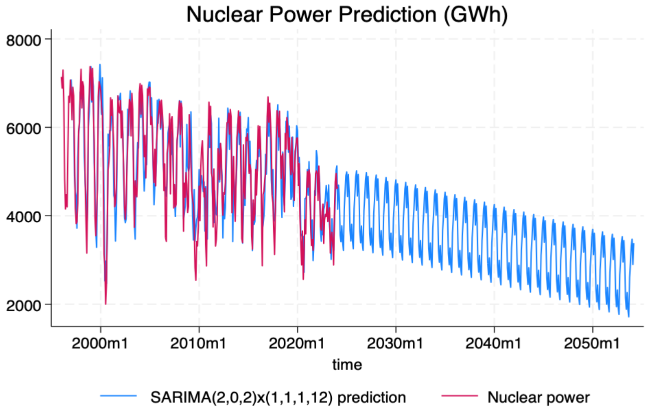


Figure A2. Predict Nuclear Power

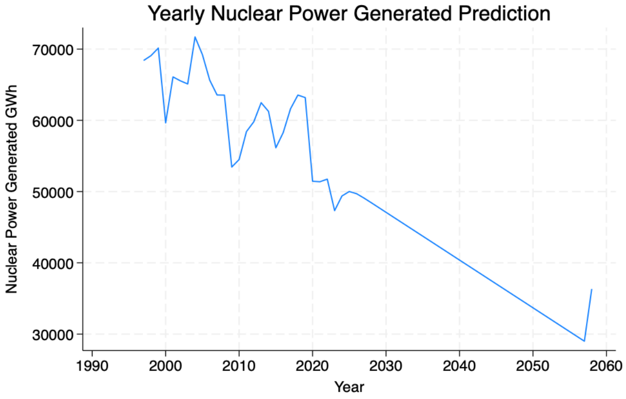


Figure A3. Predicted yearly sum of nuclear power generation

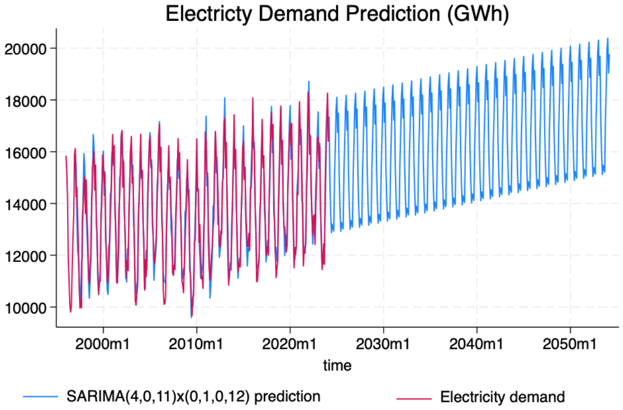


Figure A4. Predicted electricity demand

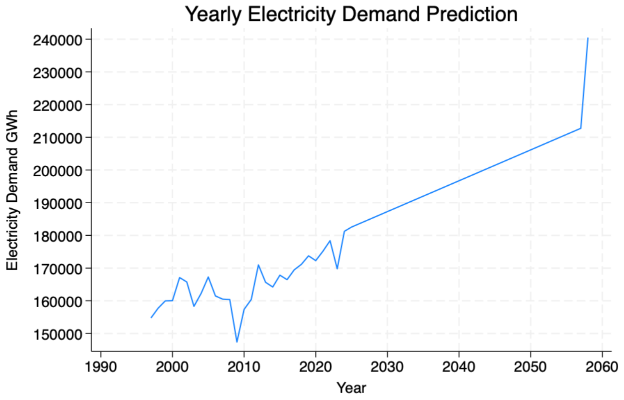


Figure A5. Total predicted energy consumption.

