Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden

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Abstract

Despite similarities in their current energy mixes, France and Sweden's pathways have been very different since the 1970s, when both systems were highly dependent on fossil fuels. After the oil crisis, both countries chose to reduce their oil consumption by developing nuclear power. However, Sweden pursued a more diversified energy policy that has subsequently allowed it to reduce its CO_2 emissions. Today, both countries have committed to a carbon neutrality goal: by 2045 for Sweden and 2050 for France. In order to understand the key factors that can drive energy transition toward a carbon neutrality goal, we propose to compare the past energy transitions in France and Sweden, two countries that have significantly reduced their CO_2 emissions and fossil fuel dependency. To assess the impacts of the current energy system and its regulations on the feasibility of meeting carbon neutrality, we use TIMES bottom-up energy system optimization models. The results show that France faces more challenges in transforming its energy system than Sweden i.e. an increase in power production, a decrease in gas consumption, the replacement of heating systems in buildings, and the electrification of industry, thus confirming that its energy policy has to be driven with a long-run perspective.

Keywords: energy transition; climate mitigation; carbon neutrality; TIMES/MARKAL; France; Sweden

Highlights

- Sweden adopted a more diversified energy policy than France following the 1973 oil crisis
- France faces more difficulties to reach a carbon neutrality goal than Sweden
- Public policies are necessary to steer the energy transition to carbon neutrality
- Public policies on energy transition require continuous, consistent support

1. Introduction

To combat climate change, countries must reduce their greenhouse gas emissions (GHG), as warned periodically by IPCC reports (IPCC, 2018, 2014, 2007). Moreover, in order to maintain the increase in global average temperatures to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C as stipulated in the Paris Agreement, global emissions pathways must achieve neutrality in the second half of this century (IPCC, 2018).

This reduction will require a profound structural change in the energy system, often referred to as an "energy transition" (Smil, 2010). This energy transition will not occur spontaneously and will require the intervention of governments (Fouquet and Pearson, 2012). Past transitions have often been driven by better service and performance, or cheaper energy (Fouquet, 2010), while environmental problems have generally been neglected until the perceived damage became significant enough to be taken into account and translated into environmental regulation (Fouquet, 2012). The current transition faces many obstacles, such as the inertia of technologies and infrastructures, the economic competitiveness of renewable

energy technologies (at least during past decades[1]), and the level of investment required. In addition to a modification of the technology and fuel used, the energy transition must involve a change in consumer behavior (notably in the transport and residential sectors). Public policies like taxes, subsidies, regulation and information have played an important role in shaping the energy system. Thus, it is important to understand the key determinants of these policies when studying the energy transition.

Regarding the future transition of the energy system, it is currently unclear how this transition will take place and what a future sustainable energy system might resemble. As emphasized in the most recent IPCC special report on 1.5°C, many pathways can be chosen to reach a carbon neutrality goal (IPCC, 2018) and countries will have to take decisions regarding the evolution of their energy system.

In order to identify how to make the transition to carbon neutrality we propose to compare the energy transition implemented in two countries that have reduced their CO_2 emissions and fossil fuel dependency and to understand the key elements that drove these evolutions. Although comparative country studies have recently been conducted, they focus on the electricity sector (Cherp et al., 2017; Geels et al., 2016) or the governance system (Laes et al., 2014), and do not analyze the entire energy system. To our knowledge, no comparison between France and Sweden has been published, although some French reports analyze the success of the Swedish energy transition (Bourdu, 2013; Cruciani, 2016; Rüdinger, 2014). Sweden, which has managed to decrease its CO_2 emissions while maintaining its economic growth, seems to be a good example to follow for France as the two countries have some

[1] The cost of renewables sources like PV and wind has significantly decreased since 2010 so that they can now compete with fossil fuels under certain conditions (IRENA, 2018).

similarities, like a high share of nuclear and hydro in power production, and a high biomass potential.

Moreover, both countries have recently committed to ambitious goals regarding their emissions: they are among the few countries in Europe that have pledged to enshrine carbon neutrality in a law, along with Norway by 2030 (Neslen, 2016) and the United Kingdom by 2050 (Walker et al., 2019). France announced in 2017 that it aims to reach carbon neutrality by 2050 (French Government, 2017) and enacted this goal in its recent Energy and Climate Law (French Government, 2019). In 2017, the main Swedish parties signed a Climate Policy Framework that includes a net zero emission target for GHG by 2045 (Cross-Party Committee on Environmental Objectives, 2016). While reducing their emissions, both nations want to rely less on nuclear power: France has committed to reduce its share of nuclear in power production to 50% by 2035[2] and Sweden is aiming at a 100% renewable energy target in the electricity sector by 2040 (Swedish Government, 2016).

The aim of this study is to identify key factors that can drive the energy transition toward a carbon neutrality goal. In order to do so, we propose to first compare the past energy transitions in France and Sweden, two countries that have significantly reduced their CO_2 emissions and fossil fuel dependency. To assess how the current energy system and its regulations impact on the feasibility of meeting carbon neutrality, we compare the future evolution of each country based on scenarios derived from TIMES bottom-up energy system optimization models. Our analysis focuses mainly on the energy system, as it is the main producer of GHG and in particular CO_2 emissions. Thus, we limit our study to a comparison of public policies regarding the energy system coupled with an analysis of the energy system. The paper outline is as follows. Section 2 describes the current situation in both countries and

[2] At the time of the adoption of the law, the target date was 2025 but it was recently postponed to 2035.

looks at the past to understand why the pathways of France and Sweden have been so different since the 1970s, despite both countries having invested in carbon-neutral nuclear power. Section 3 employs TIMES models of both countries to analyze the impacts of their past evolutions on the feasibility of carbon neutrality for both energy systems. Finally, Section 4 identifies critical factors that are important for an energy transition to carbon neutrality.

2. Past evolution of the energy systems in France and Sweden

France and Sweden share several similarities. Both are significant countries in the European Union that developed advanced market economies and welfare systems early on. The starting point of our comparative study is 1970. Three years later, the oil crisis began, leading to a considerable increase in oil prices. This event triggered the marked evolution of energy policies that still influence the current energy mix in Sweden and in France. In 1970, both countries were highly dependent on fossil fuels and especially oil. They thus had high emissions per capita (around 8.5 tCO_2/capita in France and 11.5 in Sweden). Both have since managed to decrease these levels and have some of the lowest emissions per capita in Europe (Table 1), mainly thanks to their low-carbon electricity. Moreover, neither has domestic oil reserves and they thus rely on imports. However, they have significant biomass potential, originating from agriculture and forests in France and mainly from forests in Sweden. France is the second highest consumer of solid biomass for energy purposes in the EU after Germany, while Sweden is the third (EUROSTAT, 2018). These common characteristics allow us to highlight differences that could explain the current situation in both countries. First, we will analyze the evolution of both energy systems and then present the main public policies behind these transformations.

Table 1 Economic and emissions indicators

Indicator	EU average	France	Sweden

	1990	2016	1990	2016	1990	2016
Population [thousands people]	475,188	510,277	58,227	66,730	8,527	9,851
Population growth		*7%*		*15%*		*16%*
GDP [billions € at 2010 exchange rates]	8,988	13,825	1,440	2,122	243	423
GDP growth		*54%*		*47%*		*75%*
GDP [billions € at 2010 exchange rates] per capita	18.915	27.093	24.732	31.801	28.455	42.990
GDP per capita growth		*43%*		*29%*		*51%*
Final Energy Consumption per capita [Mtoe/cap]	2.3	2.2	2.3	2.2	3.7	3.3
Energy per capita [Mtoe/cap]	3.5	3.2	3.9	3.7	5.6	5.0
CO_2 fuel combustion [$MtCO_2$]	4,126	3,234	363	315	52	37
CO_2 fuel combustion growth		*-22%*		*-13%*		*-29%*
CO_2 per capita (energy system only) – [$kgCO_2$/cap]	8.7	6.3	6.2	4.7	6.1	3.7
CO2 emissions - national total (incl. international aviation) [$MtCO_2$]	4,545	3,637	407	357	59	45
CO_2 emissions growth		*-20%*		*-12%*		*-23%*
CO_2 per capita – [$kgCO_2$/cap]	9.6	7.1	7.0	5.4	6.9	4.6
GHG emissions - national total (incl. international aviation) [$MtCO_2eq$]	5,720	4,441	555	475	73	55
GHG emissions growth		*-22%*		*-14%*		*-24%*
GHG per capita – [$kgCO_2eq$/cap]	12.0	8.7	9.5	7.1	8.5	5.6

2.1. Contrasting evolution of the French and Swedish energy systems

In 1970, the share of fossil fuels in France was slightly above that of Sweden (90% vs 80%, see Figure 1). Sweden had low coal consumption (4%) in comparison with France (23%), which possessed moderate coal mining resources to provide cheap energy. In Sweden, coal consumption was mainly confined to the industry while in France, coal was used in industry, electricity production, and buildings. In both countries, oil was used in every sector and was imported (except for a small share in France). Sweden did not use gas, while France had developed a gas network and produced part of the gas it consumed in industry and buildings. The more diversified portfolio in France is explained mainly by the presence of energy resources (coal and gas) that were absent in Sweden. Regarding the other energy carriers, France and Sweden both developed hydro power after the Second World War and both benefited from their biomass potential. Although the biomass share in Sweden was more

significant, in absolute terms France used twice as much of this energy source as Sweden (8.7 vs 3.9 Mtoe by 1970).

