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On the Way to Utilizing Green Hydrogen as an Energy Carrier—A Case of Northern Sweden

Jin Zhong [1,2] and Math H. J. Bollen [2,*]

1 Department of Electrical & Electronic Engineering, The University of Hong Kong, Hong Kong, China
2 Department of Engineering Sciences and Mathematics, Luleå University of Technology, 97187 Skellefteå, Sweden
* Correspondence: math.bollen@ltu.se

Abstract: Low or even zero carbon dioxide emissions will be an essential requirement for energy supplies in the near future. Besides transport and electricity generation, industry is another large carbon emitter. Hydrogen produced by renewable energy provides a flexible way of utilizing that energy. Hydrogen, as an energy carrier, could be stored in a large capacity compared to electricity. In Sweden, hydrogen will be used to replace coal for steel production. This paper discusses how the need for electricity to produce hydrogen will affect the electricity supply and power flow in the Swedish power grid, and whether it will result in increased emissions in other regions. Data of the Swedish system will be used to study the feasibility of implementing the hydrogen system from the power system viewpoint, and discuss the electricity price and emission issues caused by the hydrogen production in different scenarios. This paper concludes that the Swedish power grid is feasible for accommodating the additional electricity capacity requirement of producing green hydrogen for the steel industry. The obtained results could be references for decision makers, investors, and power system operators.

Keywords: carbon neutral; power transmission and power flow; hydrogen; Swedish power grid; carbon emission; renewable energy; energy carrier; electricity supply

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1. Introduction

Achieving low or even zero emissions of carbon dioxide ("carbon emissions" in short) is one of the world's urgent and essential missions. Transportation, electricity, and industry sectors are the major global carbon emitters. Other emissions are from commercial and residential activities, agriculture, land use, and forestry. A shift to a low-emission source is an essential part in the transition to a sustainable energy system. Wind and solar power are expected to play an important part in this shift from fossil-fuel-based to low-emission electricity production.

Fossil fuels have been used as the primary energy source for transportation, electricity generation, and industries for a long time. Replacing this with wind and solar power requires huge changes in the energy infrastructure.

The integration of wind and solar power introduces several major technical issues that risk becoming a barrier towards a zero-emission electricity system. The production capacity of wind and solar power is weather dependent (known as "intermittency"), which requires additional balancing sources at a range of time scales. The need for balancing is not new to the power system; electricity consumption is also intermittent; even the capacity for conventional production is uncertain over a range of time scales. The introduction of wind and solar power will, however, introduce new types of uncertainties to which the power system is not yet suitably designed. Once the intermittent renewable energy capacities reach a certain level, it is difficult to continuously supply the demand for generated electric energy. The reserve capacity and frequency regulation capacity used for real-time power balancing for a traditional power grid are not enough to match the differences between generation and consumption. This results in spatial and temporal gaps between the availability of electricity supplies and the consumption of end-users. Energy conversion and energy storage systems are the most promising ways to solve the problem and improve the utilization efficiency of renewable energy. Energy storage, at sizes that can match the capacity of wind and solar power, is a possible and often discussed solution. With sufficient energy storage, the need for real-time power balancing is no longer a critical issue.

Electricity can be stored mechanically (pump storage hydropower station, compressed air energy storage, flywheels), electro-magnetically (superconducting magnetic energy storage, super capacitor), electro-chemically (secondary batteries, flow batteries), etc. Pump storage hydropower stations and compressed air energy storage have been used in power systems to provide large-scale energy storage; however, they depend on the geographical availability of water ponds and underground caves. Flywheels and batteries have been used in some power systems for frequency regulation, demand response, etc. Their capacity sizes and battery lifecycles are the current limitations to their application in bulk electric energy supplies. Superconducting magnetic energy storages and supercapacitors could provide large-capacity energy storage and fast responses; however, they are currently not commercially available. Among various energy storage techniques, comprehensive evaluations are needed to decide which energy storage techniques are most suitable for different scenarios based all factors. For example, electricity price zones SE1 and SE2 are among the very few price zones in Europe that can directly produce green hydrogen using electricity from the power grid according to the regulations stated in [1]. Producing green hydrogen in SE1 and SE2 to replace fossil fuels used for the traditional steel industry in the area is a straightforward solution for a significant reduction in carbon emissions.

Energy storages provide flexibilities to an electricity system to accommodate more renewable energy sources. Hydrogen, produced from electricity, as an energy carrier, can be stored in tanks and transported by pipelines, trains, and roads. Hydrogen produced by electricity from renewable sources provides a solution to extend the renewable energy utilization to the transport sector and industry. By replacing fossil-based fuels, it becomes an important part of the transition to a zero-emission energy system.

