Energy Policy 84 (2015) 1–10

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Environmental and health impacts of a policy to phase out nuclear power in Sweden

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HIGHLIGHTS

- The Swedish reactor fleet has a remaining potential production of up to 2100 TWh.
- Forced shut down would result in up to 2.1 Gt of additional CO_2 emissions
- 50,000–60,000 energy-related-deaths could be prevented by continued operation.
- A nuclear phase-out would mean a retrograde step for climate, health and economy.

ARTICLE INFO

Article history:
Received 12 December 2014
Received in revised form
18 April 2015
Accepted 21 April 2015
Available online 4 May 2015

Keywords:
climate change
nuclear power
health impact
electricity production
co2 emissions

ABSTRACT

Nuclear power faces an uncertain future in Sweden. Major political parties, including the Green party of the coalition-government have recently strongly advocated for a policy to decommission the Swedish nuclear fleet prematurely. Here we examine the environmental, health and (to a lesser extent) economic impacts of implementing such a plan. The process has already been started through the early shutdown of the Barsebäck plant. We estimate that the political decision to shut down Barsebäck has resulted in ~2400 avoidable energy-production-related deaths and an increase in global CO_2 emissions of 95 million tonnes to date (October 2014). The Swedish reactor fleet as a whole has reached just past its halfway point of production, and has a remaining potential production of up to 2100 TWh. The reactors have the potential of preventing 1.9–2.1 gigatonnes of future CO_2-emissions if allowed to operate their full lifespans. The potential for future prevention of energy-related-deaths is 50,000–60,000. We estimate an 800 billion SEK (120 billion USD) lower-bound estimate for the lost tax revenue from an early phase-out policy. In sum, the evidence shows that implementing a 'nuclear-free' policy for Sweden (or countries in a similar situation) would constitute a highly retrograde step for climate, health and economic protection.

1. Introduction

Human industrial and agricultural activity is the principal cause of changes in the Earth's atmospheric composition of long-lived greenhouse gases, mainly carbon dioxide (CO_2), and will cause ongoing climate change over the 21st century and beyond (Hansen, 2013). More than 190 nations have agreed on the need to limit fossil-fuel emissions to mitigate anthropogenic climate change as formalized in the 1992 Framework Convention on Climate Change (UNFCC, 2014). However, the competing global demand for low-cost and reliable energy and electricity to fuel the rapid economic development of countries like China and India has led to a large recent expansion of energy production capacity based predominantly on fossil fuels. Because of this need for energy and economic growth in developing countries, coupled to the lack of progress on decarbonization in most developed nations, human-caused greenhouse-gas emissions continue to increase, even though the threat of climate change from the burning of fossil fuels is widely recognized (Boden and Andres, 2012).

Sweden (along with a few others nations such as France) stands out as an exception to this trend, having largely eliminated its dependence of fossil fuels for electricity production during the 1970s to 1990s via a large-scale deployment of nuclear energy (oil- and gas-based transport fuels remains a problem, hydropower was

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http://dx.doi.org/10.1016/j.enpol.2015.04.023
0301-4215/

largely pre-existing before the nuclear phase). Despite this success, several Swedish political parties, most prominently represented in the current Swedish government by Green-party politician Ms. Åsa Romson (who holds the position of minister for the environment and climate) has promoted the urgent phase-out of the Swedish nuclear program. This is a primary objective of the Swedish Green party, with passive or active support from the Left and Center parties (with the position of the dominant Social Democrat party highly unclear). The Green-party, currently in a coalition government with the Social democrats, has promised that at least two reactors are to be shutdown prematurely in the next mandate period (2014–2018), with other reactors soon to follow. According to their announcements, this is to be accomplished by raising taxes on nuclear power production to the point where continued operation of the existing plants will become economically unviable (Dagens Nyheter, 2014).

What impact might this decision have—if carried to fruition—on Sweden's future environmental standing? To tackle this timely policy-relevant question, we first quantify the impact on global greenhouse gas emissions that the Swedish nuclear program has had to date, and then calculate what impact the proposed phase-out decisions will have future emissions. In addition, we use available mortality statistics for various electricity sources to estimate the impact on energy-related deaths. Our study is carried out in detail on a reactor-by-reactor basis and follows the general approach given in Kharecha and Hansen (2013). The hope is that by providing an objective assessment of the real-world impact of this announced policy, this study will help to better inform responsible politicians of the specific climate and health impacts of political decisions regarding the Swedish nuclear fleet.

Commercial light-water reactor (LWR) technology was originally developed and deployed in Sweden to increase energy independence (primarily by reducing foreign oil imports) and to supply the increasing electricity and energy demand while protecting remaining major Swedish rivers from hydropower installations (Forsgren, 1994). The LWR program in Sweden started[1] with the grid-connection of the Oskarshamn-1 (O1) reactor in 1972, and by 1986 half of the electrical output of the country came from nuclear power plants. The active reactor fleet consists of 10 reactors with a combined capacity of 10 GWe at three nuclear power plants: Oskarshamn, Forsmark and Ringhals. In addition, the Barsebäck nuclear plant with two reactors (600 MWe each) has been shutdown prematurely due political decisions, but the reactor units at the plant have not yet been dismantled. The option of restarting the two reactors at the Barsebäck plant is considered in this study. The active nuclear fleet typically produces 60–70 TWh/y, making up 43–47% of the total electricity production of the country. The decommissioned Barsebäck units could potentially add an additional ~10 TWh/y.