From 1970 to 2015, primary energy consumption grew in both countries while the share of fossil fuels declined (Figure 1). In France, coal use decreased in steel production and particularly in the electricity sector. Coal production stopped in 2004 and its consumption is now mainly limited to the iron and steel sector, like in Sweden. In this country, its share has remained stable at around 5% since 1970. Consumption increased slightly around 1985 due to the growing use of coal in district heating, but was later replaced by biomass. Oil consumption has remained relatively stable in France because a decline in the industry and building sectors has been offset by an increase in transport. Unlike France, Sweden has managed to significantly decrease its oil consumption, especially in industry and buildings after the second oil crisis in 1979. The situation of gas is much more contrasted. Unlike France, Sweden has not developed its dependence on gas and has limited the development of a small network to some towns in the South (Meyer, 2017a). Its gas share in final energy consumption is low in comparison to France (2% vs 20% in 2015, see Figure 2), which has increased its gas consumption in industry and in the building sector through imports. Since the 2000s, the gas share in primary energy consumption in France has remained relatively stable (around 15%).

The electricity share in final energy consumption has remained higher in Sweden (15% in 1970 and 34% in 2015) than in France (9% in 1970 and 26% in 2015), although its evolution has been more significant in France. In both countries, a strong increase in nuclear electricity consumption began from 1970 with the deployment of a fleet of nuclear power reactors. Hydro production has remained constant in France, while in Sweden it increased in the 1970s but has remained stable since. In addition to other renewables sources, 93% and 99% of electricity production in 2015 was CO_2-free for France and Sweden respectively.

What is most remarkable in the Swedish pathway is the impressive increase in the use of bioenergy (Figure 1). This evolution in Sweden is mainly explained by the 118% increase in biomass use since 1990, especially in district heating (DH) and electricity production, while in France, biomass production rose by 33%. Bioenergy use is thus much more developed in Sweden than in France although, in absolute values, Sweden uses less biomass (11.6 Mtoe) than France (13.1 Mtoe). The use of biomass in industry in Sweden has been particularly substantial since the 1970s. DH, in combination with electric heating, has enabled the Swedish residential and commercial sectors to be close to CO_2-free. Therefore, Sweden has managed to almost eliminate fossil fuels from space heating. When comparing the transport sector, both countries have similar structures, except for the car fleet, which is mainly composed of diesel cars in France (almost 70% in 2015) and gasoline cars in Sweden (64% in 2015) (Commission des comptes des transports de la Nation, 2018; Transport Analysis, 2019). This leads to lower energy use for transportation per capita in France than in Sweden.

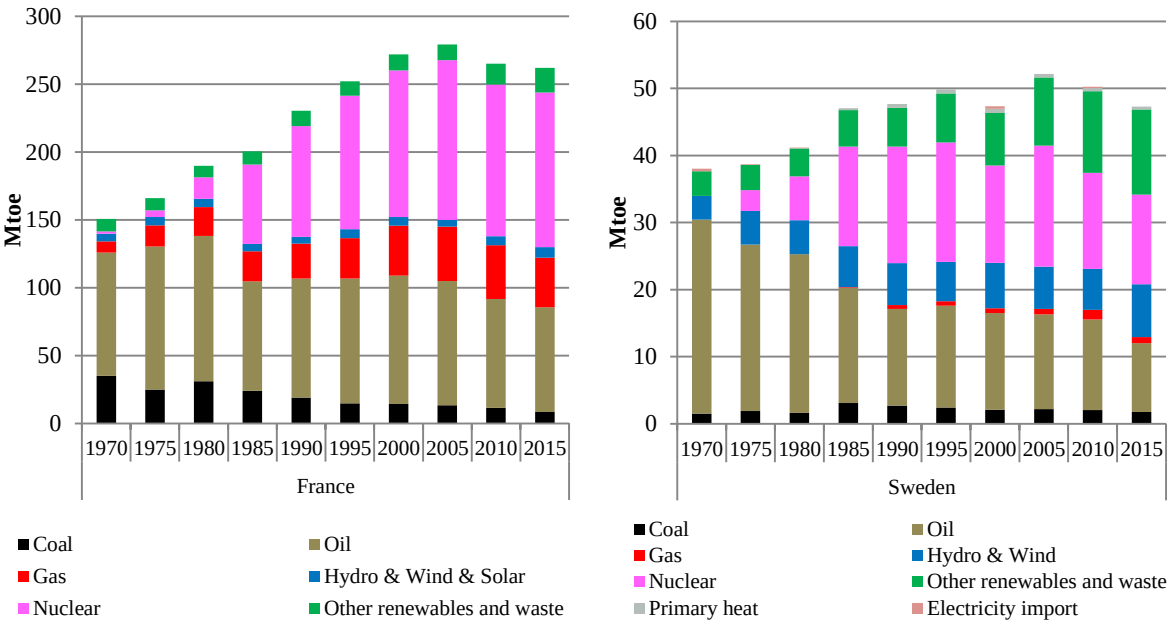

Figure 1 Primary energy consumption in France and Sweden

Notes: From 1970 to 2015, primary energy consumption grew by 74% in France but by only 24% in Sweden. The share of fossil fuels in primary energy consumption amounted to 90% in France, slightly above that of

Sweden, at 80%. It reached, by 2015, 47% in France and 27% in Sweden. The nuclear share in electricity production rose between 1970 and 1990 in both countries and covered 36% of primary energy consumption in 1990. The share of renewables and waste in primary energy consumption increased between 1970 and 2015 from 10% to 25% in Sweden, while in France it increased only slightly from 6% to 7%.

Source: Swedish Energy Agency and SoES MEDDE (France)

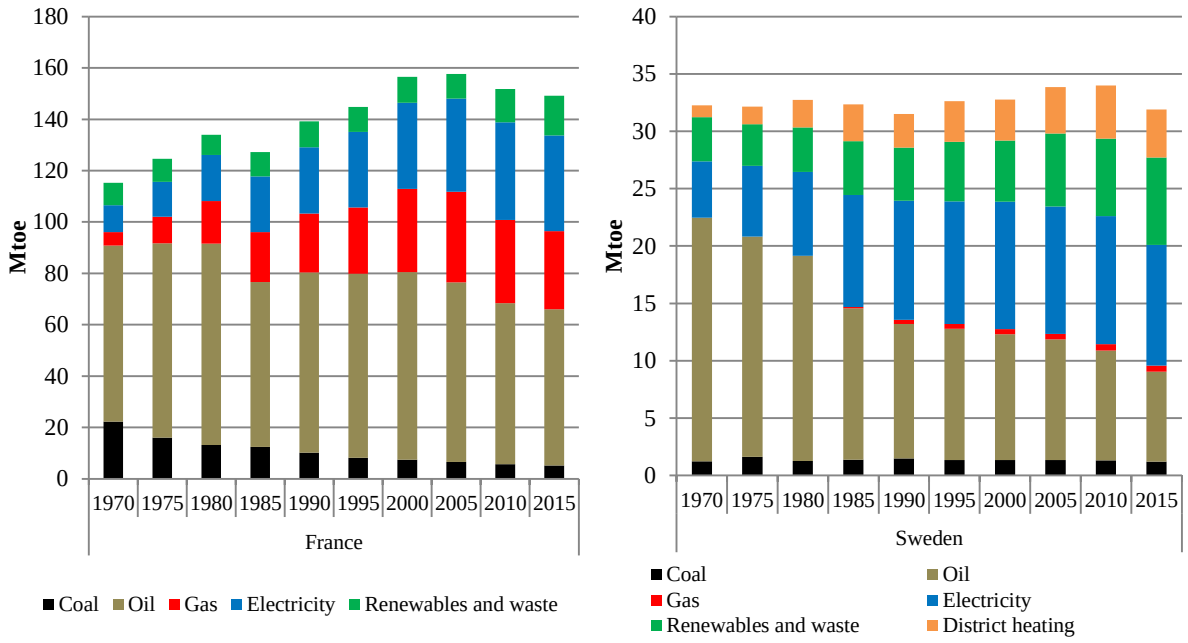

Figure 2 Final energy consumption in France and Sweden

Notes: From 1970 to 2015, final energy consumption grew by 29% in France but decreased by 1% in Sweden. By 2015, the share of gas in final energy consumption had reached 2% in Sweden and 20% in France.