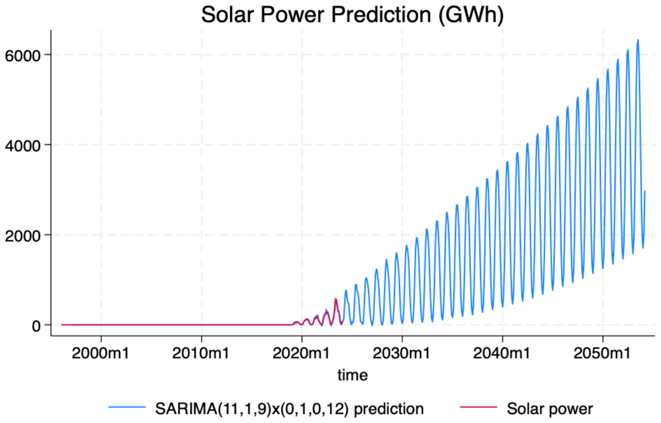


Figure A6. Predicted solar power

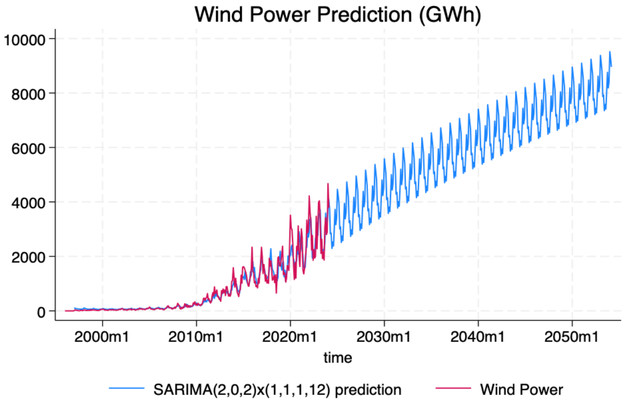


Figure A7. Predicted wind power

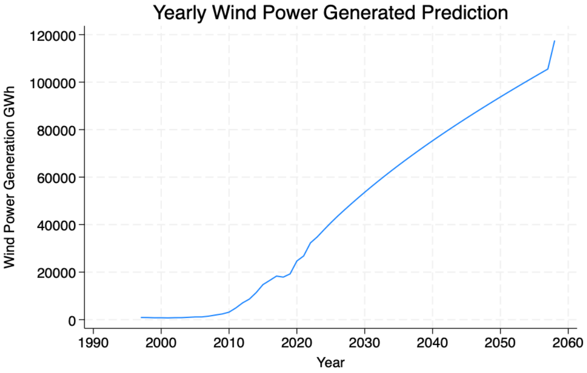


Figure A8. Yearly sum of wind power prediction.