Most power systems in the world nowadays are mixtures of fossil fuel generations and renewable energy generations. The electricity needed for producing hydrogen will require additional generation and transmission capacities. Moving the fuel supply for an industry from fossil fuel to hydrogen requires not only a new fuel supply system, but also the availability of sufficient, new, zero-emission power generation and transmission in the area.

In Sweden, the large metallurgical industry in Northern Sweden, in Västerbotten and Norrbotten, has committed itself to abandoning the usage of fossil fuels by the 2050s and, among other things, to completely shift from coal to hydrogen for steel production. The shift to hydrogen would require around 67 TWh of additional electricity per year. This is about one third of the annual electricity consumption in Sweden. Questions arising from this are as follows: (1) Will the new wind-power resources in Sweden be enough to support this additional electricity demand? (2) If hydropower and wind in Northern Sweden are used for hydrogen production, how will the power supply and electricity prices in Southern Sweden be affected? (3) Will the overall power flows in Sweden change? What are the impacts of that on the transmission grid? (4) What will be the impacts on electricity prices and emission export to other regions?

In this paper, using electricity generation and wind resource data of Sweden, we will study different scenarios to answer these questions, and discuss the feasibility of using green hydrogen for the metallurgical industry in Northern Sweden.

The paper is organized as follows: Section 2 introduces Swedish power systems. Section 3 proposes four scenarios for green hydrogen supply for Northern Sweden. The methodology is proposed in Section 4 for the feasibility study for the Swedish power grid to support the required green hydrogen. Major discussions are provided in Sections 5 and 6.

Finally, Section 7 briefly concludes the detailed discussions in Sections 5 and 6, as well as detailing future work.

2. Swedish Power Systems and Wind Energy Potential

2.1. Swedish Power Systems

The total electricity generation in Sweden was 164.4 TWh in 2019. Around 39.3% of this was from hydropower (64.6 TWh), 39.1% from nuclear and thermal power (64.3 TWh), 12.1% from wind power (19.9 TWh), and 9.5% from biomass, waste, and solar energy (15.6 TWh) [2].

The Swedish transmission system is composed of a 400 kV grid and a 130 kV grid. The 400 kV grid is owned and operated by the system operator Svenska Kraftnät. The Swedish electricity market is separated into four bidding zones (SE1, SE2, SE3, and SE4), as shown in Figure 1 [3]. The border of Northern Sweden (Västerbotten and Norrbotten counties) is marked with a bold yellow line in the figure. Västerbotten and Norrbotten counties are within the Bottenviken water district of Sweden. Electricity in Northern Sweden is mainly generated by hydropower stations along the rivers. There is a 400 kV transmission line along the Luleå river, and a number of 130 kV lines from the Luleå river southwards link the 400 kV grid with smaller hydropower stations and cities. The 130 kV grid in Northern Sweden is owned mainly by Vattenfall and Skellefteå Kraft.

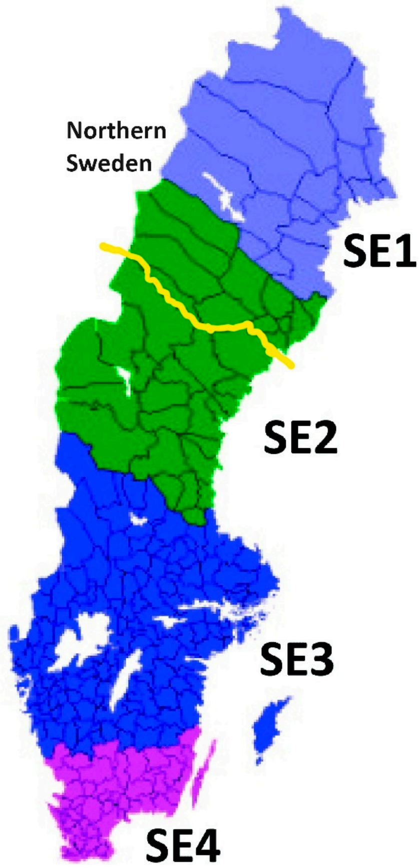

Figure 1. Swedish four electricity bidding zones and the region of Northern Sweden.

2.2. A Snapshot for Four SE Bidding Zones

The additional electricity amount of 67 TWh/year required for hydrogen production in Northern Sweden corresponds to a constant power of 7600 MW. This is calculated considering the storage capacity of hydrogen and hydropower, and the intermittency of wind power.