Source: Swedish Energy Agency and SoES MEDDE (France)

While the main evolutions of the French energy system are an increase in gas consumption and the development of nuclear power, Sweden has managed to increase both its biomass consumption and its electricity production with nuclear energy, while decreasing its oil consumption. Sweden seems to have gone further in its energy transition, with a high electrification of its energy system, in particular in industry and buildings; high use of biomass, especially in industry; and the use of oil, mainly limited to the transport sector.

2.2. Technocratic vision focusing on nuclear power in France

With limited domestic energy resources[3], France had imported most of its energy since the industrial revolution, and still purchased nearly 75% of its primary energy consumption in the 1970s. The fear of a resource shortage was already present at the end of the Second World War (Meyer, 2017a). With the economic growth of the *Trente Glorieuses*[4], French energy consumption increased rapidly, and in particular oil, which followed the development of road transport. High oil consumption in the 1970s made the impact of the 1973 oil crisis all the more significant. This event increased state concerns regarding its energy policy goals: energy independence, security of supply, and cost competitiveness (Revol, 1998). Although research regarding nuclear power started long before the beginning of the crisis in 1973, this event reinforced the nuclear program. The government ordered 18 reactors in 1974 followed by 18 other units at the end of 1975, 8 in 1980, and 4 in 1984 (Boccard, 2014; Grubler, 2010). The success of this quick transition in the electricity sector relied mainly on the strong support of a technocratic elite (state engineers grouped into the *Corps d'État*: *Corps des Mines* and *Corps des Ponts*) who could coordinate the program between the French government and the institutions in charge of nuclear power reactor deployment (Finon and Staropoli, 2001; Grubler, 2010), coupled with a unique design that resulted in economies of scale.

In addition, the government also tried to diversify its oil and gas supplies by, for instance, decreasing the share of oil imported from the Middle East (Revol, 1998). The gas network was also extended, although this was part of its continued development since the discovery of gas resources in Lacq in 1954. Another response to the oil crisis was the control of energy consumption. In 1974, measures were adopted by parliament to reduce energy consumption such as daylight saving and lower speed limits for automobiles (Chasseriaux, 1983). The state

[3] Mainly coal in the north and a gas field in Lacq (South of France).

[4] The thirty years from 1945 to 1975 following the end of the Second World War in France.

also created an Agency for Energy Savings (AEE) in 1974 to control and lower energy consumption (Virlouvet, 2015) and in particular oil. The Agency's early reports were positive (1970s) with energy efficiency campaigns and incentives to industry. However, a drop in oil prices, especially in the 1980s and 1990s, and the development of nuclear power decreased the need for energy consumption control. All efforts for energy efficiency measures were abandoned. Starting from the early 2000s, the growing focus on climate change renewed the concern to lower energy consumption.

Although France has large biomass potential thanks to its forest industry and agricultural sector, only a few measures were implemented to promote its deployment between 1970 and 2000. While biomass use by the pulp and paper industry for generating electricity increased, its use for residential heat remained stable. However, since the mid-2000s, new measures have been adopted that have resulted in a slight increase in bioenergy use, and especially the development of biogas and biofuel.

French municipalities were not interested in the development of district heating (DH) (Cassitto, 1990) and its numbers and development have remained limited, because electricity was very competitive thanks to nuclear power in addition to the fact that the climate is warmer than in Sweden and the heating season shorter. On the contrary, due to nuclear overcapacity, the state-owned company EDF (*Électricité de France*), supported by the government, promoted electricity use in the 1980s, especially for electric heating in the residential sector (Finon, 1996). Thus, the electricity sector is now very climate sensitive, since a variation of 1°C results in a power demand of about 2.4 GW (RTE, 2017). The Grenelle laws in 2009 then introduced an objective to decrease energy consumption in buildings by 38% in 2020 compared to the 2008 level, but the tools implemented will not be sufficient to reach this target (Giraudet et al., 2011). However, thanks to different measures like the Heat Fund set up in 2009, nowadays almost half of the DH energy supply comes from

renewable energy, while the other half comprises gas and other fossil fuels (AMORCE, 2016).

Unlike Sweden, France does not have a tradition of taxing energy. The introduction of a carbon tax has been debated since the beginning of the 2000s, but two attempts in 2000 and 2009 were rejected by the Constitutional Council, which considered that there were too many exemptions breaking the principle of equality. Finally, a carbon tax was introduced in 2014 at a rate of €7/tCO_2 in the Energy Transition for Green Growth Law (French Government, 2015) with the objective to reach €100/tCO_2 in 2030 following the recommendations of the Quinet report (Quinet, 2009). Although its value for 2030 is written into legislation, each year the value of the carbon tax has to be endorsed by the finance bill. In 2018, this enabled an accelerated increase in carbon tax: instead of €39/tCO_2, its value rose to €45/tCO_2. However, due to significant popular protests, the increase in 2019 and the coming years was frozen. This slowing down in the evolution of the carbon tax could last a long time. As its introduction is rather recent, its effects on the energy system are difficult to determine (Gloriant, 2018).

The liberalization of the energy sector since the 2000s raises the question of the place of the state, which wants to keep control of its energy policy by setting strategic goals for energy shares. However, its lack of vision for the future has hindered clear goal-setting. For instance, since the enactment of the Energy Transition for Green Growth Law in 2015, which has a goal of decreasing the nuclear share in electricity production to 50%, the implementation of nuclear closure following a specific calendar has been postponed every year: first to the next government, then the announcement of a postponement from 2025 to 2030 (EURACTIV.fr and AFP, 2017), and more recently to 2035 (Wakim, 2018). The government must also deal with the delayed commissioning of the Flamanville plant, foreseen in 2022, 20 years after the first discussion on the launch of a new nuclear plant.

2.3. Multiple tools translating Sweden's ambition to be a frontrunner

Sweden has striven to be a frontrunner and a leader in environmental and climate issues since the 1970s (Matti, 2009). In 1972, Sweden hosted the Stockholm Conference, which marked a turning point in the consideration of environmental issues as international concerns. As Robert Poujade, the first minister of the environment in France, put it, "Sweden was considered the best example in terms of the environment" (Poujade and Frioux, 2012). The country's first climate targets were enacted in 1988 (Swedish Government, 1987) and aimed at stabilizing carbon dioxide emissions. Its most recent climate objectives, which are part of the cross-party agreement of June 2016, are once again among the most ambitious of developed countries: Sweden aims at reaching a goal of 100% electricity from renewable energy by 2040 (Swedish Government, 2018) and aims at carbon neutrality in 2045 by allowing the use of international credits (Cross-Party Committee on Environmental Objectives, 2016). For domestic GHGs, this means that Sweden has committed to an 85% reduction by 2045 in comparison with its 1990 levels; the remaining 15% can be offset by reduction abroad, bio-energy with carbon capture and storage (BECCS) or increased CO_2 uptake in land use, land-use change and forestry (LULUCF). Despite having a 100% renewable target by 2040, the government bill (Swedish Government, 2018) clearly states that this date is not a deadline for banning nuclear power, nor does it mean closing nuclear plants through political decisions[5].

Sweden does not possess any national fossil fuel resources and has suffered from its dependence on oil and coal imports, especially during the Second World War when it had to import coal from Germany. Similar to France, nuclear power research started after the Second

[5] The goal includes a contradiction, the consequence of a very broad parliamentary situation. In Swedish: "…målet år 2040 ska vara 100 procent förnybar elproduktion. Det är ett mål, inte ett stoppdatum som förbjuder kärnkraft och innebär inte heller en stängning av kärnkraft med politiska beslut."

World War with the creation in 1947 of Atomenergie AB. The state was concerned above all by its energy independence (Kaijser and Högselius, 2019) but also considered nuclear energy as a tool for its soft power in the Baltic region, by exporting its nuclear electricity (Meyer, 2017a). Swedish -mainly energy-intensive- industries were also supportive of a nuclear program because they considered it as a means to access cheap electricity. The development of nuclear power began in 1970 with the construction of the Rhingals nuclear power reactor which opened in 1972. The choice of nuclear power was then reinforced by the oil crisis in 1973. In total, twelve nuclear power plants were built until 1985.

However, the Three Miles accident in 1979 triggered some concerns in the population regarding security. Since then, there have been regular announcements that Sweden will phase out nuclear energy, but the move has always been modified, postponed or cancelled, even though the majority of the different political parties in Sweden agree on avoiding nuclear energy. For instance, although the construction of new nuclear power reactors was prohibited with the Nuclear Technology Act of 1984 (Michanek and Söderholm, 2009), the government managed to circumvent the ban by allowing companies to increase the power of existing plants (Meyer, 2017b). More recently, four reactors were shut down in the 2000s and the last announcement regarding nuclear phase-out was made in 2016: the government declared an aim of 100% renewables by 2040 but specified that this was not a deadline for banning nuclear power.