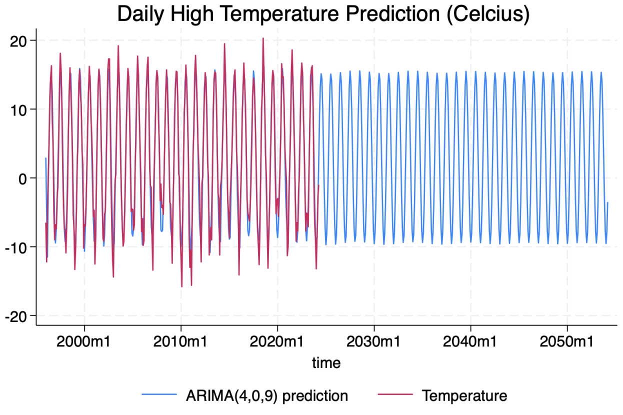


Figure A9. Predicted daily high temperature

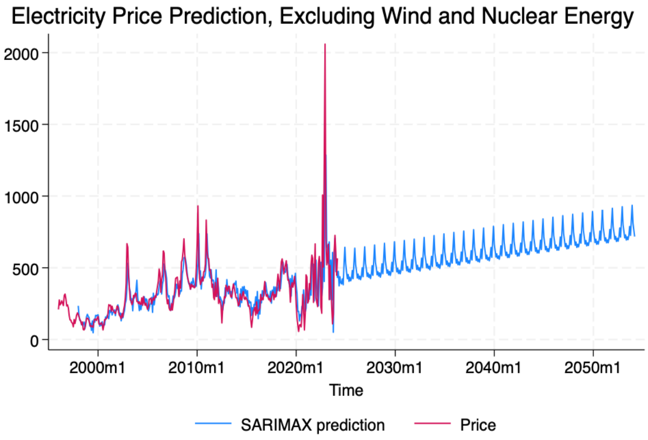


Figure A10. SARIMAX(2,0,2)x(1,1,1)$_{12}$ prediction excluding wind and nuclear power.

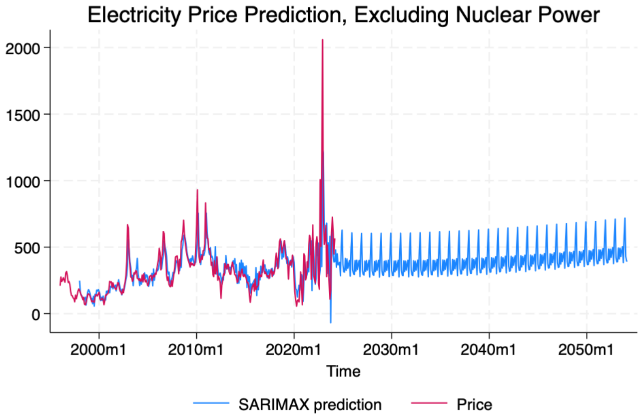


Figure A11. SARIMAX(2,0,2)x(1,1,1)$_{12}$ prediction excluding nuclear power.

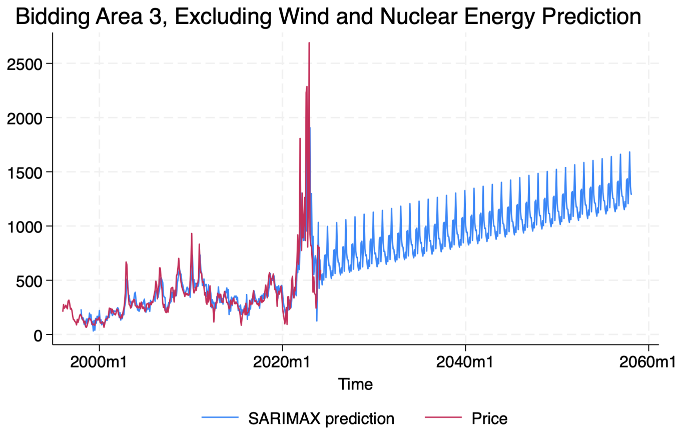


Figure A12. SARIMAX(2,0,2)x(1,1,1)$_{12}$ prediction excluding wind and nuclear power using bidding area 3 prices.

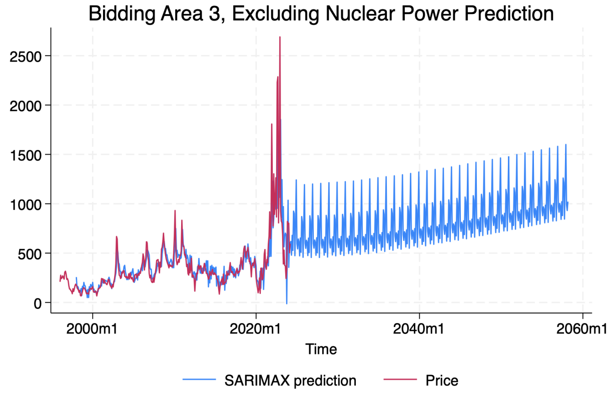


Figure A13. SARIMAX(2,0,2)x(1,1,1)$_{12}$ prediction excluding nuclear power using bidding area 3 prices.