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Economic and environmental costs of replacing nuclear fission with solar and wind energy in Sweden

Sanghyun Hong[a,*], Staffan Qvist[b], Barry W. Brook[a]

[a] Faculty of Science, Engineering & Technology, Private Bag 55, University of Tasmania, Hobart 7001, Australia
[b] Department of Physics and Astronomy, Uppsala University, Sweden

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ABSTRACT

Nuclear power is facing an uncertain future in Sweden due to political directives that are seeking to phase out this energy source over coming decades. Here we examine the environmental and economic costs of hypothetical future renewable-energy-focused cases compared with the current nuclear and hydroelectricity-centred mix in Sweden. We show that if wind and photovoltaics replace entire nuclear power while maintaining the current level of dispatchable backup capacity including hydroelectric power and peak gas power, 154 GW of wind power will be required and will generate 427.1 TWh (compared with the actual demand of 143.7 TWh) to reliably meet demand each hour of the year. As a consequence, the annual spending on electricity systems will be five times higher than the *status quo*. Increasing dispatchable power, increasing transmission capacities to other countries, and generating electricity from combined heat and power plants even when there is no heat demand, will together reduce the required capacities of wind and solar photovoltaic by half, but it will double the greenhouse-gas emissions during the combustion process. In conclusion, our economic and greenhouse-gas emissions analyses demonstrate that replacing nuclear power with renewables will be neither economic nor environmentally-friendly with regards to the climate.

1. Introduction

The electricity generation sector in Sweden has changed dramatically in the almost half-century since the first nuclear reactor started to operate (IEA, 2016a), with consumption more than doubling, from 65 TWh in 1971–150 TWh in 2014 (Swedish Energy Agency, 2015). However, unlike many other nations, where increasing fossil-fuel consumption has been required, Sweden is one of few countries (along with South Korea, Germany, France and Japan) that historically selected a nuclear power expansion program as the principal energy source for meeting demand growth (Cherp et al., 2016). In 2014 in Sweden, nuclear power generated 63.8 TWh and hydroelectricity 61.7 TWh, with the sum of all the other sources (wind, solar photovoltaic, biofuels and gas) amounting to 24.4 TWh ($<$ 16.3% of the total electricity generation). Wind, in particular, provided a 7.5% share in 2014. The greenhouse-gas emissions of electricity and heat production in Sweden vary over time during the last three decades (SCB, 2016). The largest amount of greenhouse-gas emissions was 13.5 Mt CO_2e in 1996, and the smallest amount was 6.4 Mt CO_2e in 2015. The energy sectors including electricity, heat production and transport (excluding the emissions of industry and agriculture) emitted 29.1 MT CO_2e in 2015.

In 1980, the Swedish government decided to phase out nuclear power following the nuclear referendum (WNA, 2017). However, the decision was revoked in 2010 (WNN, 2017), and the debate on the use of nuclear power is still ongoing. Recently, several Swedish political parties are arguing for a rapid transition away from nuclear in the Swedish electricity system (Qvist and Brook, 2015). Although it might seem possible to replace a unit of nuclear power generation with a unit of renewable generation, technical and economic barriers exist if the penetration of intermittent power grows large (Amoli and Sakis Meliopoulos, 2015; Huber et al., 2014). A large share of non-dispatchable renewables will require substantial backup generation capacity, as well as additional transmission capacity, if reliable power and grid frequency are to be maintained, unless Sweden attempts to rely on the remainder of the European grid to cover peak demand. We also noted that the phase-out of nuclear policies in Sweden and is not driven primarily by environmental or economic concerns, but they are based on political decisions or a lack of public acceptance (Qvist and Brook, 2015).

Recently, a study evaluated the possible environmental consequences of replacing nuclear power generation with wind and lower-carbon fossil systems in Sweden (Wagner and Rachlew, 2016). This

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[*] Corresponding author.
E-mail address: Sanghyun.hong@utas.edu.au (S. Hong).

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study examined the required capacity and operation strategies of backup power (natural gas), the role of energy storage and the operational conditions of hydroelectric power systems. The key finding of the study is that to replace 63.8 TWh of electricity generation from nuclear power (9 GW peak capacity) 22.3 GW of wind along with 8.6 GW of gas backup would be required, generating 64.8 TWh (with small spillage). The CO_2 emissions of such the proposed scenario were estimated to be twice that of the *status-quo* generation and demand conditions. The Wagner and Rachelew (2016) paper was an important contribution that highlighted the difficulty in replacing nuclear power without increasing environmental impacts. However, the study did not consider five key aspects of system viability: (1) the transmission limitation between internal geographic bidding areas, (2) the economic costs of the transformation, (3) the seasonal water inflows for hydroelectric power, (4) the potential contribution of solar photovoltaic, if installed at a large scale, and (5) the role of distributed bioenergy if electricity and heat production processes are decoupled.[1]

The Carbon-Neutral Scenario (CNS) was published by the IEA in 2016 which was aiming a near carbon-neutral energy system in the Nordic region by 2050 (IEA, 2016b). The report concluded that wind could replace both fossil fuels (coal) and nuclear by increasing the wind share from 7% to 30% by 2050. Nordic countries would then export 53 TWh of electricity to the rest of Europe. Sweden would phase out all nuclear fleets by 2050 while increasing wind capacity up to 31.4 GW by 2050. The results of this report have two serious issues that should be addressed. First, the high penetration of variable renewables, mostly wind, will require technical (e.g., energy storage and backup power) and economic (e.g., demand response and market mechanisms) balancing mechanisms. Second, for the expansion of wind, the interconnection between Nordic countries and with other European countries will require substantial upgrades.