To study the possibility of having 67 TWh/year (or 7600 MW) electricity generation for the steel industry, we start with a regular power flow scenario in Nordic countries. Figure 2 shows a snapshot of the power flows. The electricity generation and consumption for SE1, SE2, SE3, and SE4 are calculated and marked in the figure. Generation is marked in each zone with the yellow/orange color. Consumption is marked in the box filled with the dark blue color. The summary of the data is shown in Tables 1 and 2.

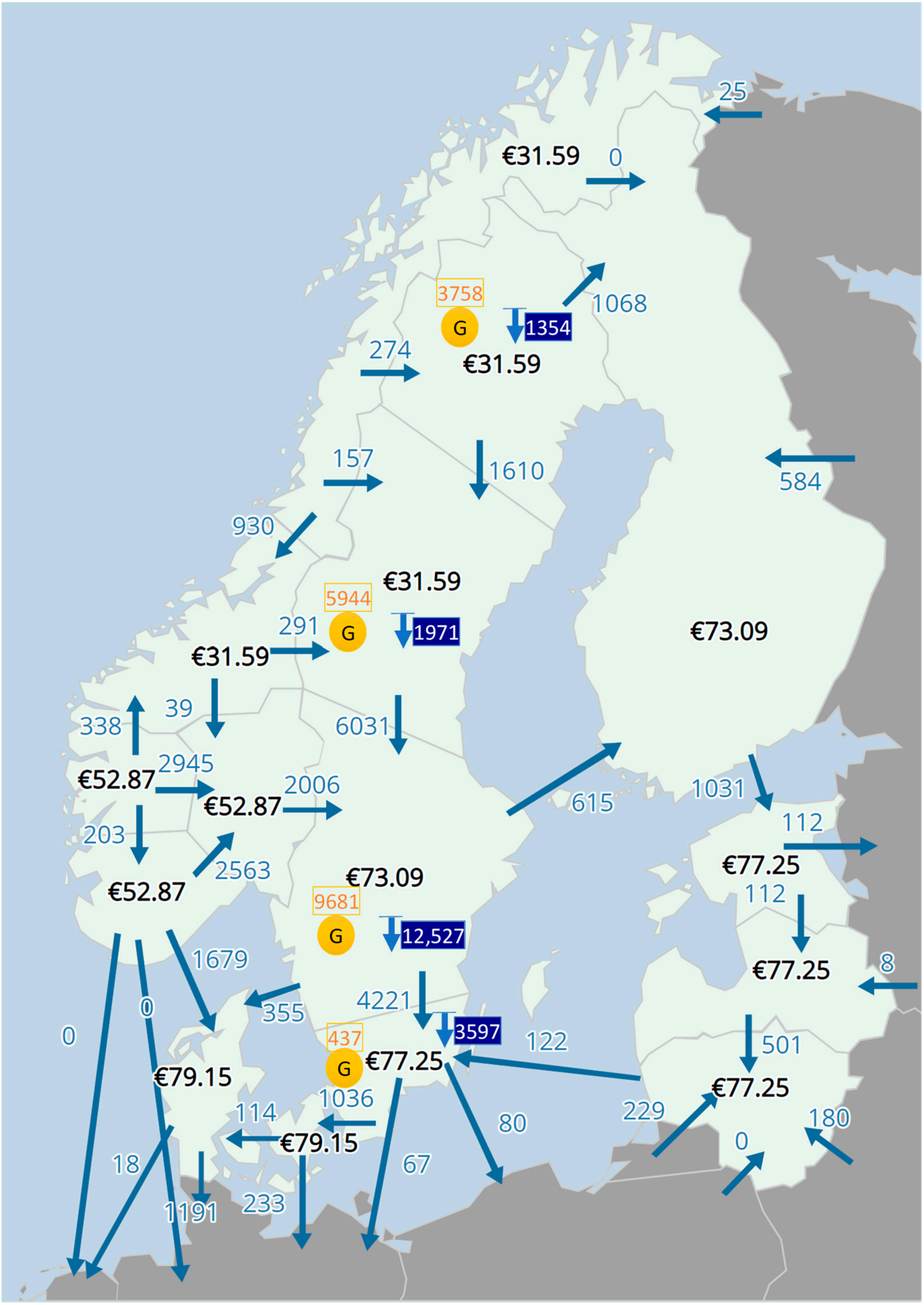

Figure 2. The snapshot of power flow, production, consumption, and prices in four SE bidding zones on 18 March 2021, 7:19 (https://www.svk.se/drift-av-transmissionsnatet/kontrollrummet/ (accessed on 18 March 2021)).