The Swedish naming convention for reactors use the first letter of the plant name and a numeral corresponding to the chronological reactor start of construction; the reactors are abbreviated B1–B2, O1–O3, F1–F3 and R1–R4. The current reactor fleet and its age profile are summarized in Table 1. The naming convention used for different types of reactors in the study is taken directly from the IAEA PRIS database (International Atomic Energy Agency (IAEA), 2014). There is no specified constraint for the lifetime of specific reactors, in part because most of the systems and components can and have been replaced one or more times. Reactor operators apply for a renewed operational license from the Swedish Radiation Safety Authority every 10 years, and as long as it is granted they may continue to operate. An estimation of the probable lifetime, consistent with the statements of reactor owners and operators, have been made based on the reactor type with the following results:

- The first generation of BWRs (ABB-1): 50 years,
- The second generation (ABB-II) and smaller third-generation BWR units (ABB-III, BWR-2500): 60 years
- The larger third generation BWR units (ABB-III, BWR-3000): 60–80 years (60 years was used for all calculations)
- The Westinghouse PWRs: 60 years, except for R2 which has been designated for a 50-year lifespan (Radio, 2014)

Given Sweden's 10-year review approach to licensing, the decision to decommission (if not forced by political decisions) will likely not be based on any technological limits but rather on whether the economic analysis favor decommissioning and full reactor replacement over that of further upgrades to reactor components. Sweden has recently performed very extensive upgrade projects (some which are still on-ongoing) in several reactors that involve the replacement of turbines, valves, cables and control and safety equipment. Thus, rather than being up to 40 years old, much of the equipment in these plants is brand new. The only components that are typically not subject to upgrade analysis are the reactor pressure vessel and containment structure, which are seen as so expensive and difficult replace that a complete reactor replacement is preferable. One of the most age-critical component in the Swedish nuclear fleet is the pressure vessel of the O1 reactor, which is in good condition according to the reactor safety experts that periodically examine the vessel and has an estimated technical lifetime exceeding 60 years (Gärdinge, 2013).

Interesting to note is that while the age of reactors (measured not in the age or condition of components critical to safety, but as the time between the present and when the reactor was started) has received much attention in the media and political debate, no such attention has been paid to the, for the most part, significantly older hydropower installations that provide the other half of Swedish electricity.

2. Methods

2.1. CO_2 emissions impact of the Swedish nuclear program

To estimate the impact that nuclear power has had and will continue to have on electricity-generation-related CO_2 emissions, the emissions caused by nuclear power need to be compared to those from competing technologies. Reference values for the life-cycle emissions of nuclear and competing baseload electricity generation alternatives are given in Table 2. The life-cycle assessment (LCA) of emissions covers the areas of construction and dismantling of power plants, fuel production & transport, plant operations, and handling of residual products and waste. Three values have been added for nuclear due to the noticeable disparity of data. The most comprehensive LCA study specifically for the Swedish nuclear fleet are the periodic reports of the Swedish state-owned power producer Vattenfall, which produce LCA-emissions assessments based on the international ISO 14040 and ISO 14044 standards (Vattenfall, 2012). Notably, the largely theoretically derived values used by the Intergovernmental Panel on Climate Change (IPCC Working Group III—Mitigation of Climate Change, 2014) as well as from a comprehensive review study (Lenzen, 2008) for global nuclear are 2–10 times higher than those estimated specifically for Sweden by Vattenfall based on actual

[1] A very small (60 MWt, 12 MWe) dual-purpose (district heating and electricity) nuclear plant predates the O1 reactor and was connected to the grid in the Ågesta suburb of Stockholm in 1964. This reactor was the first part of the later abandoned "Swedish Line" program of natural-uranium fueled heavy-water-moderated reactors that were also meant to serve a role in the Swedish nuclear weapons program.

Table 1
The Swedish Nuclear Reactor Fleet (International Atomic Energy Agency (IAEA), 2014).

Reactor name	Power [MW]	Reactor model	Start of commercial operation	Estimated years of technical lifetime	Remaining years of operation
B1	600	ABB-II	1975-06-01	60	35[a]
B2	600		1977-06-01	60	32[a]
O1	492	ABB-I	1972-02-06	50	7
O2	845	ABB-II	1975-01-01	60	20
O3	1450	ABB-III, BWR-3000	1985-08-14	60–80	31–51
F1	1022	ABB-III,	1980-12-10	60	26
F2	1158	BWR-2500	1981-07-07	60	27
F3	1212	ABB-III, BWR-3000	1985-08-18	60-80	31–51 (31)
R1	910	ABB-I	1976-01-01	50	11
R2	847	W (3-	1975-05-01	50	21
R3	1117	loop)	1981-09-09	60	27
R4	990		1983-11-21	60	29

[a] The B1 and B2 reactors were shutdown by political decision after having operated 24 and 28 calendar years respectively. Since the "aging" of nuclear power plants is mainly related to their operation (for instance the radiation damage to the reactor vessel), the remaining years of operation for B1 and B2 is calculated as their total estimated operating lifetime minus the years they operated (B1: $60-24.5=35.5$, B2: $60-28=32$).

Table 2
Life-cycle assessment of CO_2 emissions from electricity sources.

Electricity source	CO_2 emissions [g/kWh] Mean value (range)	Source
Coal	1045 (909–1182)	Jaramillo et al. (2007)
Natural gas	602 (386–818)	
Nuclear	5	Vattenfall (2012)
	12 (3.7–110)	IPCC Working Group III—Mitigation of Climate Change (2014)
	65 (10 – 130)	Lenzen (2008)

operational data. However, to remain conservative, we used the highest mean value of the three references (65 g-CO_2/kWh) and applied this for Swedish nuclear in all calculations in this study. For this analysis, due to a lack of reliable future projections, we have assumed that the values as given in Table 2 will remain stable within the relevant timeframe (~30 years in to the future). The future average emission rates for coal will depend on what types of coal are being used, to what extent co-generation is implemented (for instance for district heating) and the potential future success of industrial-scale carbon capture and storage technology. If emissions-reducing technologies are vigorously supported and pursued in the coming decades, there is a chance that the value as stated in Table 2 (1045 g-CO_2/kWh) will eventually represent an overestimation of actual future coal emission rates.

It is often erroneously stated that if the Swedish nuclear fleet would be replaced by an equivalent amount renewable power-generating capacity (if this turned out to be a technical possibility), the resulting near-zero effective change in the total CO_2 emissions caused by the change in the type of electricity production would not harm efforts to mitigate climate change. However, such a naïve analysis misses two key points: (i) If dispatchable ('baseload') power sources are replaced by variable (intermittent) generators, then system costs will increase disproportionately due to impacts on frequency control and the additional need for grid extensions,

Table 3
Fossil-fueled electricity production in countries neighboring to Sweden (TWh/year) (World Bank, 2014).

