Feasibility assessment of replacing global fossil fuel electricity production by nuclear power based on data from Sweden's nuclear program

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ABSTRACT

Based on the empirical data from the Swedish light water reactor program of 1962-1986, the potential for global nuclear power expansion to replace fossil fuel electricity production was estimated.

The data shows that if the world built nuclear power at the per capita rate of Sweden during its expansion, fossil fuel electricity could be replaced within 5 years. Taking in to account relevant factors such as the relative economic output, current and past unit construction time and costs, future electricity demand growth projections and the decommissioning of existing nuclear plants, the estimate is that the global share of fossil fuel electricity could be replaced in **25±2** ***years***.

This assumes that the relative expenditure globally does not exceed that of Sweden during its expansion. Given the increasing urgency regarding changes in the earth's climate due to greenhouse gas emissions from fossil fuel sources, this can be considered a rather conservative assumption.

1) Nuclear capacity impact on CO_2 emissions

Between 1960 and 1990, Sweden more than doubled its inflation-adjusted gross domestic product (GDP) per capita while reducing its CO_2 emissions/capita through a rapid expansion of nuclear power production. As shown in Figure 1, in the pre-nuclear era (1960-1972), relative Swedish CO_2 emissions matched and even exceeded the relative increase in economic output. Once commercial nuclear power capacity was brought online, starting with the Oskarshamn-1 plant in 1972, emissions started to decline very rapidly. By 1986, half of the electrical output of the country came from nuclear power plants, and total CO_2 emissions per capita (from all sources) were down by 75% from the peak level of 1970.

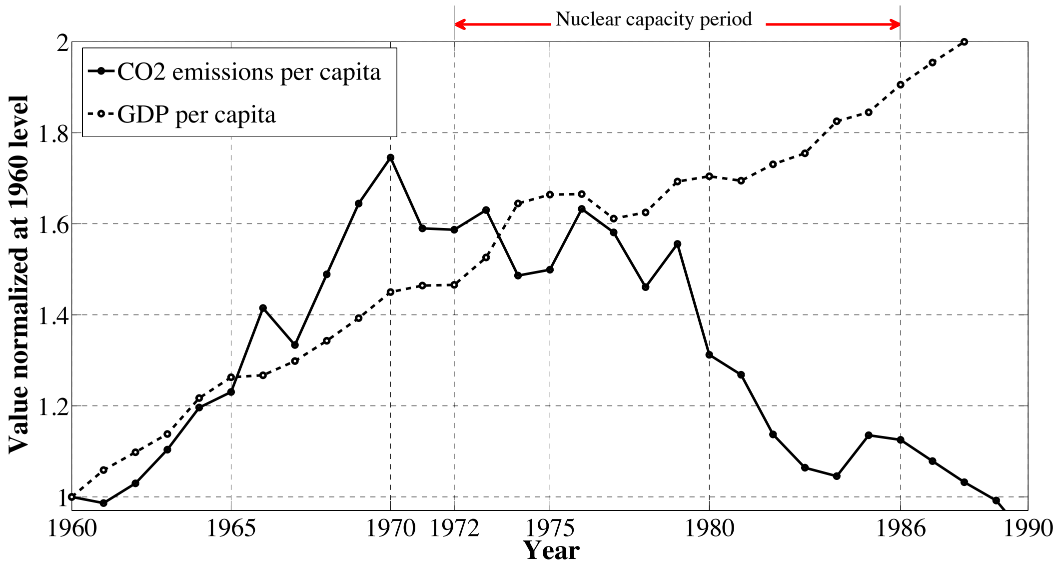

Figure 1, Swedish total CO_2 emissions and GDP per capita 1960-1990

This is the most rapid installation of CO_2-free electricity capacity on a per capita basis that the world has ever seen. Emissions were reduced due to the closing of fossil power plants and the electrification (by nuclear power) of heating and industrial processes that were previously fossil powered.

2) The rate at which nuclear electricity production was added

Out of the 12 commercial reactors that were built in Sweden during this period, 9 were of completely indigenous designs that were developed without the use of foreign licenses. Another 2 reactors of indigenous design were exported to Finland and started operation during the same period (1979-1982). Research on commercial light water reactor technology was initiated in Sweden in 1962, which means it took 24 years between the start of research until the technology provided half of the electricity output of the nation. The rate of addition of nuclear electricity is presented in several different ways in Table 1.