Table 1. Generation, demand, and zonal prices for a snapshot of Swedish price zones.

Price Zone	Generation (MW)	Demand (MW)	Zonal Price (in Euro)
SE1	3578	1354	31.59
SE2	5944	1971	31.59
SE3	9681	12,527	73.09
SE4	437	3597	77.25

Table 2. Power flow between Swedish price zones.

From	To	Power Flow (MW)
SE1	SE2	1610
SE2	SE3	6031
SE3	SE4	4221

At this instant, the Northern Sweden (region SE1) exports 1068 MW to Finland and 1610 MW to Southern Sweden; meanwhile, 274 MW is imported from Norway. The online operation data are obtained from the Swedish system operator, Svenska Kraftnät [4]. The price difference between SE2 and SE3, with electricity more than twice as expensive in Southern as in Northern Sweden, indicates that the power flow (6031 MW) between SE2 and SE3 has reached the limit of the transmission capacity. It is less than the 7600 MW that is continuously needed for reaching 67 TWh/year. This means that adding 7600 MW of consumption in SE1, without adding new production, results in there being almost no electricity left for transporting to Southern Sweden (SE3 and SE4). Southern Sweden would have to import electricity produced from coal on the continent and there would be no net global saving in emissions. This results in the marginal emission issue. New renewable energy production is therefore needed for hydrogen production without additional carbon dioxide emissions.

2.3. Hydropower Potential in Northern Sweden

In Northern Sweden, electric energy is generated by hydropower stations on several rivers. Transmission lines are built along the rivers. The other green energy resources are biomass and wind power.

According to [5], the total installed capacity of hydropower stations on the rivers are as follows:

- Luleå river: 4365 MW;
- Skellefteå river: 1070 MW;
- Umeå river: 1807 MW.

The total of the above is 7242 MW.

The simple calculation above shows that if electric energy generated by existing local power plants in SE1 and SE2 are used for producing hydrogen, there is no electricity left to transport to the south. New renewable energy generation capacity is needed. As the water reservoir capacity has reached the limit, wind power, bioenergy and solar energy will be used.

2.4. Wind Energy Potential in Sweden

The next questions are whether Sweden has enough wind-power resources to cover the additional 67 TWh/year and where should the wind-power electricity come from? Reference [6] uses a detailed GIS-based method studying the distribution of available wind energy resources in Sweden. Selecting only those clusters with 80% land availability in clusters of at least 3 km^2, within a 10 km distance of power grids, the total wind energy potential in Sweden is around 205 TWh. Among the 205 TWh wind energy, bidding zone SE1 has 59 TWh, SE2 has 109 TWh, SE3 has 35 TWh, and SE4 has 2 TWh. The total wind energy in grid cells with 80% land availability in clusters of 3 km^2 are also provided by

Västerbotten county and Norrbotten county in this paper. It shows that wind energy potential in Norrbotten is 46 TWh and in Västerbotten is 45 TWh [6]. The numbers show that the potential wind energies in Norrbotten and Västerbotten are enough to cover the 67 TWh needed for water electrolysis for hydrogen production.

3. Four Scenarios for Green Hydrogen Supply

The security of the green energy supply depends on the availability of wind resources, the transmission capability of the power grid, the form of energy storage, etc. As discussed above, the availability of wind-power resources in Sweden is high enough. The locations of new wind-power capacities affect the methods of energy transport. We use four scenarios as examples to discuss the impacts of wind farm locations. Scenarios I and II assume energy is transported in the form of electric energy. Scenario III assumes the energy is transported in the form of hydrogen, and Scenario IV is a combination of the other scenarios. Four scenarios are introduced in the following subsections, and the calculations of power flows for Scenarios I and II and provided in Section 4.

3.1. Scenario I: New Wind Power Only in SE1 and SE2

In this scenario, we assume all hydropower generation and wind-power generation in Norrbotten and Västerbotten are used for local electricity demand and hydrogen production for the metallurgical industry (LKAB and SSAB). The transmission corridor between SE2 and SE3, and the electric energy transport to SE3 will remain as before. The local power grid to LKAB and SSAB might need to be strengthened if energy is to be transported in the form of electric energy. The hydropower and wind power in other counties of SE2 will be responsible for electric energy export to the south. There is a possibility that the power flow between SE1 and SE2 is reduced or even changes the direction.