Country	Coal	Natural gas	Oil	Sum
Germany	286.4	70.0	9.5	365.9
Finland	7.4	6.6	0.4	14.4
Denmark	10.6	4.2	0.4	15.2
Poland	136.3	6.1	2.1	144.5
Estonia	10.2	0.1	0.1	10.4
Lithuania	~0	2.7	0.2	2.9
Latvia	~0	3.0	~0	3.0
Sum	450.9	92.8	12.6	556.3

higher reserve capacities ('overbuild' of peak generation potential) and spinning reserve with high ramp rates (typically supplied by open-cycle gas) (OECD-NEA, 2012); and, most importantly, (ii) The European national electricity grids are interconnected and integrated, and all excess electricity produced by nuclear power will reach a consumer somewhere within the grid(s), given adequate transfer capacity.

Today there is an annual trade of ~300 TWh/y (more than twice the total production of Sweden) in the Nordic/Baltic electricity-trading network "NordPool" alone (NordPool, 2014). Building for example new renewable sources in Sweden corresponding to the electricity production of a nuclear plant means that the nuclear plant, if kept operating beyond that required for purely domestic demand, is free to replace the production from for example coal or gas-fired plants within the connected electricity grids. The current Swedish electricity export capacity is 9750 MW, 6090 MW of which is directly connected to countries with a large fraction coal production (Germany, Poland, Denmark and Finland), meaning that in theory (if it was not needed for domestic demand), two thirds of the nuclear power could already be exported to displace coal even without transmission capacity expansions (Swedish National Grid, 2014). The fossil-fueled electricity production in the countries neighboring to Sweden is summarized in Table 3. There is a total of 556 TWh/y of fossil-fueled electricity production in the surrounding area, 81% of which (451 TWh/y) is derived from the burning of coal (World Bank, 2014). The Swedish nuclear fleet would therefore have to be replaced about *ten times* over by new renewables production (then completely displacing fossil fuels in the nearby grids) before the argument can be validly made that there is no potential to prevent emissions by continued nuclear electricity production in Sweden. The Swedish nuclear fleet is an already built, tested, profitable and well operating low-CO_2 electricity production machine with an exceptional safety track record that is capable of supplying up to 80 TWh/year of electricity (at 90% capacity factor with all reactors operational). Not allowing it to operate by political decision is from a climate impact perspective equivalent to building a new renewable resource and then deciding not to connect it to the grid. This impact is exactly the same even if an equivalent amount of low-CO_2 production is built as a "replacement" for the lost nuclear capacity (even if the replacement is new nuclear), as long as any fossil-fueled production remains on the grid.

The current production cost structure of electricity in the Nordic/Baltic and northern European market means that Swedish nuclear electricity production is directly coupled to the production from coal; that is, a decrease in nuclear production results in an equivalent increase in the production from coal, and vice versa (NordPool, 2014). To assess the impact on CO_2 emissions (and in the following section, impacts on health) of current and future Swedish nuclear electricity production, three scenarios were modeled here:

1. Nuclear is replaced by (or replaces) 100% coal
2. Nuclear is replaced by (or replaces) 90% coal and 10% natural gas
3. Nuclear is replaced by (or replaces) 80% coal and 20% natural gas

For this analysis, all reactors are assumed to continue to operate for the rest of their technological lifespans (Table 1) at their individual lifetime integrated capacity factors (up to 2013) as reported to the Power Reactor Information System (PRIS) (International Atomic Energy Agency (IAEA), 2014). Using the values of Table 2, the potential difference in CO_2-emissions (per kWh of electricity produced) by not allowing the Swedish nuclear reactor fleet to operate is calculated as:

$$\Delta \text{Emissions} = x_1{*}1045 + x_2{*}602 - 65\left[\frac{\text{g}}{\text{kWh}}\right] \quad (1)$$

Where x_1 and x_2 is the fraction of coal and natural gas that nuclear could be displacing respectively ($x_1+x_2=1$), and constants are the respective emissions factors by energy source. The results are summarized in Section 3.1.

2.2. Health and safety

The production of energy and electricity does not only impact the long-term climate through the release of greenhouse gases but also directly impacts human health due to, for instance, particulate and heavy-metal air pollution from fossil plants or harmful doses of radioactivity in the event of severe nuclear accidents. The mortality factors for the relevant electricity sources in this study per TWh of electricity produced are summarized in Table 4. The factors are based on analysis for Europe and represent the sum of accidental deaths and air pollution-related effects in Table 2 of ref. (Markandya and Wilkinson, 2007). The mortality factor for coal is the mean of the factors for lignite and hard coal in ref. (Markandya and Wilkinson, 2007). Even though there have been no reported deaths from the operation of Swedish nuclear plants to date, the calculations assume a non-zero mortality rate of nuclear as given in Table 4 for both past and future nuclear operation. Using this information, the impact of a nuclear phase-out on the number of deaths stemming from electricity production can be conservatively estimated in much the same way as emissions in the previous section. Using the values of Table 4, the potential difference in energy-related-deaths by not allowing the Swedish nuclear reactor fleet to operate is calculated as:

$$\Delta \text{Fatalities} = x_1{*}28.67 + x_2{*}2.821 - 0.074\left[\frac{\text{Deaths}}{\text{TWh}}\right] \quad (2)$$

Where x_1 and x_2 is the fraction of coal and natural gas that nuclear could be displacing respectively ($x_1+x_2=1$), and constants are the respective death rates by energy source.The results are summarized in Section 3.2.

2.3. Direct economic impacts

Beyond climate and health implications, the new proposed policy has potentially severe economic implications. Estimating the overall impact on the total Swedish economy and industrial production as a result of a premature shutdown of the technology that currently supplies over 40% of its electricity involves a complex suite of interactions and dependences that is beyond the scope of this paper and would require a much more thorough analysis. SKGS, the organization representing Swedish basic industry (which employs 400,000 Swedes and accounts for a large fraction of Swedish export income), reports that the future of Swedish industry is under severe threat if the current fleet of nuclear power plants is not replaced by new nuclear capacity rather than intermittent weather-dependent electricity sources once its reaches its technical lifetime limits (Axelsson, 2014). The impacts of a premature decommissioning without any coherent plan for replacement capacity are naturally far more severe.