In our analysis, we presented ‘alternative present’ cases based on the current electricity demand profile to reduce any uncertainties due to technological and economic changes, and assumptions for more complex modeling works. Our modeling is underpinned by transparent and objective optimization algorithms. First, we determined the electricity capacity and generation required to replace nuclear power generation with wind and solar power using public data from Sweden (SMHI, 2015; Swedish Energy Agency, 2015). We then estimated the annual electricity cost using the levelized cost of each electricity generation option, as reported in by the Swedish Government Energy Commission (Energikommissionen) (2016) and NREL (2016) reports, and the greenhouse-gas emissions of electricity based on the Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). We also modeled a range of variations that could affect the electricity system in Sweden, such as the initial reservoir levels of hydroelectric power dams, the installed dispatchable backup capacity, and both the international transmission capacity and interconnector flow between bidding areas in Sweden. Our aims were to: (i) compare the greenhouse-gas emissions and electricity costs of the *status quo* and hypothetical renewable-energy-focused cases, and (ii) identify any alternative presents using renewables that avoid increasing annual costs or greenhouse-gas emissions.

2. Methodology

2.1. Assumptions

We included on-shore wind and photovoltaic solar power to replace nuclear power output. We also assumed that renewable energy resources are not limited by geographical, legal or economic barriers in Sweden. Although there are other renewable options such as off-shore wind power and concentrating solar power, these options were excluded from this analysis on the grounds of economic competitiveness and low solar irradiation levels (Köberle et al., 2015). Although the electricity price of solar photovoltaics is also currently economically unviable in Sweden (Köberle et al., 2015), we included this source for its potential ability to complement periods when wind output is extremely low or zero, while backup power sources are fully exploited. Energy storage is likely to reduce required backup capacity and provide balancing services in many countries in the future (Palizban and Kauhaniemi, 2016). However, because of the country's extensive hydroelectric power resources, which provide system flexibility, it is unlikely to play a large role in Sweden (Huber et al., 2014). Based on the constraints listed above, the most cost-competitive mix for each energy-system condition, for a range of cases, was optimized using a simulated annealing algorithm.

Currently, the Swedish electricity grid is divided into four geographic bidding areas (Swedish Energy Agency, 2015). The bidding areas, including SE1, SE2, SE3 and SE4, are connected via high-voltage transmission lines. Sweden is also linked to neighboring nations through high capacity transmission lines including Denmark, Norway, Finland, Lithuania, Poland, and Germany. The maximum capacities (GW) of the transmission lines are considered to be a physical limitation for intra-national and international transmission. We treated the international connection as primary ‘batteries’ that will supply electricity when it is required. The total amount of electricity that the other nations can supply is determined from the historical electricity inflow from neighboring nations between 2011 and 2013 (SMHI, 2015).

2.2. Data

We anchored our cases in actual hourly generation, consumption and weather data from each bidding area for the years 2014. We obtained the wind speed from 98 stations and solar irradiation values from 14 stations (SMHI, 2015). We then modeled the hourly wind and photovoltaic output profile of each site and averaged these to obtain the power output of each bidding area. We adjusted the hourly wind speed data measured from the height of weather stations to the wind power station's hub height (120 m) using a wind-gradient equation:

$$V_{hub}(h) = V_m{*}(h_{hub}/h_m)^a \tag{1}$$

where V_m = obtained wind speed, V_{hub} = estimated wind speed at the hug height, h_{hub} = hub height, h_m = measured height, and a = the Hellman exponent (Hong et al., 2013). The power output at hub height from the wind speed at the hub height was estimated using the wind speed and power equation.

$$P = 0.5{*}V_{hub}^3{*}\pi r^2{*}C_p{*}\rho \tag{2}$$

where p = wind power output, r = length of a blade (68 m), C_p = efficiency (40%), and ρ = density of air (1.23 kg m^{-3}). For the calculation, we applied 3 m s^{-1} for the cut-in and 25 m s^{-1} for the cut-off speed of the wind turbines. The modeled wind power station reaches the maximum power output when the wind speed reaches 15 m s^{-1} (rated wind speed) (Vestas, 2016). The wind power output is normalized to between 0 (minimum) and 1 (maximum) to be multiplied by the installed wind capacity of each model.

For solar photovoltaic, we used the power output information of the BP 280 W photovoltaic module, with normal operating assumptions (BP Solar, 2011). The hourly water inflow data for hydroelectric power plants were estimated from the weekly inflow data obtained from Svensk energi (2015a), spread equally across 168 h. The generation capacity and fuel consumptions are from Svensk energi (2015a) and IEA (2016a).

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[1] Due to economic reasons, combined heat and power plants in Sweden are operated during winter seasons to produce both electricity and heat. However, in our modeling, we assumed that combined heat and power plants can be operated either to produce both electricity and heat or to generate only electricity.