3.2. Scenario II: New Wind Power in All Four Zones over the Country

This scenario assumes that new wind power is distributed all over the country. The new wind-power generations in SE3 and SE4 (both on-shore and off-shore) will increase the electric generation sources in the south. The pressure on the transmission corridor between SE2 and SE3 could be reduced. The amount of electric energy transport to the south could also be reduced. The hydropower generation and wind-power generation in SE2 will be transported to SE1 to supply additional energy use for LKAB and SSAB. The power flow direction may be changed to "from SE2 to SE1". SE1 may become a new load center. The transmission corridor between SE2 and SE1 may become a bottleneck. If this is the case, it is possible that electricity prices in SE1 may sometimes be higher than in SE2.

3.3. Scenario III: Hydrogen Is Produced Close to New Wind Farms

This scenario assumes that existing power grid operation is maintained the same as before, and most new wind-power capacities are not connected to the grid. Hydrogen is produced close to wind farms and stored locally. Hydrogen is then transported through pipelines and by road to LKAB and SSAB. This requires constructions of new transportation infrastructures. The storage and transport of hydrogen and its safety will be the major challenge.

3.4. Scenario IV: A Combination of the above Scenarios

The combination of the above scenarios will most probably happen during the constructions of wind farms and hydrogen storage and transportation facilities. Some new wind farms are connected to the power grid; this may affect power flows and requires strengthening of the local power grid. The other new wind farms are not grid connected and produce hydrogen directly as a product. The hydrogen is delivered to customers by pipelines and road transportation.

With new wind-power capacities, and hydrogen storage and transportation, there are impacts on power system operation. (1) Power flow and its direction may be different than before, and Svenska Kraftnät may need to adjust the dispatch method; (2) The storage of hydrogen provides a new energy storage form in addition to hydropower water storage. This increases the total energy storage capacity of the country to compensate for wind-power fluctuation, as well as providing power balancing and regulation services for the power grid operation.

How much energy is transported in the form of electric energy (requires power grid strengthening) and in the form of hydrogen (requires pipeline and road infrastructure) is a complicated optimization problem with multiple sectors involved.

4. Feasibility Analysis for the Swedish Power Grid Supporting Green Hydrogen Production

In this section, we study whether the existing transmission corridor in Sweden can support Scenario I and Scenario II. We draw the following conclusions based on the analysis shown in Figures 3 and 4. If all new wind power is installed in SE1 and SE2, the existing transmission corridor between SE1 and SE2 is sufficient. Norrbotten becomes a heavy electric load center. If new wind power is evenly distribution in the north (SE1 and SE2) and the south (SE3 and SE4), the transmission pressure on the corridor between SE2 and SE3 is actually released. More hydropower in the north will be used for local electricity consumption. In both scenarios, the existing transmission capabilities of the corridors between the bidding zones are sufficient. The local power grid within the bidding zones might need to be strengthened, especially close to the locations of new wind farms and the increased electricity demand.

Figures 3 and 4 illustrate Scenario I and Scenario II, respectively, based on the snapshot of the power flows shown in Figure 2, assuming the new electricity demand for producing hydrogen is around 7000 MW, and new wind power is marked in green with the wind turbine logo in the figures.

In Figure 3, the assumption is made that the electricity load of the steel industry is located in SE1 with a continuous electricity demand of 7000 MW. New wind power is installed only in SE1 and SE2. The wind power in each area can continuously provide 3500 MW electricity (coordinated with hydropower and energy storage) to supply the new electricity consumption in SE1, without affecting the power flow to the south. It is calculated that the power flow between SE1 and SE2 will change direction, and an amount estimated to be around 1890 MW will flow from SE2 to SE1. SE1 becomes the load center in this case. The transmission corridor is okay to support this amount of power flow.

In Figure 4, an assumption is made that the electricity load of the steel industry is supplied by new wind power distributed in the whole country. New wind power in SE1, SE2, and SE3 will be 2000 MW, 3000 MW, and 2000 MW, respectively. This assumption has the benefit that SE3, as the conventional load center, will have some new generation resources, which will release the burden of a heavy power flow from the north to the south. The bottleneck between SE2 and SE3 could be released, and hence lower the electricity prices in SE3 and SE4. With this assumption, it is calculated that the power flow between SE2 and SE1 is around 3390 MW. If this amount is higher than the capability of the transmission corridor, more wind power could be installed in SE1 or use stored hydrogen. The power flow between SE2 and SE3 will be around 4031 MW, which is significantly reduced compared to the current situation, and the bottleneck is released.