The plentiful hydropower resources along with the remarkable success of the Swedish nuclear program led to electricity production costs that are among the lowest in the world. As a result, Sweden has a special niche in world trade because its exports tend to highly energy-intensive (Nordhaus, 1997). Rising energy costs in Sweden is thus likely to hurt the overall economy to a greater extent than most other countries (Table 5).

Any replacement capacity that is built will need to recover costs by either by direct rate increases or indirectly from subsidized, in the end both paid for by Swedish consumers and companies, but the costs of building replacement capacity is just a small fraction of the total cost (also counted as loss of potential income) of a premature decommissioning.

In this section, we only study some direct and immediate economic impacts that can easily be calculated to give at least a lower bound to total costs. However, we will make no attempt to calculate the costs associated with any replacement of this production capacity. The remaining production potential of the

Table 4
Mortality factors of different electricity sources (Markandya and Wilkinson, 2007).

Electricity source	Deaths/TWh, mean (range)
Coal (excl. China)	28.67 (7.15–114)
Natural gas	2.821 (0.7–11.2)
Nuclear	0.074 (range not given)

Table 5
Potential future tax revenue of nuclear power in Sweden (Swedenergy, 2014).

Factor	Cost	Potential future tax revenue
Energy consumption tax	0.29 SEK/kWh	609 b SEK (92 b USD)
Effect tax (current level)	12648 SEK/MWt	118 b SEK(18 b USD)
Property tax	0.03 (SEK/kWh)	63 b SEK (9.5 b USD)
Sum taxes		790 b SEK (120 b USD)

Table 6
Prevented CO_2 emissions (current and future) by Swedish nuclear (based on emissions factors given in Table 2).

Reactor	Prevented CO_2 emissions vs. replacement technology mix (million tonnes)					
	100% coal		90% coal, 10% NG		80% coal, 20% NG	
	To-date	Future	To-date	Future	To-date	Future
B1	77	151	74	144	71	138
B2	106	136	102	131	97	125
O1	98	20	94	19	90	18
O2	151	120	145	115	139	110
O3	222	327	213	314	204	300
F1	223	206	214	197	205	189
F2	215	238	206	228	197	218
F3	239	292	230	280	220	268
R1	177	66	170	64	162	61
R2	189	59	181	56	173	54
R3	201	218	193	209	184	200
R4	192	217	184	208	176	199
Sum	2090	2049	2004	1965	1918	1880
Sum excl. B1–B2	2090	1762	2004	1690	1918	1617

Swedish nuclear fleet is 2100 TWh with the Barsebäck plant and 1800 TWh without it. The direct costs for the state, in the form of lost future tax revenues, can be estimated in a simplified way using the taxation levels for nuclear power of Table 5, assuming that the Barsebäck plant would be restarted. The results are summarized in Section 4.3.

3. Results

3.1. Impacts on CO_2 emissions

The calculated prevention of CO_2 emissions (the difference between emissions caused by the reactors and the emissions caused by the equivalent production from the energy mixes listed above) is summarized in Table 6.

It is clear that the current Swedish nuclear program as a whole has just recently reached past its halfway point of production. The results show that the reactors have the potential of preventing about 1.9–2.1 gigatonnes (Gt) of future CO_2-emissions if allowed to operate their full technological lifespans. This corresponds to over 30 times the total current annual Swedish CO_2 emissions from all sources (including transportation) (International Energy Agency, 2013).

From a climate perspective alone, not allowing the Swedish reactors to operate by political decision (whether it is by a moratorium or by taxing it out of operation) is equivalent to deciding to disconnect all of Germanys operating wind and solar plants from the grid (combined production of 76.9 TWh/y in 2013) (Burger, 2013).[2]

There is a large disparity in the remaining potential for production and corresponding emissions-prevention of different reactors. The least-utilized reactor (as a fraction of its total possible production), Barsebäck-1 (B1), was decommissioned prematurely (by political fiat in 1999) when it had reached about 1/3 of its full production potential. If the B1 reactor had instead been allowed to displace a corresponding amount of coal power production in nearby Denmark and Germany, an average of 10700 t of CO_2 emissions per day would have been prevented. Integrated through to October 2014, the lost prevented emissions stemming from the shutdown of B1 alone are close to the total annual CO_2 emissions from all sources in Sweden. To date, the premature decommissioning of the B1 and B2 reactors have meant the lost opportunity to prevent an estimated 94.4 million tonnes of CO_2 emissions. If B1-B2 were restarted (or had not been shutdown), the total prevented CO_2-emissions the reactors could have achieved is around 265 Mt (the equivalent of 4.5 years of current total Swedish CO_2 emissions from all sources).

The units with the least relative and absolute production that remain in operation are the O1, R1 and R2 reactors. O1, the smallest and oldest of the Swedish power reactors, has already produced over 80% of its potential lifetime production. The remaining CO_2-emission-prevention potential of the O1 reactor is ~20 Mt, equivalent to the total emissions from the transport sector of Sweden during one year. On the other side of the scale, the newer and larger units such as the O3 (the world's most powerful BWR) and F3 have, individually, about twice the remaining production capability of all the smaller reactors (O1, R1, R2) combined. Thus, an early decommissioning of any of these large and high-capacity units will obviously have a much larger impact. The complete historical and future potential emissions prevention of the Swedish nuclear reactors, assuming nuclear is displacing 100% coal and vice versa, is illustrated in Fig. 1.

Table 7
Potential prevented deaths (current and future) by Swedish nuclear using the mean mortality factors from Table 4.