Table 1, Production addition by the Swedish nuclear program

Time period	**Production addition[1]**		**Years to replace current global fossil electricity at Swedish rate globally**	
	kWh/y[2] /capita	**kWh/y[2] /¢-GDP**	**Per capita**	**Per GDP**
Start of research to last grid connection, 1962-1986	330.8	1.45	N/A	N/A
Start of first construction to last grid connection, 1966-1986	389.6	1.63	5.15	15.90
First grid connection to last grid connection, 1972-1986	538.7	2.13	3.72	12.18
"Steady-state" addition period 1975-1986	652.8	2.53	3.07	10.28
Peak 5-year addition 1981-1986	831.5	3.07	2.41	8.45
Peak addition year per capita 1986	1326.2	4.61	1.51	5.63
Peak addition year per $GDP 1981	1286.0	5.02	1.56	5.17

[1]The values represent the sum of change in nuclear electricity production in the period. Thus 1974-1986 starts with the change in production between 1973 and 1974, and ends with the change in production between 1985 and 1986. The values are then divided by the total number of production years in the span, in this case 11+1= 12 years.

In order to build globally at any of the rates of Table 1, nearly all construction would have to occur in industrialized countries with an already established and experienced nuclear regulatory and licensing infrastructure in place. This fact presents no major hurdle since all current major world energy consumers are nuclear power producers with active regulatory institutions.

As time progresses, the impact on the average addition rate by the initial time lag where installations are being planned, licensed and built but have not yet been put online (in the Swedish case; 1966-1972) diminishes. Once the initial ramp-up period is over and the first installations begin to come online, the addition rate will approach a steady state. By 1974/1975, Sweden had reached a steady-state of addition that was essentially maintained for more than a decade (as seen in **Figure 2**). The Swedish experience indicates that in steady-state, nuclear power can be added at a rate of about 2.5 kWh/y^2/¢-GDP, which if multiplied by current global GDP amounts to ~1500 TWh/y^2 (10% of current global fossil fuel electricity production). The peak annual addition rate per GDP in Sweden occurred 1980-1981 and corresponds to a GDP-weighted annual addition of 3000 TWh/y^2, or 20% of the current global fossil fuel electricity production.

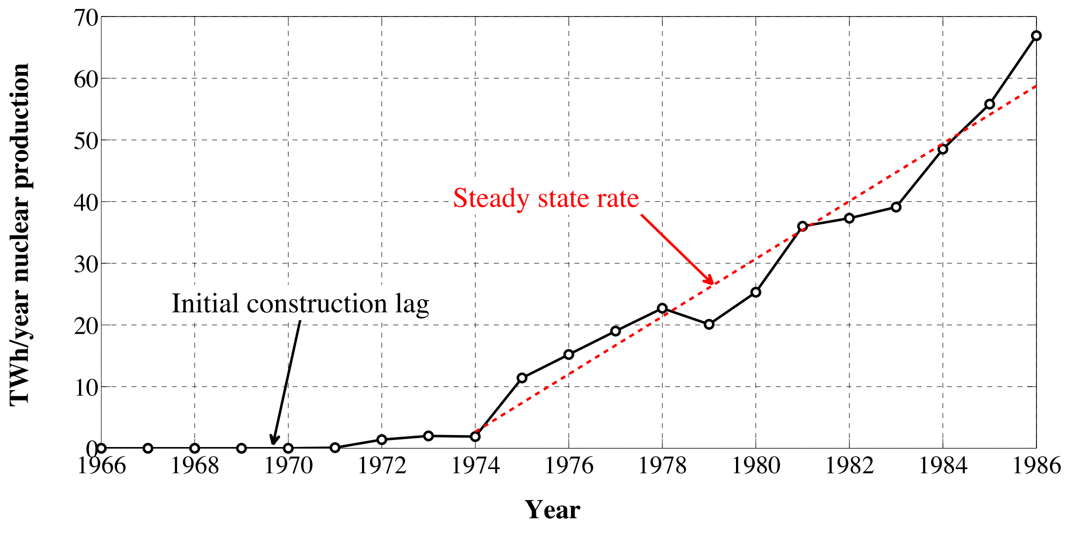

Figure 2, Swedish nuclear electricity production 1966-1986

3) Unit cost and construction time

For a valid comparison, both the unit cost of nuclear reactors and the construction-time of the plants must be assessed between the global situation today and the Swedish experience. The relevant data is presented in Table 2.