To conclude from the above analysis, it appears to be feasible to design a power and hydrogen system that can supply the needs of the steel industry in Northern Sweden, as well as the needs of the rest of the country. However, there are many degrees of freedom and several commercial actors involved, which requires collaboration in order to find the global optimum solution that minimizes the negative impacts (cost, environment, convenience, etc.) for all parties and maximizes the environmental benefit.

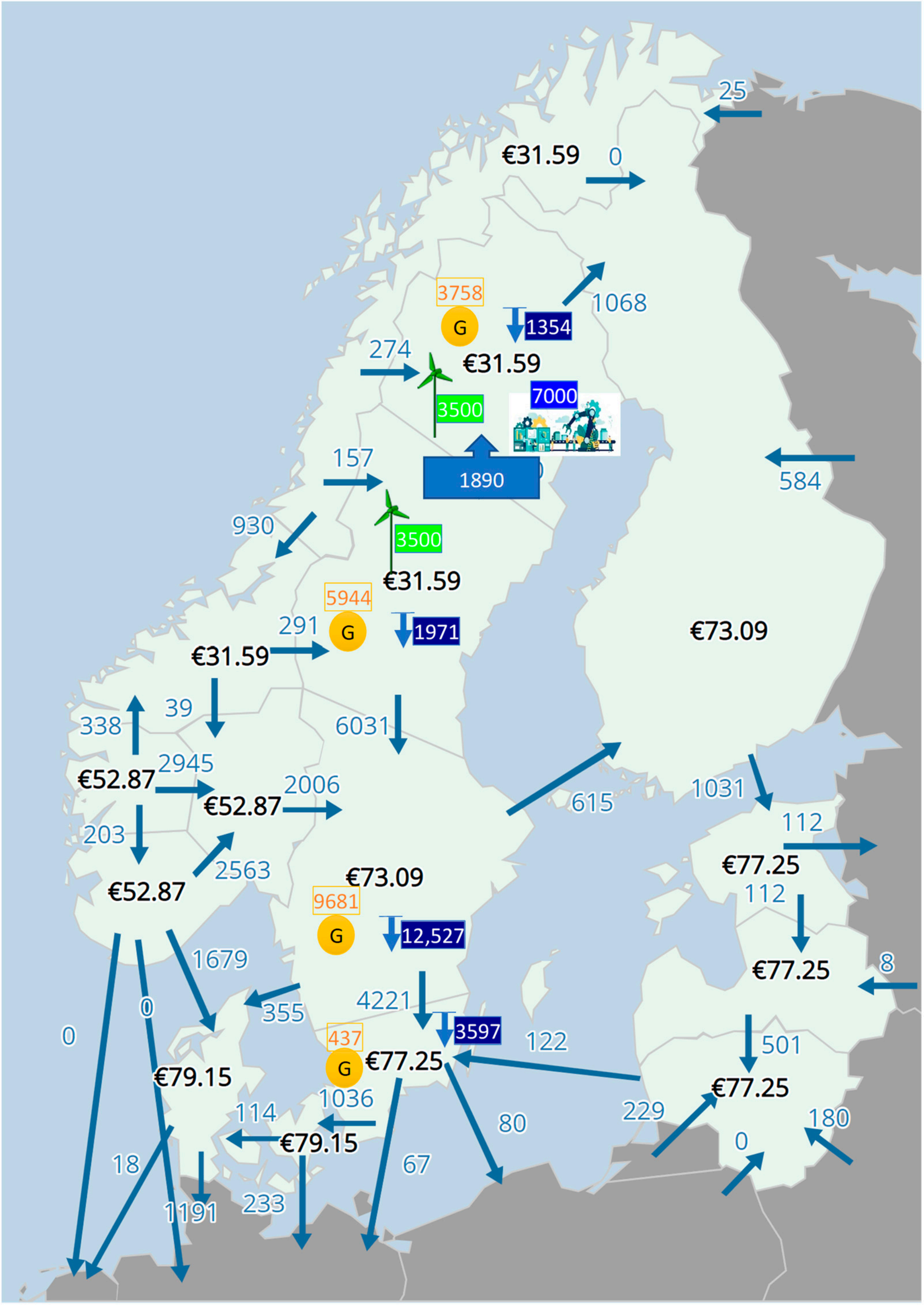

Figure 3. The snapshot of power flow, assuming new wind-power stations are installed in SE1 (3500 MW) and SE2 (3500 MW).