Reactor	Prevented deaths vs. replacement technology mix					
	100% coal		90% coal, 10% NG		80% coal, 20% NG	
	To-date	Future	To-date	Future	To-date	Future
B1	2259	4394	2054	3997	1850	3600
B2	3090	3976	2810	3616	2531	3257
O1	2850	578	2592	526	2335	474
O2	4404	3498	4006	3181	3608	2865
O3	6487	9543	5901	8681	5314	7818
F1	6515	6009	5926	5466	5337	4922
F2	6264	6934	5698	6307	5132	5680
F3	6985	8514	6354	7745	5723	6975
R1	5161	1940	4695	1765	4228	1589
R2	5515	1709	5017	1555	4518	1400
R3	5858	6370	5329	5794	4799	5219
R4	5608	6324	5101	5752	4594	5181
Sum	60,995	59,790	55,482	54,385	49,968	49,960
Sum excl. B1–B2	60,995	51,419	55,482	46,771	49,968	42,123

3.2. Health impacts of phasing out nuclear power in Sweden

The results for the prevented deaths by nuclear power production (current and future) in Sweden are summarized by reactor unit in Table 7.

In total, through to October 2014, Swedish nuclear power production has prevented an estimated 50,000–60,000 deaths as compared to what would have occurred if fossil-based alternatives were used in its place. The potential for future prevention of death is also 50,000–60,000, which gives a total estimated potential energy-related death prevention by the Swedish nuclear program (if allowed to run its technological course) of 100,000–120,000 lives.

If used to replace coal production, the individual Swedish reactors have the potential of preventing anywhere from 80 (O1) up to 318 (O3) deaths per year for the rest of their operational life. The to-date and future potential death prevention of the Swedish nuclear reactors, assuming nuclear is displacing 100% coal and vice versa, is shown in Fig. 2.

These values and the methodology with which they were calculated match well with those of the large European Commission study on the external costs of electricity production (ExternE), which estimates an increased energy-production-related death toll of ~200 lives/year as a direct consequence of the premature shutdown of the Barsebäck plant (European Commission, 1999). Using the ExternE reference values, the premature shutdown of the Barsebäck plant has caused an estimated 2400 deaths to date from air pollution caused primarily by fossil power production in nearby Denmark and Germany, which could have been avoided. Denmark operates a major coal plant and several large natural gas plants less than 30 km from the Barsebäck site. The decision to shut down the Barsebäck plant thus stands out as the policy decision with by far the most serious negative energy-production-related health and climate effects in the history of energy production in the Nordic countries.

The safety track record of both Swedish hydro and nuclear power is exceptional, and far exceeds that of all other comparable major industrial activities as well as the transportation sector (The Swedish National Board of Health and Welfare, 2013). It is very difficult to find any data to support the high level of political and activist group concern about the safety of Swedish energy

[2] The main differences being that Swedish nuclear power provides baseload power and bears its own costs (plus additional special taxes for nuclear) while the German wind and solar plants are intermittent and heavily supported by subsidies.

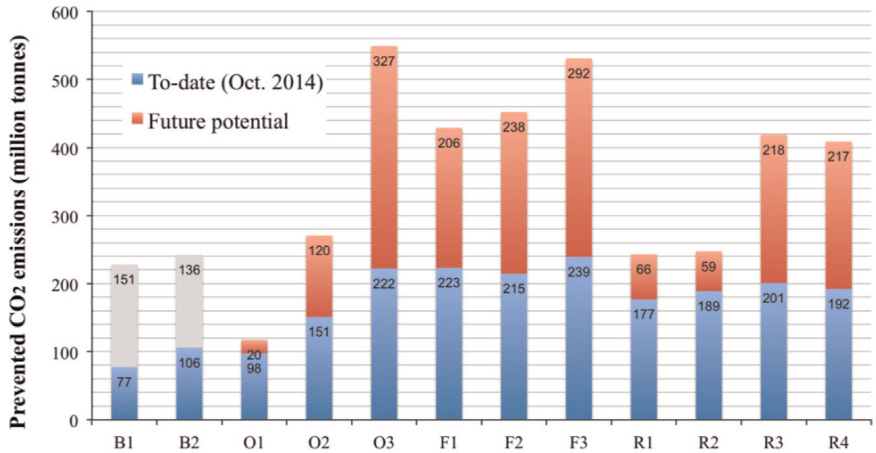

Fig. 1. Maximum prevention potential for greenhouse gas emissions of the Swedish reactors (million tonnes of CO_2).

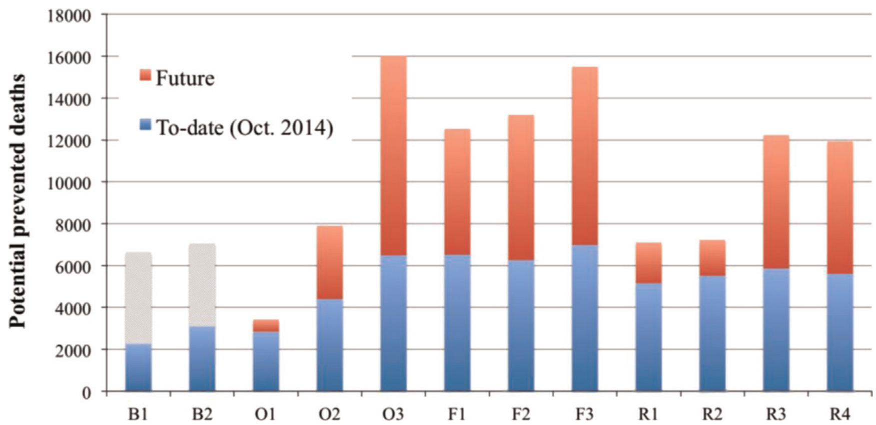

Fig. 2. Maximum potential deaths prevented by Swedish nuclear reactors. Note that reactors B1/B1 were shutdown prematurely.

installations as compared to other industrial activities, suggesting that at least part of the concern stems from misinformation. There have been no accidents resulting in an impact on the environment or people in the history of Swedish nuclear power (the most severe incident is ranked as a 2 on the INES scale (International Atomic Energy Agency, 2008), but there have been several hydropower dam breaks. In 1973, the dam failure near the town of Sysslebäck in Värmland County resulted in the death of a 47-year old woman and the destruction of a number of residential homes (Lönnroth, 1979). The much larger break at the Noppikoski dam in 1985 released about one million m^3 of water and destroyed several roads and bridges, but fortunately did not result in any fatalities (County Council of Dalarna, 2012). In the summer of 2000, a large dam failure at the Aitik mine could have had serious consequences, but since the downstream dam did not fail, the consequences were limited to material damage. More recently, two hydropower dam failures in 2010 destroyed roads and nearby buildings but did not result in any fatalities (The Government of Sweden, 2012).