Table 2, Nuclear power plant construction time and cost comparison

<table>
<tr><th>Parameter</th><th>All nuclear units brought online 2012-2014</th><th>Swedish nuclear program 1966-1986</th></tr>
<tr><td># of units</td><td>8</td><td>12</td></tr>
<tr><td>Median unit capacity (MWe)</td><td>1018</td><td>935</td></tr>
<tr><td>Average unit capacity (MWe)</td><td>990</td><td>871</td></tr>
<tr><td>Median unit construction time</td><td>5.1 years</td><td>5.7 years</td></tr>
<tr><td>Average unit construction time</td><td>5.8 years</td><td>5.9 years</td></tr>
<tr><td>Median unit cost per kWe (2005 USD)</td><td>1364</td><td rowspan="2">~1400[1]</td></tr>
<tr><td>Average unit cost per kWe (2005 USD)</td><td>1546</td></tr>
<tr><td>Average unit cost per kWe per GDP/capita (2005 USD)</td><td>~0.18</td><td>~0.06</td></tr>
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Table 2 shows that unit size, construction time and absolute costs are about the same for the nuclear reactors that were brought online 2012-2014 compared to the Swedish experience. The difference in historic Swedish GDP/capita and the current global GDP/capita means that the relative cost is three times higher globally averaged today. Worth noting is that only three countries connected new reactors to the grid in 2012-2014: China, India and South Korea. Data from these countries (particularly China and India) are most important since they will constitute the bulk of energy demand and new production in the coming decades.

While the cost of construction is currently falling in these countries, a large-scale global expansion of nuclear power would mean increased operating costs as the price of uranium ore and fuel is driven up. The expansion of nuclear power production inevitably entails a proportional expansion of pressure vessel fabrication capacity as well an expansion of the entire nuclear fuel cycle; mining, enrichment, fuel fabrication and disposal. A truly global expansion of the type analyzed here would necessitate a transition to fast reactor systems

[1] Only specific cost data for the Oskarshamn NPP was found

before the turn of the century to ensure adequate fuel supply. Both construction times and costs are significantly lower in China/India/South Korea than what is expected currently in Europe and North America, but this is partly outweighed in this comparison by the fact that these regions are far richer (as measured in GDP/capita) than Sweden was during its expansion period.

4) Conclusions

The estimated time it would take the world to replace the fossil share of total electricity with nuclear power based on Swedish experience using the data of Table 1 and Table 2 is ~20 years. This number takes in to account both the relative difference in per capita GDP between the global average today and Sweden at the time (both adjusted for inflation to 2005 level of USD), and it also includes the total planning, build-time and cost of all the reactors. However, global electricity production has grown at a more rapid rate than the GDP/capita averaged over the last decade (+26% vs. +16% between 2000 and 2011). The rapidly increasing electricity demand and the closing of aging existing nuclear installations makes the challenge of replacing the share of fossil electricity larger than it would first appear.

A more realistic estimate – which leverages all the relevant data and also takes in to account decommissioning of existing plants and future electricity demand vs. GDP increase projections – is that the fossil share of electricity production can be completely replaced by nuclear globally in **25±2 years**.

Replacing fossil fuel electricity and heat production eliminates roughly half of the total source of anthropogenic CO_2 emissions. Continued nuclear build-out at this provenly modest rate coupled with an electrification of the transportation systems (electric cars, increased high-speed rail use etc.) could reduce global CO_2 emissions by ~70% before 2050.

5) References

- All non-cost data pertaining to nuclear reactors were extracted from the IAEA PRIS database: http://www.iaea.org/PRIS
- All data for global economy, emissions and energy were extracted from the World Bank Database: http://data.worldbank.org
- Reactor cost data was collected from official press releases. When costs were only given as a lumped sum for multiple units at a plant, the cost for a single unit was calculated by multiplying the total plant cost by the power output of the unit relative to the total plant power output.
- Monetary values were all converted to the value of the US dollar in 2005 using the Consumer Price Index (CPI-U) data as provided by the U.S. Department of Labor Bureau of Labor Statistic.