In comparison to France, Sweden has a long tradition of using bioenergy, and even after its industrialization, the share of biomass in energy consumption was still high (nearly 40% in Sweden in 1900 vs 10% in France) (Gales et al., 2007). But after the Second World War, Sweden diminished its biomass share and increased that of oil. The oil crisis thus had a tremendous impact on the economic system. In parallel with the development of nuclear power, bioenergy research programs were launched in order to reduce the country's

dependence on oil (Johansson et al., 2002), like the research program "Whole Tree Utilization" (1974-1977). These programs improved energy efficiency and brought down the cost of forest fuels thanks to rationalization and learning by doing (Björheden, 2006). With increasing environmental concerns, bioenergy development was no longer driven only by the ambition of avoiding fossil fuel imports, but now also with the goal of phasing out nuclear energy (Björheden, 2006). Moreover, the development of policies to use wood was supported by municipalities and by the forestry and pulp and paper industries, which saw it as a way to develop the biomass market (Ericsson and Werner, 2016). All of the research programs, tax incentives and subsidies put in place have benefited from continued, consistent political support (Andersson, 2012; Ericsson et al., 2004) resulting in an impressive increase in biomass use of nearly 170% from 1983 to 2016.

This increase was also enabled by two other factors. First, the existence of numerous DH systems that used mainly coal and could switch to biomass. The development of DH was favored by the Million Homes Program (1965-1974) that was put in place to tackle the housing shortage in Sweden (Di Lucia and Ericsson, 2014; Ericsson and Werner, 2016). After the oil crises, these systems switched to coal, spurred by different incentives, and in the 1990s to biomass, with the result that the residential sector is now almost carbon neutral with a very low consumption of fossil fuel. Secondly, the introduction of a carbon tax in 1991, as part of a major fiscal reform, had the effect of making biomass highly competitive. Along with energy taxes, the carbon tax is considered by the government as a key factor in the success of reducing CO_2 emissions while maintaining economic growth, since the new taxation system maintained a constant tax pressure.

Influenced by ecological modernization, Sweden also relies significantly on innovations that are considered as a means to solve the challenge of climate change (Meyer, 2017c). This trust in innovation was already present in the 1970s when industries and the state collaborated

to invest in new solutions to improve energy independence. Industries were keen to participate in these programs that increased energy efficiency in order to become frontrunners in the development of solutions (Bergquist and Söderholm, 2016). They considered it as a means to improve competitiveness and growth.

After the first oil crisis in 1973, to reduce the country's oil consumption, the government enacted legislation in 1977 to create energy planning for municipalities coupled with energy advisory services for households (Kjeang et al., 2017). Despite its fluctuating role over time, this policy tool stresses the significant role played by the local level in implementing public policies in Sweden, and thus the country's institutional organization. In fact, the establishment of a welfare state model and its institutional arrangements have played a key role in the transformation of the Swedish energy system (Westholm and Beland Lindahl, 2012). Although the model was not designed for this type of energy policy, its evolution in the 1980s with the specific "combination of welfare and competition politics" made the transition possible. The elaboration of public policies in Sweden is known to be pragmatic, rationalist and consensual, thanks in particular to the continuous dialogue that takes place in government commissions between the different stakeholders (Bergh and Erlingsson, 2009).

2.4. Lessons from past energy transitions

The development of the French and Swedish energy systems was the result of different drivers during the 1970s which led to a more diversified energy mix in Sweden than in France. The initial characteristics of an energy system play a crucial role, as they influence its evolution and can generate considerable inertia, as underlined in (Unruh, 2000). Resource availability and geostrategic factors influence energy systems pathways: the discovery of a gas field in France resulted in the development of a gas network and its later expansion, although France has had to import gas. Sweden, which has never had gas resources,

developed its gas network much later and only in the south. Both countries had to import all of the oil that they consumed. The two oil crises, especially the one in 1979, questioned this model. In response to the crises, both countries managed to decrease their oil consumption, but by reacting differently. Although both chose to develop nuclear power to foster their energy independence, Sweden also promoted DH systems, while France reinforced electricity consumption in its residential sector. Sweden fostered bioenergy research and biomass use and managed to increase its consumption faster than France thanks to coherent public policies.

Past public policies were important to govern energy transitions in both countries. They both underwent an energy transition in the power sector with the development of nuclear energy. Sweden also pursued another energy transition in its heating sector, with a strong decrease in oil consumption in the residential and services sector, and the increase of DH, mainly fueled by biomass. Without the set of measures put in place in each country, these energy transitions would not have occurred.

In Sweden, the energy policy is balanced between different public policies. Although most of them were originally designed to reduce oil consumption, they also proved to be effective in reducing CO_2 emissions when environmental concerns emerged. In particular, the energy policy has made it possible for biomass to play a significant role in the Swedish energy system. This country was indeed marked by a more environmentalist vision and stressed the potential role of renewable energies earlier. The success of the Swedish climate policy is also supported by the long-term vision of its government fueled by a culture of consensus and dialogue. This is illustrated once again by the agreement of June 2016 between the opposition and majority parties, which aims at reaching carbon neutrality by 2045. Like Sweden, France prides itself on being a leader on the international climate scene, and recently announced a goal of carbon neutrality by 2050. However, until recently, France had not implemented

strong public policies aimed at changing its energy system. Yet in the future, both countries will have to clarify their energy policy regarding nuclear power. Despite the significant role of nuclear, its future is unclear: Sweden is aiming for a 100% renewable electricity system by 2040 without banning nuclear power, while the French goal of 50% in the mix by 2025 has been postponed to 2035.

3. What transition for the future? Comparison of pathways to carbon neutrality

To analyze the future evolution of the French and Swedish energy systems toward carbon neutrality, we conduct an analysis by comparing the results of bottom-up optimization models. Each model underlines the challenges associated with trajectories to net zero emissions in each sector of the energy system.

3.1. Presentation of TIMES modeling

To study the future evolution of the French and Swedish energy systems, bottom-up optimization models from the MARKAL/TIMES family of energy models are used (Loulou et al., 2016). Energy system optimization models such as TIMES provide a systematic structure of the alternatives described in the model and identify the most cost-efficient measures to meet the given target. Unlike human beings, who are biased forecasters, models have no preference for any particular technology option (Samouilidis, 1980). In addition, comprehensive models can capture cross-sector synergies and conflicts, which are not considered when analyzing an isolated sector. This is of particular importance when assessing how our limited availability of biomass and/or carbon storage capacity can be used in the most cost-efficient way to reach climate targets.

These models have been developed since the mid-1980s within the Energy Technology Systems Analysis program of the International Energy Agency (IEA) and are based on an optimality paradigm: by minimizing the total discounted cost of the energy system over the considered horizon the model selects technologies that can satisfy energy service demands. Each sector of the energy system features a detailed representation of the technologies available and the associated energy flows, along with their technical and economic characteristics, availability date for new technologies, and deployment potential (e.g. for wind or solar). With their technologies, energy and material commodities, and the links between them, the different sectors form a reference energy system. This system features the different potentials of primary resources as well as the different transformation steps to ultimately satisfy energy services. Energy service demands include demands from buildings (heating, cooking, hot water and specific electricity), disaggregated demands for mobility of goods and passengers depending on the transport mode (road, rail, air or river), and lastly demands from agriculture and industry. By explicitly representing the technologies in each sector of the energy system and the commodity flows, the model can describe the system's evolution and show different possibilities of substitution between the different sectors. The French TIMES-FR version and the Swedish TIMES-Sweden version have the same main structure, as described in (RES2020, 2009), and have been adapted to their national contexts to capture the specificities of each country in (Assoumou, 2006) for France and in (Krook-Riekkola, 2015) for Sweden. Both models can explicitly represent all of the CO_2 emissions related to energy combustion.

3.2. Key assumptions

The prices for primary energy resources are specified exogenously and are derived from the "New Policies" scenario of the IEA (2016). The CO_2 prices within the EU Emissions

Trading System (ETS) come from the results of the PRIMES model (Swedish Environmental Protections Agency, 2018, based on reference scenario runs with the European PRIMES model, personal communication). To follow the specificities of each national context, the scenarios for France and Sweden make different assumptions for energy service demands and the limits to available technical options. The costs and other technical characteristics of the process are not necessarily the same, as they can be derived from national data. Moreover, some options are not available in both models, e.g. the power-to-gas option is only available in TIMES-France. The insulation process for buildings is endogenous in TIMES-France, while it is part of an exogenous assumption in TIMES-Sweden. For the representation of biomass, TIMES-Sweden is particularly accurate (Krook-Riekkola and Sandberg, 2018). For France, the lifetime of nuclear plants can be extended by 20 years at a cost of €1,200M/kW, while in Sweden this option is not available since the lifetime of nuclear plants has already been extended. The discount rate is 4.5% in France following the recommendations of (Quinet, 2013), and 3.5% in Sweden in line with the Swedish Transport Administration's 2014 recommendations (SIKA, 2014). The horizon is 2050.