A commonly held belief is that while nuclear power is statistically among the safest large-scale electricity production technologies, a severe accident in a nuclear facility has much larger consequences than accidents/events for competing technologies such as hydro or fossil power. This is not supported by either local Swedish or international experience and modeling. The failure of the Banqiao Reservoir Dam (and the resulting failures of downstream dams) in China in 1975 remains the most severe energy-production-related accident in history, resulting in the loss of as many as 230,000 lives and the collapse of 6 million buildings, directly affecting the lives of 11 million people (Graham, 1999). The April 1986 Chernobyl accident is the world's only source of fatalities from nuclear power plant radiation fallout to date. According to the latest assessment by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 43 deaths are conclusively attributable to radiation from Chernobyl as of 2006 (28 were plant staff/first responders and 15 were from the 6000 diagnosed cases of thyroid cancer) (United Nations Scientific Committee on the Effects of Atomic Radiation, 2008). An earlier study using the conservative linear non-threshold model for the biological effects of ionizing radiation by the Chernobyl Forum, a group of nine United Nations agencies, estimated that a total of up to 4000 people could eventually die of radiation exposure due to the Chernobyl accident (UN Chernobyl Forum, 2006).

While accidents in Swedish electricity production have caused only a single fatality (in the hydropower accident of 1973), available modeling results suggest a similar relation as that mentioned above between the potential consequences of Swedish hydro and nuclear power accidents. For example, the Suorva dam that regulates the Akkajuare reservoir in northern Sweden connects to the Lule River, which flows through the cities of Boden and Luleå with a combined population of 65,000. A failure in the dam, releasing some fraction of the six billion m^3 of water in the reservoir (over ten times the volume of the Banqiao Reservoir) would result in the complete destruction of the cities of Boden and Luleå, as well as the main Norrbotten County hospital serving a population 250,000 (Suorva är ingen lyckad konstruktion (Interview with Peter Stedt of Vattenfall AB), 2014).[3] In addition to Suorva, failures in other critical dam facilities such as the Trängslet dam on the Dalälven River would strike cities such as Mora and Orsa with combined population that exceeds 15,000.

In comparison, according to the final report of the Swedish Energy Commission of 1994, a very severe accident in the Barsebäck plant (which is located close to the major cities of Malmö, Sweden and Copenhagen, Denmark) could potentially lead to 100–500 fatalities in Europe over the next 50 years, assuming that radiation filters are not working at their design efficiency and, for the higher value of 500 deaths, weather patterns are the least favorable possible (Swedish Energy Commision, 1994). The health impact of the decommissioning of the Barsebäck plant, using the ExternE numbers, is thus already equivalent to that of the estimated impacts of up to 15 very severe accidents in the Barsebäck reactors (of course in reality the plant could not suffer more than one severe accident before being shut down).

The probability of failure for any of the 20 major Swedish dams that could have very serious consequences is estimated as 0.002, or 1 failure in 500 years (Swedish Civil Contingencies Agency, 2012). The likelihood of dam break in a safety-critical facility (which inevitably will have external consequences) is therefore at least four times higher than the estimated likelihood of an event causing core damage in any Swedish nuclear plant[4] (a type of event which, outside of the Chernobyl accident, has never caused a fatality in the history of commercial nuclear power).

Swedish nuclear power is regulated in the specific law of nuclear installations (Swedish Law 1983:3), the radiation protection law (1988:220) and general environmental law ("Miljöbalken"), with construction and operation at all times subject to the approval of the Swedish Radiation Safety Authority. The laws and nuclear safety requirements are extensive and deal not only with technical matters but also with issues such as emergency planning, organization development, administration and training. In contrast, the concept of hydropower dam safety is not clearly defined in Swedish law and there does not exist a specific law or authority for its governance (or for any other electricity source except nuclear) (Idenfors et al., 2012), but some regulations regarding the dams are included in the general water and emergency rescue laws (1983:291, 1986:1102).

Similarly, there are no defined insurance requirements for the very large and safety-critical hydropower dams, while the nuclear plants are subject to strict regulation on required reserves (to be immediately available for compensation at the moment of an accident) as well as total liability in the case of an accident. Paradoxically, the insurance issue has often been raised by the ideological opponents of nuclear power as a form of "hidden subsidy", since it is not possible for any single company to completely insure against the worst conceivable nuclear accident scenarios. The same is of course true for a large number of the Swedish hydropower dams, oil storage tanks near cities, any type of transport of dangerous materials, passenger ferries and cruise ships, air traffic, oil and gas platforms, chemical industries, water treatment and distribution systems, any large sporting event or concert and numerous other activities which may (with low probability of occurrence) cause accidents far larger than could be insured against (Radetzki and Radetzki, 1997). The insurance and reserve requirements levied on the Swedish nuclear industry are unique among comparable industries and similar requirements are currently not imposed on other energy production technologies.

Thus it appears from all available data that if one would aim to reduce accidental deaths and environmental pollution from industrial activity, the already highly safe and clean Swedish energy-production sector (whether it be hydro or nuclear) should be very far down the list of priorities. If one despite this would still choose to focus political and economical resources on this issue, the first objective should be to increase safety and regulation of hydropower installations rather than the already tightly regulated nuclear installations.

The health and environmental impacts of hydro and nuclear power in Sweden, properly accounting for the non-zero probability of accidents in either technology, is near-negligible compared to all available large-scale baseload power sources that they are able to displace by continuing to operate (European Commission, 1999). Thus, any imposed regulation that raises the relative price of electricity from either nuclear or hydro compared to these alternatives will have a strong negative overall health and environmental impact. As described earlier, none of these facts are altered in any way by a potential replacement of Swedish nuclear and hydropower by relatively safe and environmentally friendly intermittent sources such as wind and solar power (if this was to be technically possible to do without fossil-fuel backup).