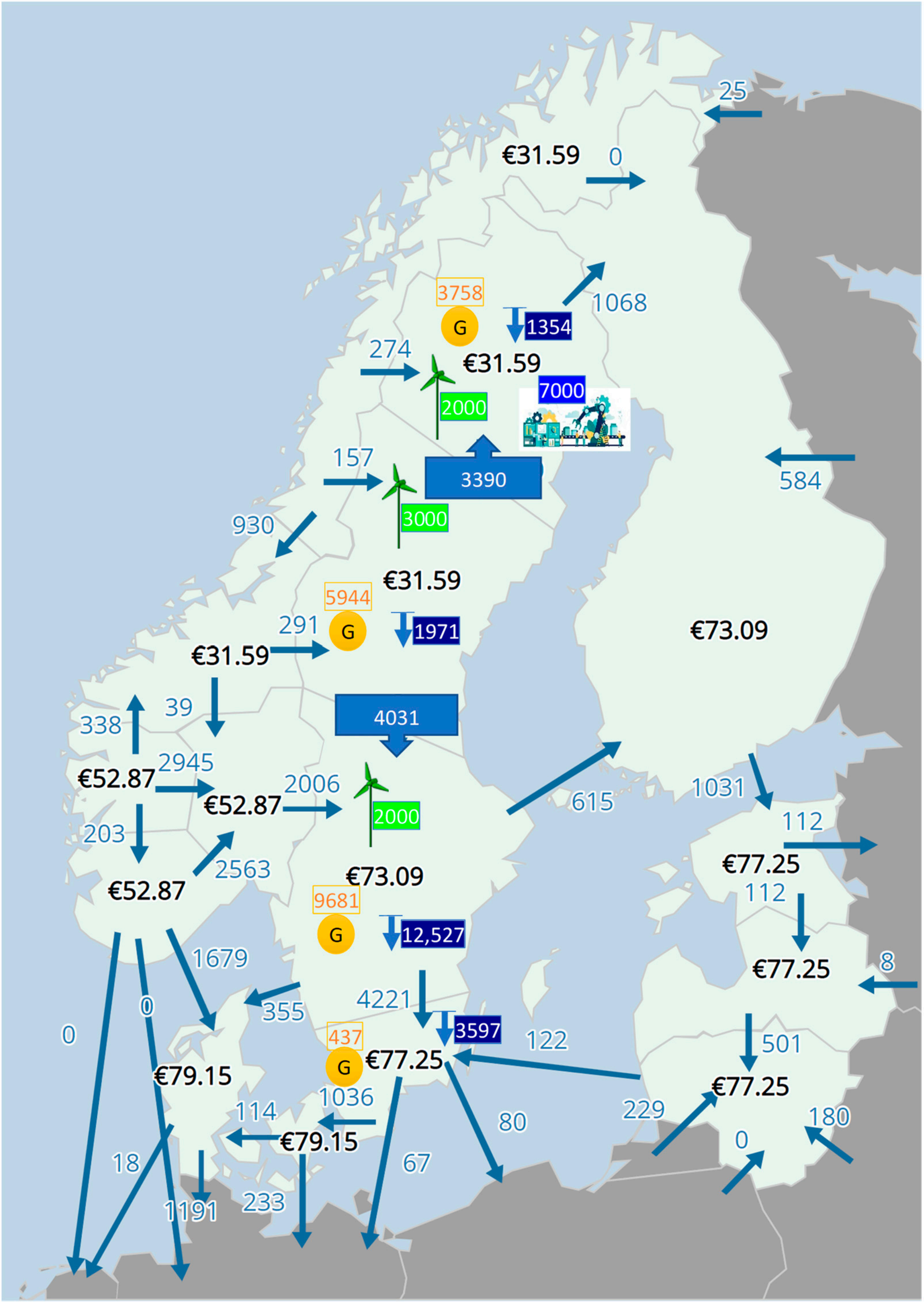

Figure 4. The snapshot of power flow, assuming new wind-power stations are distributed in SE1 (2000 MW), SE2 (3000 MW), and SE3 (2000 MW).

5. Impacts on Electricity Prices and Emission Export Due to the Implementation of the Hydrogen Plan

According to the rules set in Article 7(2) of Directive (EU) 2018/2001 [7] and in [1], currently, the hydrogen produced by electricity withdrawn from the SE1 and SE2 zones within the power grid is defined as green hydrogen. The above analysis assumes that 7000 MW of new wind power is installed. However, building wind farms takes time. If the increased electricity demand (for example, for hydrogen production) will grow faster than wind-power production, some of the hydrogen will be produced by electricity generated by fossil fuels, or imported from fossil-fuel-generation-dominated regions or countries. The hydrogen procured would result in a net export of carbon emissions to other regions. In this section, we discuss the impacts of the new hydrogen demand on electricity prices, and the emission export issues due to the hydrogen plan before the required renewable capacity is fully installed.