For France, the scenario *FranceNeutrality* respects two main constraints. The first, for carbon neutrality, consists in reaching approximately 11 $MtCO_2$ in 2050. This value was calculated by taking into account plausible reductions in other sectors that are not represented in the reference energy system (waste, non-energy use in agriculture and industrial processes) and by assuming that a sink of 75 Mt will be available (thanks to LULUCF or other means). The level of carbon capture and storage (CCS) available is 20 Mt including 6.5 Mt for the industry sector. The second constraint regarding nuclear states that nuclear electricity production should not exceed 50% by 2035 following the latest government bill (French Government, 2019). Evolutions of energy services demand are derived from assumptions used for national scenarios (BEPM, 2015). Moreover, a carbon tax is introduced according to the

value established in the French Energy Transition for Green Growth Law and concerns all sectors excluding industry and electricity and heat production. It starts at €14.5/tCO_2 in 2015 and reaches €100/tCO_2 in 2030 until 2050.

For Sweden, the scenario is *SwedenNeutrality*. The carbon neutrality target (in communication with the Swedish EPA) has been translated into a net zero CO_2 emission target with the use of BECCS to achieve a maximum of 6.5 Mt negative CO_2 emissions (corresponding to 10% of the emissions in 1990). The scenario respects a linear CO_2 constraint between 2030 and 2045 with a reference emission level in 2030 and a net zero emissions target from 2045 until 2050. The scenario includes existing Swedish taxes (energy and carbon taxes). The evolution of demand for energy-intensive services and goods is based on drivers obtained by soft-linking the TIMES-Sweden model with a national computable general equilibrium model of Sweden (EMEC) (Krook-Riekkola et al., 2017), and transport demand is adjusted according to the official projections of demand (personal communication with the Swedish Environmental Protection Agency).

3.3. Results

3.3.1. Final energy consumption

French final energy consumption decreases by 24% between 2015 and 2050, while in Sweden it decreases by 7% (Figure 3). Electricity consumption in France increases by 60% compared to only 33% in Sweden. The challenge of increasing power production is therefore more significant in France than in Sweden. In France, gas consumption increases until 2035 but decreases afterwards. Natural gas is however replaced by different sorts of gas, biomethane and hydrogen in the gas network. In 2050, more than half of the gas circulating in the network is composed of biomethane. The decrease in gas consumption is thus another

challenge that Sweden will not have to face. Indeed, Swedish gas consumption remains at very low levels throughout the horizon. In Sweden, heat and geothermal energy remain stable in the energy mix. Between 2015 and 2050, the main difference is oil consumption, the decrease in which is partly offset by an increase in electricity consumption.

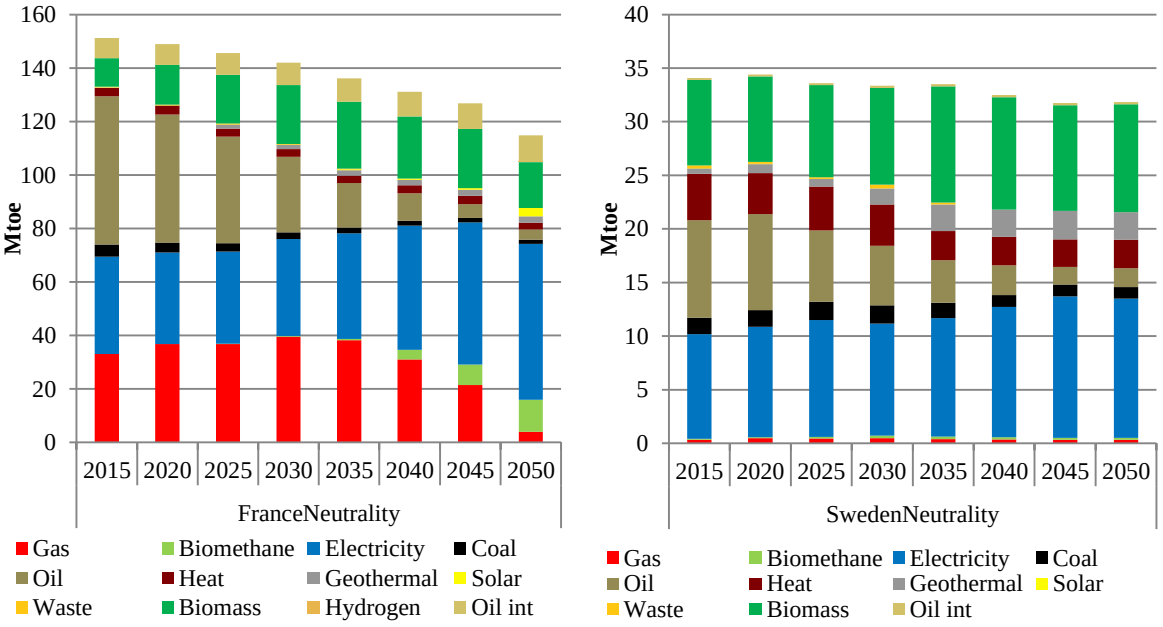

Figure 3 Final energy consumption[6]

3.3.2. Power sector

The results of the French electricity sector show a significant increase in electricity production amounting to 31% in 2050 (Figure 5). Thus, the electrification of the French energy system implies a considerable increase in capacity installations (Figure 4). As the lifetime of some nuclear plants is not extended, there is a slight decrease until 2025. In order to decarbonize the whole energy system, electricity is used more extensively in all sectors. Unlike France, the electrification of the Swedish energy system is already significant. Thus,

[6] Oil int. refers to the oil consumption in international sectors: aviation and bunkers. As there is no constraint on international emissions, oil used for international sectors is differentiated from oil for domestic use.

the power production increase is moderate: + 25% between 2015 and 2050. In comparison to Sweden, France faces more challenges in its electricity sector.

Both countries install significant wind and solar capacities, but Sweden only starts building solar capacities from 2040. France faces difficulties in phasing out nuclear power. Despite the massive installation of renewable capacities and the constraint on nuclear production (maximum 50% of electricity production from 2035), new nuclear power reactors are built from 2040. In addition to the increase in electricity production, France also has to deal with its nuclear dependence, since the current nuclear power reactors are extended. In a scenario with no new nuclear plants, the system finds itself in an "over-constrained" state. To respect the constraints, materials and energy are imported by the system at a very high price. In Sweden, nuclear capacities decrease to zero by 2050. Unlike France, where installation of BECCS (Bio-energy with Carbon Capture and Storage) capacities is limited with the building of only 1.5 GW, Sweden builds 2.6 GW of BECCS by 2045. Moreover, although biomass capacities decline, the higher availability of their load factor leads to an increase in production.