3.3. Direct economic (tax revenue) impacts

Assuming current tax levels remain in place, the remaining production potential of the Swedish nuclear fleet has the potential to provide nearly 800 billion Swedish kronor (SEK; 120 billion USD) of direct future tax revenue potential (at current tax levels, not including potential tax on the profit of utilities), the bulk of future operating income from current nuclear power plants is also effectively a direct gain for the state since the Forsmark and Ringhals plants are majority-owned by the state utility Vattenfall. Assuming an annual discount rate of 5%, the net present value of the potential remaining tax revenue over the next 30 years is ~400 billion Swedish kronor (SEK; 60 billion USD).

An additional tax of 0.022 SEK/kWh (46 billion SEK future potential) is levied on the reactors to finance the nuclear waste repository, which is not included in the future tax revenue potential since costs related to the waste repository (which has to be built either way) would be lower if the plants were to be shutdown prematurely. The total future spending needed for the repository program is estimated at 99billion SEK, out of which 49billion SEK is already available in the repository fund. About half of all remaining costs are in some direct way related to the amount of future nuclear waste produced and could therefore be reduced by some fraction by an early decommissioning of the nuclear fleet. Even using the most optimistic assumptions, early decommissioning leaves the required repository program significantly underfunded (SKB—Swedish Nuclear Fuel and Waste Management Co, 2013).

3.4. A hypothetical nuclear phase-out by 2022

In this section, we analyze a potential phase-out of Swedish nuclear analogous to that announced for the German Energiewende (German Federal Ministry for Economy and Technology, and Federal Ministry for Environment, Conservation, and Reactor Safety, 2010), meaning no more nuclear production by

[3] The Suorva Dam was initially constructed inside of a national park in 1919–1923 and subsequently extended three times, most recently in 1966–1972 (concurrent with the construction of the O1 reactor). In the morning of the 4th of October 1983, Mr. John Tomma (a local member of the Sami people, not affiliated with the operation of the dam) discovers a leak in the dam, the flow from which threatens his outhouse. Mr. Tomma alerted authorities at Vattenfall (the owner and operator of the dam), whose experts spent a full week searching for the cause of the leak before finding and stopping it (Bjurholt and Gustafsson, 2004).

[4] Calculated using the values quoted for the core damage frequency of current US nuclear plants (Swedish data was not found in open literature) from the World Nuclear Association (2014).

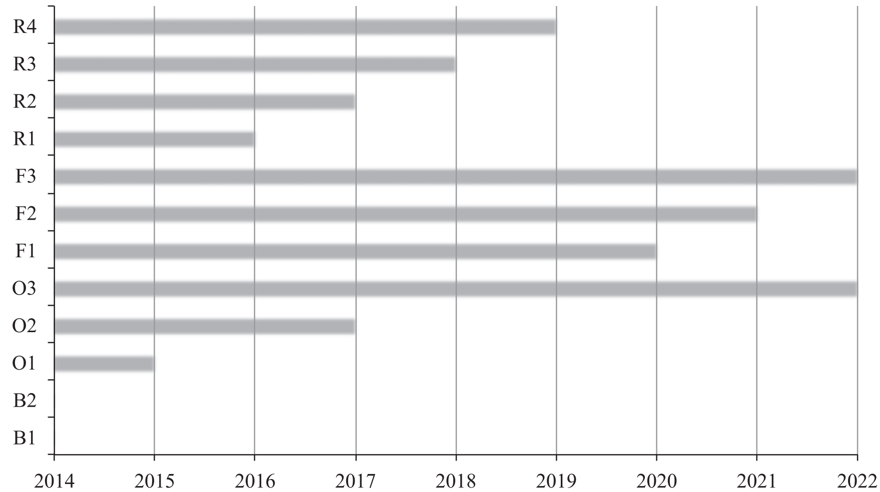

Fig. 3. Example of a planned phase-out of Swedish nuclear by 2022.

2022. It would seem that the least environmentally and economically damaging strategy to phase-out nuclear would be to run all plants up until 2022 and then simultaneously shut them all down to meet the phase-out target, but it is highly unlikely that such a strategy would be pursued in reality. More likely, a sequential shutdown starting with the smallest and oldest reactors would be implemented, similar to what is planned for Germany. As noted in the Introduction, the Swedish minister for the environment & climate has already proposed the first step of such a strategy, starting with the decommissioning of the O1 and R1 reactors within the next four years (before 2018). However, once draconian tax measures have been imposed to force the first units in to decommissioning, it is unlikely that utilities will decide to continue operating nominally more profitable reactors at next-to-no profit. Most certainly, no investments of consequence for replacement parts, upgrades or improved operational performance and safety would conceivably be carried out at any reactor once such policies are put in place by the government.

Because of these factors, it is quite difficult to anticipate at what rate a purely diminishing-profits-driven decommissioning would occur. In this sense, it would in fact be preferable to have a set timeline for the decommissioning of certain units that is not entirely determined by their economic performance. If the decommissioning is carried out on a predetermined time and production schedule (as in Germany), there is a chance that adequate capacity for the import of natural gas and other fossil-fueled baseload power (including the construction of new transmissions lines) to cover the loss of production could be made while limiting blackouts and extreme increases in energy costs for consumers.

Despite these uncertainties, for the purpose of analyzing the impact of a phase-out of Swedish nuclear by 2022, below we present a hypothetical sequential phase-out plan based on the profitability, size and age of reactors. The plan, shown in Fig. 3, is unlikely to represent an optimal or even probable phase-out plan, but in the absence of any specific schedule it serves well to approximate the likely impacts of any such plan regardless of the specific details.

The phase-out plan as shown in Fig. 3 includes about 340 TWh of remaining production in the Swedish nuclear fleet, or 16% of its remaining technological potential. Rather than utilizing the full potential of preventing roughly 2 billion tonnes of CO_2, the 2022 phase-out plan has the potential for nuclear to prevent about 330 million tons CO_2. Notably, the difference of ~1700 million tonnes of unprevented CO_2 emissions corresponds to the estimated emissions by all sources in Sweden until the year 2040 (if current rates remain unchanged).