5.1. Impacts on Electricity Market Prices

The transition of traditional fuels to hydrogen significantly increases the electricity demand in SE1. It is possible that SE1 will become a new load center. Zonal prices in Sweden may be affected once SE1 becomes a new load center. Power flow and its direction may be different than before. The dispatch method may have to be adjusted. SE2 will export electricity to both SE1 and SE3. Most probably, the zonal price of SE1 will become higher than before.

The storage of hydrogen provides energy storage in addition to hydropower. This increases the total energy storage capacity of the country to compensate for the fluctuation in wind power, as well as providing power balancing and regulation services. The storage capacity of hydrogen could be used for peak shaving and hence lower the electricity peak prices.

5.2. Emission Export Issues

If the hydrogen is procured from SE3 and SE4 (before new wind capacities are fully installed), or in a neighboring country, such as Finland, the additional dispatch of fossil-fuel-based generations, will result in additional carbon emissions outside of Northern Sweden. Although it is clean for the steel factories in Northern Sweden, carbon emissions are exported to other regions. Applying a carbon tax/carbon price and carbon footprint in hydrogen trading could be one of the solutions to having the export of emissions counted in decision making.

The carbon emission export cannot be eliminated unless enough renewable capacities are installed to cover the need for hydrogen production. The "marginal" concept has been utilized for electricity pricing in the traditional electricity market. Similarly, the marginal emissions of a system depend on the carbon emissions of the system's marginal unit. Carbon emissions and green energy utilizations are considered separately in the carbon trading market and hydrogen market. Meanwhile, the real-time electricity market does not reflect the values of energy storages provided to the energy system, and there are not enough incentives for conversions of different types of energy forms.

To reach the goal of higher utilization of green energy and lower carbon emissions, interactions between the markets of electricity, hydrogen and carbon are needed. A future energy market design should include all types of energy trading and carbon trading, as well as carbon footprint indications.

6. Energy Storage in the Form of Hydrogen and Electrofuels

Sweden has a large hydropower reservoir, which provides flexible capacities to wind-power fluctuations. In practice, a portion of energy consumption can be supplied by bioenergy, which is abundant in Sweden. The hydrogen produced during the hours with surplus wind power can be stored in the form of H_2 gas and electrofuels. The stored gas can produce electricity by a fuel cell or gas turbine. The storage of hydrogen and electrofuels extend the energy storage capability of the Swedish energy system.

With the large storage capacity of hydropower reservoirs and new energy storage capacities in the form of H_2 gas and electrofuels, the daily variation in wind power is not an issue for energy supply. The water storage in reservoirs will coordinate well with wind-power generation. Furthermore, the storage of hydrogen or electrofuels could further increase the safety margin during the weak wind periods. The relationship between the safety margin and the amount of hydrogen or electrofuel storage could be calculated once the scenarios of wind-power locations are determined. It is expected that distributed energy storage (hydrogen and electrofuel) in a wide area will be more efficient to coordinate with distributed wind power, and will have less of a requirement on the power grid transmission capability.

Storing wind power in the form of hydrogen or electrofuels has more advantages and could provide more flexibility than traditional hydropower reservoir storage.

- Energy stored in the form of hydrogen or electrofuels can be used to generate electricity (storage discharge) during peak periods in electricity consumption. Storage tanks can be charged during off-peak periods or strong-wind periods and discharged during peak periods. They could be used to reduce the daily peak in consumption.
- Energy stored in tanks could be transported in other ways than through the power grid. This releases the pressure on the transmission grid, and it is not necessary for it to be limited by the real-time power balance.
- Storing renewable energy in the traditional fuel form for a relatively longer time can guarantee the energy security of the society, and reduce the influences of a global energy crisis and energy price fluctuations.

7. Conclusions and Future Work

It is concluded that it is feasible for the Swedish power grid to add 67 TWh of electricity consumption for producing hydrogen. The power flow, dispatching mode, and electricity prices will be affected by the new demand of hydrogen production. It is necessary to install 67 TWh of wind power to avoid a net export of emissions. The impacts on electricity prices and issues of emission export have been discussed in detail in Sections 5 and 6.

The approach presented here can also be applied to other countries and regions with a shift to low-carbon processes or activities with increased electricity needs.

This paper focuses on the technical feasibility analysis of Swedish power grid operation for replacing fossil fuels with hydrogen for the Northern Swedish steel industry. Another important issue for practical implementation is cost evaluation, which is the next step and the subject of future work.

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