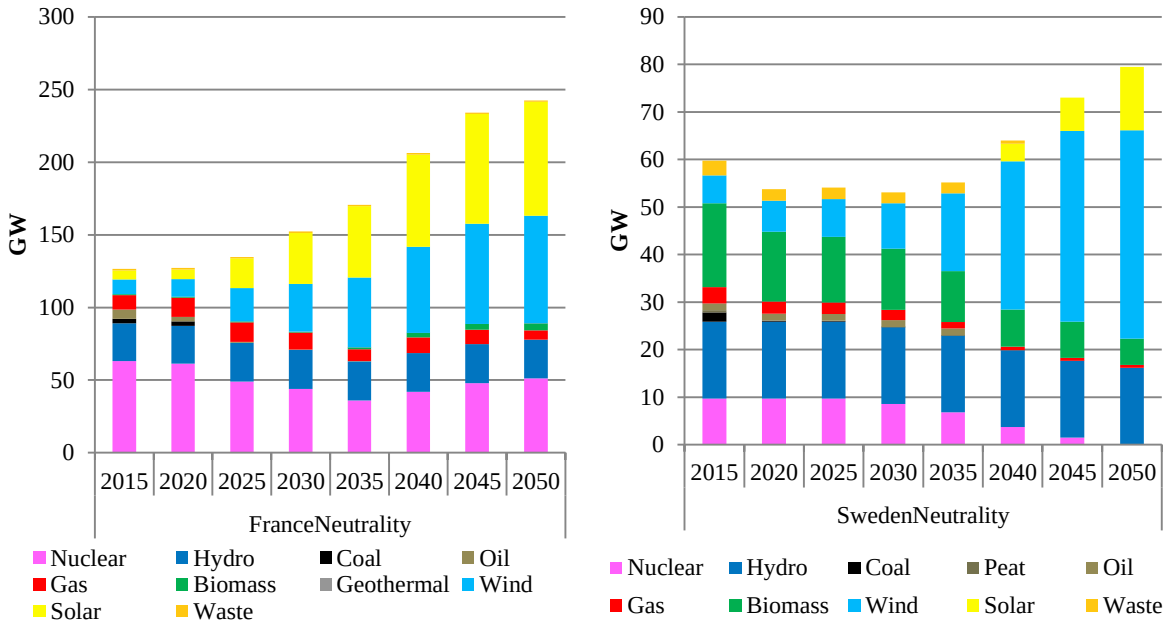

Figure 4 Power plant capacities

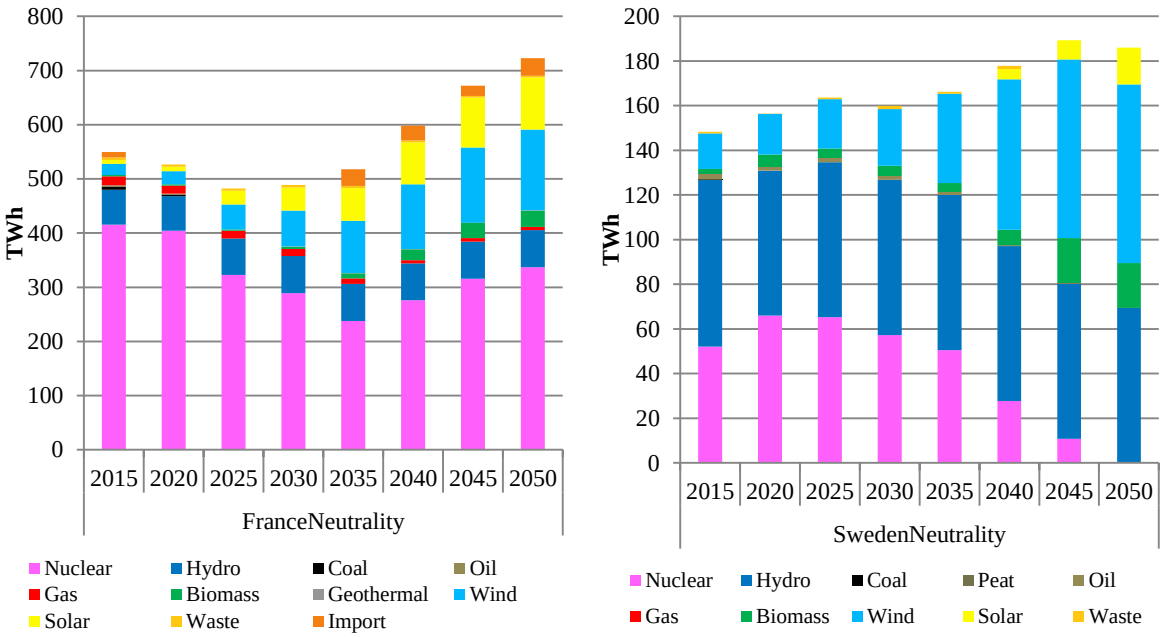

Figure 5 Electricity production

3.3.3. Buildings and agriculture

In Sweden, final energy consumption in the building and agriculture sectors (Figure 6) increases by 6% in 2050 in comparison to 2015, while in France it decreases by 19%. This difference can be explained in part by the development of insulation in France, a technical option that is not available in the Swedish model. Moreover, in France, gas consumption decreases significantly while biomass and biomethane consumption increases. However, for the last period of the horizon, in order to reach carbon neutrality, there is a massive shift toward heat pumps and solar heating. In Sweden, geothermal and biomass consumption increase while electricity consumption remains stable.

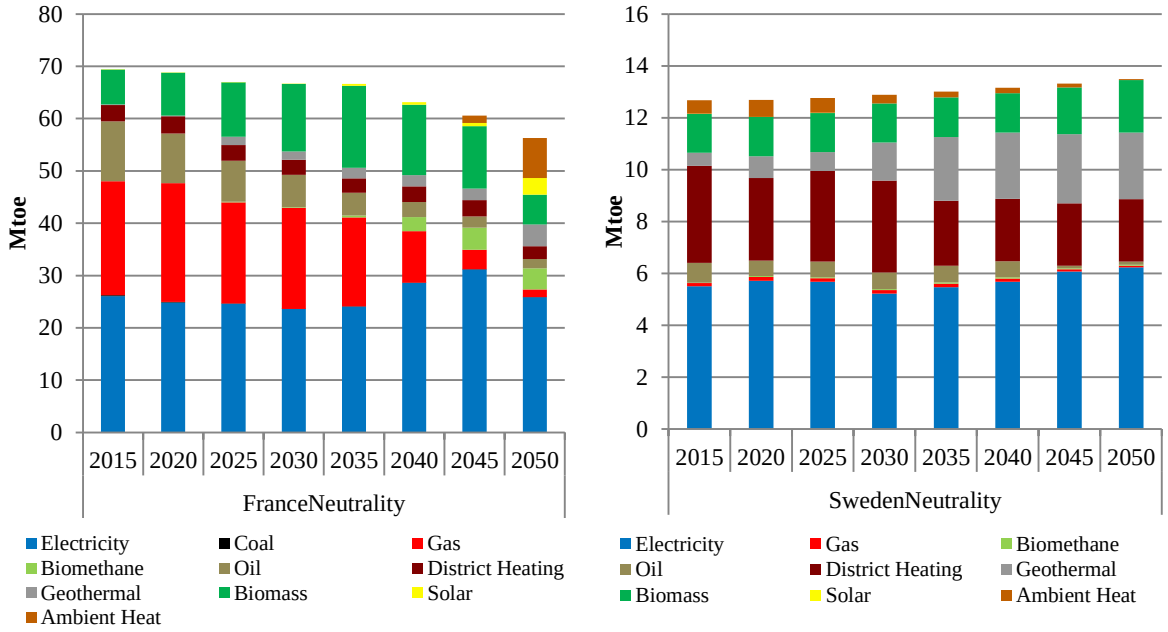

Figure 6 Final energy consumption in the building and agricultural sectors

3.3.4. Industry

As mentioned above, the electrification of the French energy system increases, and particularly in the industry sector. Industry's final energy consumption (Figure 7) increases by 11% in France while it remains stable in Sweden. French gas consumption increases until 2040 before decreasing very quickly in order to reach carbon neutrality. France thus has to decrease its gas consumption in the industry sector, unlike Sweden. Biomass consumption is doubled in France while it increases by only 8% in Sweden. The final biomass share in 2050 remains much more significant in Sweden than in France: 45% vs 12%. The stabilization in Sweden can be explained by biomass use in other sectors, and in particular in BECCS. As its potential is limited, the most cost-efficient way of achieving net neutrality is to use biomass for negative emissions and not to increase its use in industry. Moreover, the overall energy mix changes slightly between 2015 and 2050. The industrial sector has indeed already put in place the cheapest measures to decarbonize its energy consumption. The share of fossil fuels (oil, coal and gas) in final energy consumption is already at a low level, as it amounts to 26%

by 2015 and decreases to 16% by 2050. The French trend is steeper as it goes from 62% by 2015 to 17% by 2050.

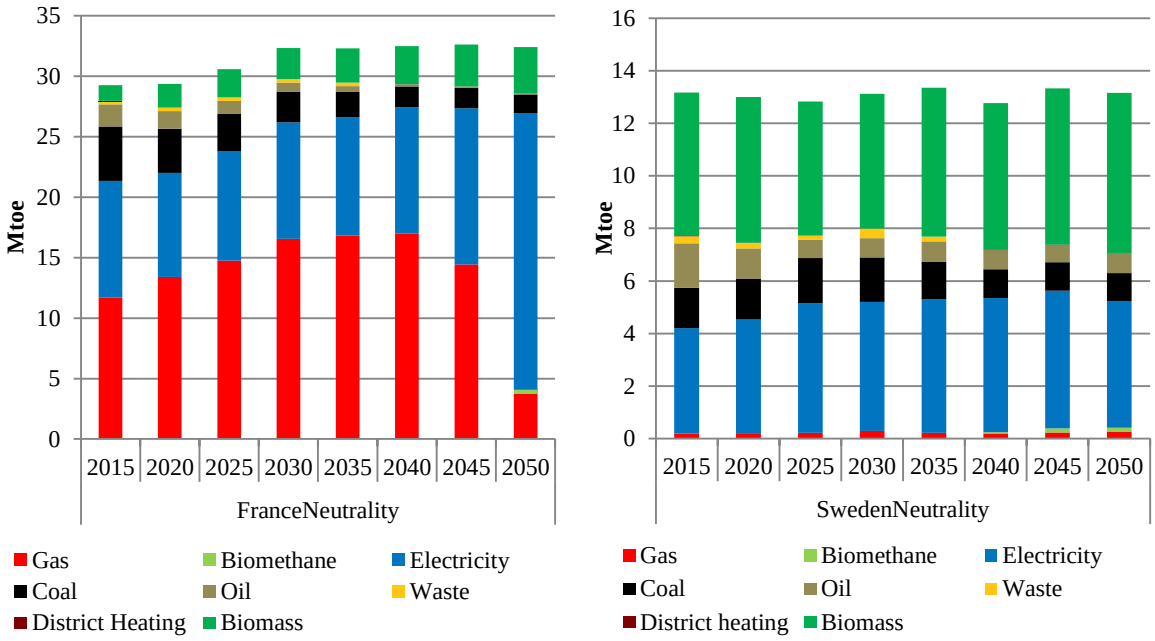

Figure 7 Final energy consumption in industry

3.3.5. Transport

Although in the past neither country has put in place specific policies regarding the transport sector, we observe significant differences in their future evolution (Figure 8). In France, gas consumption increases significantly between 2015 and 2040 and is used in buses and vehicles for goods transport. By 2050, this gas is totally replaced by biomethane. In Sweden, biogas consumption remains very low and biofuels are used more widely. In both countries, electrification of the transport sector increases starting from 2030, but this shift occurs more gradually in France than in Sweden.