The direct loss of tax revenue for the state (disregarding tax on utility profit and the direct income from state-owned reactors) is on the order of 660 billion SEK (100 billion USD). The lost potential to displace coal also reduces the potential for preventing energy-related deaths by ~50,000 lives (from 10,000 to 60,000).

4. Discussion

In any modern industrial society, the combination of electricity production technologies and available import/export capacity must match power demand on the national grid at every moment throughout the year to maintain grid frequency and avoid blackouts. This challenge is currently met in Sweden primarily through the regulated power output of fast-response hydropower, which operates on top of the baseload production by nuclear. Sweden has already expanded hydropower to its maximum production potential since the remaining untouched major rivers (Kalix älv, Torne älv, Piteälven, Vindelälven and 15 other rivers and river sections) are protected from installations by Swedish law. Hydropower cannot be expanded to replace any of the lost capacity as nuclear is phased out or to regulate any large-scale installation of intermittent power.

While the plans for a nuclear phase-out have already reached the initiating stages (and the Barsebäck plant has already been prematurely shut down), no plans have been put forth to explain what will be replacing the lost capacity. Sweden has a rapidly increasing population, a large and successful heavy industry sector and a climate-driven push toward the electrification of the entire transport sector, which means there is very little room for a decrease in the total electricity demand over the coming decades. For example, the energy use for domestic transport (which is currently $>93\%$ fossil-fueled) is around 86 TWh/y, larger than the total production capacity of either nuclear or hydropower (Swedish Energy Agency, 2014). Because of the superior efficiency of modern electrical and hybrid vehicles compared to combustion engines, the total required energy is most likely lower than this but still very substantial.

The only major government-driven plan for new electricity production that is currently being pursued is a heavily subsidized push toward 30 TWh/y of wind power by 2020 (up from ~10 TWh/y in 2013/2014) (Swedish Government, 2014). This political decision has been taken without a clearly defined motivation (other than referring to other political decisions requiring 49% “renewable” energy by 2020), determined budget or published feasibility and consequence study, and appears to have no direct link to the current phase-out plans for nuclear.

The installation of a large fraction of intermittent sources requires a correspondingly expanded regulation/backup capacity. According to the Swedish grid operator (Svenska Kraftnät), the Swedish Energy Agency (Energimyndigheten) and the Royal Swedish Academy of Sciences, there is no room for expansion of the current regulation capacity of Swedish hydropower (Swedish National Grid, 2008) (The Royal Swedish Academy of Engineering Sciences, 2002) (Swedish Energy Agency, 2008). Indeed, it has been shown that if the current hydropower system is, in the future, regulated more actively to match wind power variability, it could have devastating effects on the local environment (The Royal Swedish Academy of Engineering Sciences, 2002). The Swedish grid operator estimates an increased need for regulating power of 4.3 – 5.3 GW for an additional installation of 12 GW of wind power (corresponding to 30 TWh/year of total Swedish wind power) (Swedish National Grid, 2008), without factoring in the potential loss of nearly 10 GW of available baseload power from a nuclear phase-out. It therefore appears highly unlikely that 30 TWh/year of intermittent wind power, for which there is no existing or proposed regulation power, would be able to replace 60–70 TWh/year of baseload power from nuclear successfully.

The current Swedish wind power installations reach a combined yearly minimum of a ~0.3% of the installed power averaged over one hour. For example, on an hourly-basis, a potential future 12,000 MW Swedish wind power fleet using the current reliability figures can relied upon to produce about 36 MW of power at any given hour of the year. The power level that could be maintained 90% of the hours in the year is estimated at ~6% of the installed capacity. Since wind power has no impact on the effect balance of current Swedish electricity supply, the grid operator has generously assigned the assured power from wind sources at 6% (nuclear is at 90%) (Swedish National Grid, 2014).

The impact on the effect-balance of the grid by the difference in assured power when exchanging nuclear production by wind power is profound. The peak estimated power demand for a cold winter in Sweden is 28,200 MW, for which the total current assured power production capability is an adequate match (Swedish National Grid, 2014). Since the timing and severity of the peak power demand depends primarily on the temperature, peak power demand typically coincides in northern Europe, leaving little to none assured import capacity (estimated as 0 – 350 MW by the Swedish National Grid Operator (Swedish National Grid, 2014). No coherent explanation or plan for how to replace the loss of 9 GW of assured power supply from the nuclear fleet (the current nuclear fleet at 90% capacity factor), every watt of which is needed during cold winter days, has been put forward by the proponents of a nuclear phase-out.

5. Conclusions and policy implications

We have presented a systematic appraisal of the probable direct effects and policy implications of a premature retirement of the Swedish nuclear fleet, based on the best available data on energy-related emissions, pollutants and infrastructural costs. The conclusions are stark and concerning, in terms of the combination of health, environmental and economic impacts. Given that no plausible alternative energy plan has been mapped out by proponents of the nuclear phase-out policy, and faced with the inherent daily and seasonal limitations on wind and solar energy in Scandinavia, it appears virtually certain that the bulk of the missing electricity supply will be met by some combination of imported fossil fuels and new combustion-based power plants. This will compromise the Swedish Government's policy to reduce greenhouse gas emissions by 40% by 2020 (Government of Sweden, 2014) and seriously undermine any long-term mitigation goals.

Our analysis reveals that a ‘no nuclear’ decision, in enacted as a formal Government policy, would be expected to lead to tens thousands of untimely deaths, billions of tonnes of additional climate-changing greenhouse gases emitted, and over a hundred billion dollars in lost revenue for Sweden, compared to the ‘default’ position of simply allowing the reactor fleet to operate over its potential lifetime. Beyond its national implications, a nuclear phase-out policy might encourage other countries to copy Sweden's lead in energy policy, which would have serious global environmental and health implications. Given the urgency with which the world economy must decarbonize to avoid dangerous climate change, such a policy runs completely counter to the recent United Nations *Sustainable Development Goals*, as espoused in Rio+20 (United Nations, 2014), and ought to be opposed on the grounds of international obligations to future human welfare.

Acknowledgments

The authors would like to extend gratitude to Jessica Lovering of the Breakthrough Institute for helpful comments and feedback.

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