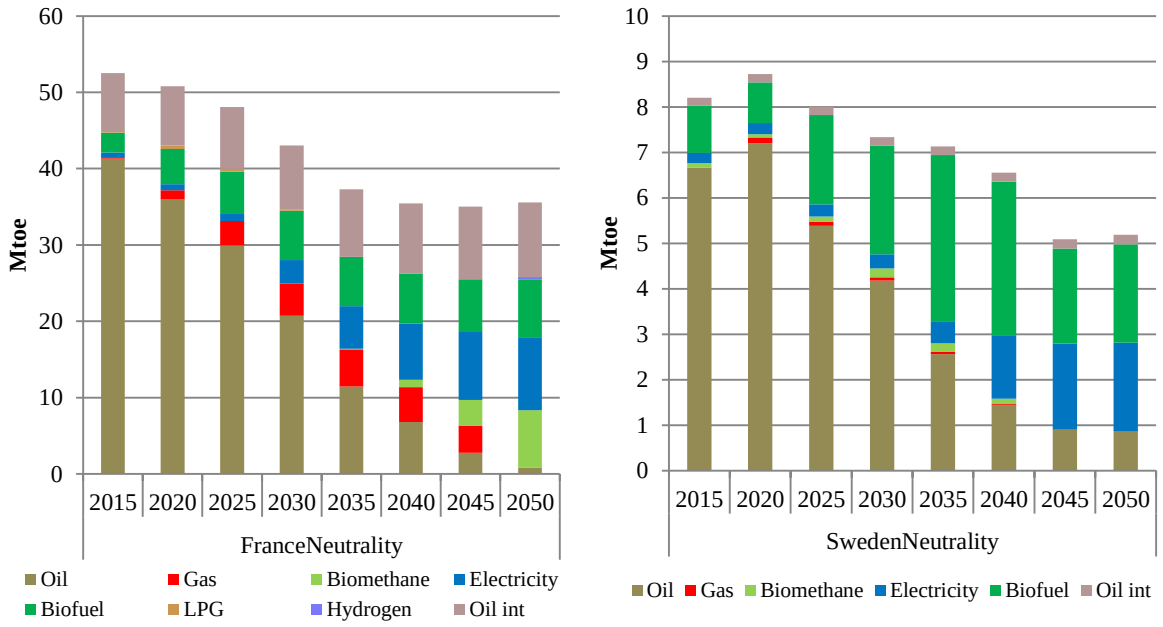

Figure 8 Final energy consumption in the transport sector

3.3.6. CO_2 emissions and marginal cost

In Sweden, between 2015 and 2030, emissions decrease first in the transport and power sectors (Figure 9). From 2030 to 2040, emissions from the industrial sector decrease to a low level. By 2045, the residual emissions from the industrial, transport and agricultural sectors are offset by negative emissions from the power sector. In France, emissions from the industry sector start to decrease after 2035. By 2050, the remaining emissions from the transport, services and industrial sectors are offset by negative emissions coming from the supply sector.

Indeed, respecting the carbon neutrality constraint in France is possible thanks on the one hand to a massive increase in electricity production as seen above, and on the other hand thanks to negative emissions. These negative emissions come from BECCS (bio-energy with carbon capture and storage) in the power sector and from the purification of biogas to biomethane in the supply sector (see Appendix Figure 11). In fact, in order to inject biogas into the gas network, the CO_2 contained in biogas must be removed. Storing CO_2 in the

ground makes it possible to obtain negative emissions (as biogas is a renewable energy that emits no CO_2). Sweden also relies on negative emissions that come mainly from BECCS in the power sector, but does not purify biogas to biomethane. The total volume of carbon stored in the ground amounts to 6.5 $MtCO_2$ per year in Sweden, while in France it amounts to 20 $MtCO_2$ per year.

The value of the marginal CO_2 cost in France is more than €1,000/tCO_2 by 2050 while it amounts to €380/tCO_2 in Sweden (Figure 10). However, by 2045, the French marginal cost amounts to €422/tCO_2 for a constraint to reduce CO_2 emissions by 84% compared to the 1990 level instead of 97% by 2050. The last tons of CO_2 are indeed particularly expensive to compensate as they concern sectors with few possible substitutions, like the iron and steel industries, non-ferrous metal industries, and the agriculture sector. The Swedish pathway thus seems more easily achievable and could translate more realistic goal-setting by politicians.

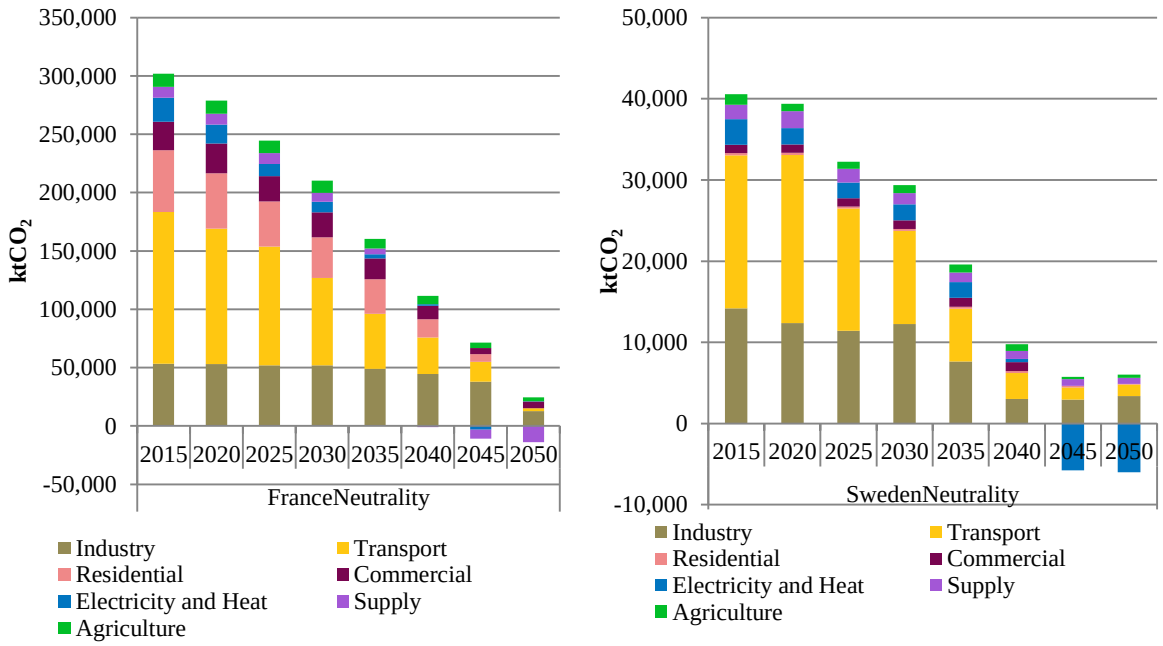

Figure 9 CO_2 emissions

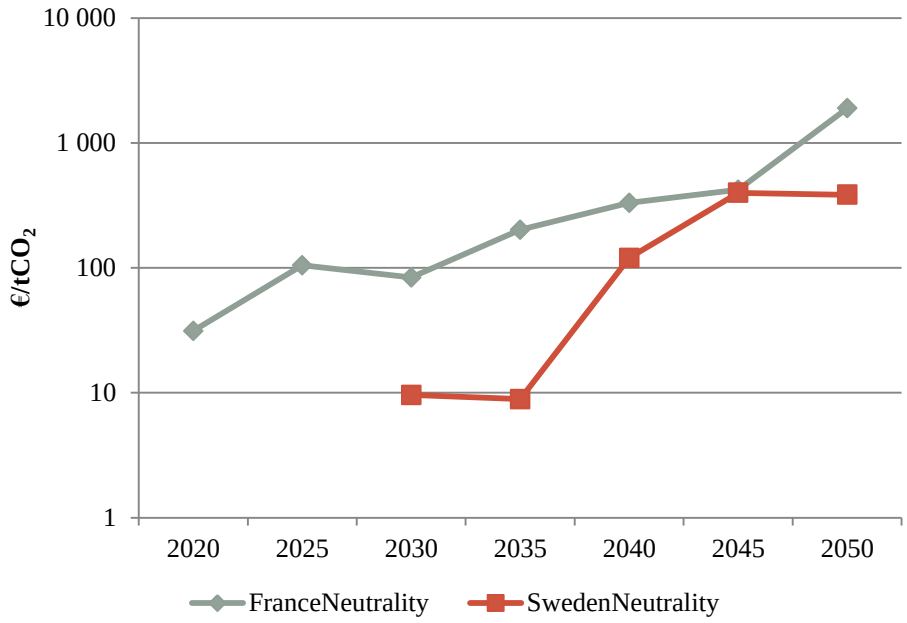

Figure 10 Marginal CO_2 Cost

3.4. Lessons from a prospective analysis

Sweden has already decarbonized many of its sectors and its main challenge is now the transport and industry sectors. On the contrary, France faces many more challenges: although its power sector is almost CO_2 free, its industry sector is not as electrified as Sweden's, and its building sector still consumes considerable amounts of fossil fuels (mainly natural gas but also some oil). As in Sweden, the decarbonization of the transport sector will be a significant challenge with the development of electric vehicles and the associated infrastructures. Moreover, gas consumption in France is significant and will have to be reduced in order to reach carbon neutrality even if biomethane is developed to replace natural gas. France also has to significantly increase its electricity production, which implies the massive development of power capacities, particularly wind and solar. Moreover, bioenergy will have to increase significantly in all sectors. In both countries, hydrogen plays a small role, as both TIMES models instead choose to develop biomass options (biomethane in France and biofuel in Sweden), seen as a more cost-effective solution than hydrogen. Finally, in both countries,

negative emissions are needed to attain the carbon neutrality goal and to offset the remaining emissions from some energy-intensive sectors that are difficult to completely decarbonize (e.g. iron and steel and cement industries). The actual feasibility of developing negative emissions is highly uncertain (Anderson and Peters, 2016) and its unavailability could make it much more difficult to reach carbon neutrality. Moreover, in France, the last official energy pathways rely on a CCS potential of 15 $MtCO_2$ (DGEC, 2019), thus lower than the 20 $MtCO_2$ assumption in the *FranceNeutrality* scenario. The use of this technology must indeed be based on a strong investment in research and development coupled with a concrete institutional commitment which, for the moment, remains theoretical in France (INERIS, 2017). However, since CO2 re-use in materials is not represented in either model, taking it into account could actually reduce the difficulty of reaching stringent climate targets (Detz and van der Zwaan, 2019).

4. Conclusion and policy implications

This paper discusses the differences between the Swedish and French energy transitions in the past and for the future. An analysis of the past public policies in each country makes it possible to explain the current structure of the energy mix. The Swedish and French energy systems shared several similarities in the early 1970s (use of oil, hydropower and nuclear program). With the energy crisis, their energy mixes evolved differently: Sweden put in place a balanced set of measures while France mainly focused on nuclear power and therefore the development of electricity, despite the availability of similar renewable energy resources (hydro and biomass). The energy transition of the power sector with the development of nuclear energy occurred in both countries, while Sweden also had an energy transition in its heating sector with the development of DH fueled by biomass.

Public policies have played an important role in these energy transitions, but they were not driven by environmental concerns since they were neither designed to reduce CO_2 emissions nor to embark on an energy transition. Their goals were to foster energy independence, decrease oil consumption, and preserve cost competitiveness. The common characteristic of these effective public policies was strong, continuous political support. The decision to launch a nuclear program in both countries was made prior to the oil crisis, but the latter reinforced support to move to nuclear energy. The move to bioenergy in Sweden was initially an attempt to reduce oil consumption, although it later proved efficient in reducing CO_2 emissions. As climate awareness grew, past decisions in the country turned out to be effective to reduce emissions and establish a low-carbon energy mix. In particular, the introduction of a carbon tax proved to be effective in the building and power sectors because alternative technologies were available. Despite the high level of this tax, it has not been sufficient to trigger an energy transition in the transport sector (Tvinnereim and Mehling, 2018).

The future transition to a low-carbon energy system will not look like the past transitions. Both countries need a long-term vision for the future of their energy systems in order to take a new direction and avoid inertia. With the TIMES modelling framework, we analyzed the implications of carbon neutrality goals on the evolution of the energy mix in each country and their feasibility. According to our scenarios, the higher marginal CO_2 cost in France shows that the Swedish goals seem to be more consistent and realistic than the French ones. As French public policies were initially almost solely focused on the development of electricity, it is now difficult to align legislation objectives with the competitive development of the energy system.

Initial conditions and national resources have an impact on the optimal evolution of an energy system, as shown by our analysis. However, public policies play an important role in steering the energy transition. Several policy implications emerge from the analyses presented

above. First, the energy transition to net zero emissions should be accompanied by diverse public policies like taxes, subsidies, regulation and information. Secondly, public policies should set realistic and achievable climate goals since they determine different energy system trajectories. A stricter carbon neutrality goal in France implies a significant increase in the marginal CO_2 cost, and is difficult to achieve unless new low-carbon technologies emerge or unless energy services demand decreases more than expected thanks to changing lifestyles or lower industrial production. Thirdly, these targets should be supported by a long-term vision for the energy system. Investments must be anticipated in some technologies, like nuclear and CCS. Lastly, public policies should benefit from consistent, long-term support in order to make their targets credible and to foster investment in low-carbon technologies. In Sweden, biomass could grow thanks to continuous political support.

Cross-country comparisons are very useful because they highlight the similarities and differences that each country will have to take into account for their future energy systems pathways. In the European case, with an overall EU target, this means that each country will have to follow a specific trajectory and therefore that different public policies will have to be put in place to reach European objectives. Undifferentiated measures would not support sectors that are specific to certain countries (e.g. exit from natural gas). Governance structures also vary widely from one country to the next (e.g. centralized vs decentralized). Pair studies show what works in one country and could apply to others, while highlighting the challenges and barriers that each country faces.

Finally, as shown above, governance will be crucial for guiding the transition to a climate neutral energy system. Although the energy policies of both countries were influenced by the presence of natural resources, they were still driven by the government. Until recently, despite a decrease in CO_2 emissions in both countries, public policies have not been driven by climate issues. France has always planned its energy investments in a very centralized way, while the

Swedish energy system has been influenced by municipalities' energy planning. Moreover, there has been no centralized body in either country that could help monitor the national energy transition. New governance tools have lately emerged to lead the energy transition with the establishment of bodies inspired by the British system: the Climate Policy Council in Sweden and the High Council for Climate in France. Their effectiveness will have to be assessed over the coming years.

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7. Appendices

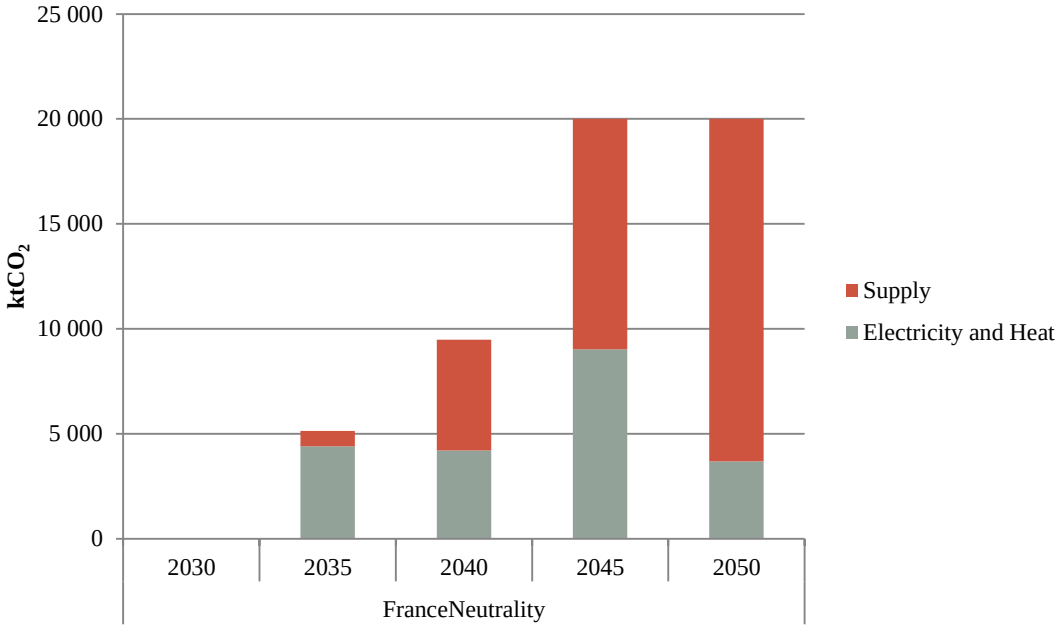

Figure 11 Origin of CO_2 emissions to be stored (Level of CCS)