Modeling the low-carbon energy transition of the territories: a TIMES-SUD PACA model to assess the long-term decarbonization strategy of the south-east region of France

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Abstract

The SUD Provence-Alpes-Côte d'Azur Region in southern France recently redefined its objectives concerning the decarbonization of its territory and especially of its energy system. This was a response to guidelines specified in different climate-energy laws and plans, which establish both national targets for greenhouse gases, energy production, and air quality, and strategies to reach a low-carbon scenario in 2050. In addition, the NOTRe law gives the French regions the necessary competences to develop their own energy system and policies related to other climate topics. Thus, a TIMES-SUD$_{PACA}$ bottom-up optimization model representing the electricity sector of the Région SUD was developed in order to analyze the impact that these policies might have on the decarbonization of the electricity sector. This decarbonization presents specific challenges compared to the rest of France, such as risks for electricity supply due to a non-looped electricity grid (a situation qualified as an electricity peninsula) that affects the east of the region, and a high level of renewable potential, but a low local energy production. First results from the model show that decarbonization of the Région SUD electricity sector is possible involving the use of local available renewable resources.

Key words: Regional energy system, Long-term modelling, TIMES-SUD$_{PACA}$, Low carbon transition

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1. Introduction

Studies of energy systems developed rapidly following the oil crises in the 1970s, with the effect that global, multi-country, and national energy systems started to become strategic analysis tools. The most relevant issues studied by these models initially centered their attention on forecasting demand, substituting or optimizing the use of oil, and determining the effects of energy prices on supply disruption, trade and oil production (Charpentier, 1974, 1975; J.-M. Beaujean & Charpentier, 1978). Towards the end of the twentieth century, new concerns about the use of fossil fuels and the detrimental effects of carbon-based societies on the environment, the climate and people's health, pushed policy makers and the modelling community to consider new constraints when studying and

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modelling energy systems, especially the reduction of greenhouse gases (GHG) and the use of alternative energies (Markandya, 1990). In order to reduce energy-related GHG emissions, energy model analyses started to include high levels of renewable energies in a centralized production. This is because renewables can provide an important source of clean energy, even though their intermittent nature introduced a challenge in order to allow fast, widespread development of these types of energy (Henning, 1997; Iniyan, Suganthi, Jagadeesan, & Samuel, 2000; Lew, 2000; Rozakis, Soldatos, Papadakis, Kyritsis, & Papantonis, 1997; Santisirisomboon, Limmeechokchai, & Chungpaibulpatana, 2001). With the liberalization of energy markets at the beginning of the twenty-first century, and the paradigm shift of producing energy from a centralized perspective to a decentralized one, the interest in modelling smaller geographical energy systems increased, namely intra-national energy systems (Caramanis & Haurie, 2017; Cormio et al., 2003; Freppaz, Minciardi, Robba, & Rovatti, 2004; Knoeri, Christof ; Goetz, Alessandra ; Binder, 2014; Maier & Gemenetzi, 2014; O'Keeffe, Majer, Drache, Franko, & Thrän, 2017; Sarafidis, Diakoulaki, Papayannakis, & Zervos, 1998; Schmidt et al., 2012; Thellufsen & Lund, 2016). Modelling intra-national energy systems allows the representation of local available resources in the area under study, and local specific energy challenges. These models focused their attention on analyzing individual energy systems, with the purpose of achieving decentralized energy production, covering urban areas, regions and states. However, they failed to study the relation of these systems with their neighbors or with domestic energy systems, at the risk of providing incomplete insights.

In 2015, France adopted a law on "Energy Transition for Green Growth" (*Transition énergétique pour la croissance verte* (LTECV) in French) and redefined its national objectives on greenhouse gases, energy production and air quality, integrating in particular a low-carbon strategy that all energy planning schemes must integrate. At the same time, a law called the New Territorial Organization for the Republic (*Nouvelle Organisation Territoriale pour la République* (NOTRe) in French), also adopted in 2015, modified the division of territorial competences and made the French regions responsible for energy, air and climate issues. It also created the Regional Plan for Urban Development, Sustainable Development and Equality of Territories (*Schéma Régional d'Aménagement, de Développement Durable et d'Égalité des Territoires* (SRADDET) in French) which aims to rationalize the number of existing documents by merging several sectoral schemes, including The Energy Transition for Green Growth (*Plan Climat Air Energy Territorial* (SRCAE) in French) to improve coordination of regional public policies on spatial planning. Moreover, on December 2018, the Ministry of the Ecological and Solidarity Transition published the draft revised National Low Carbon Strategy (*Stratégie Nationale Bas Carbone* (SNBC) in French), establishing the different strategic directions, for all activity sectors, that will lead to the transition to a low-carbon and sustainable economy throughout France. Its adoption is scheduled for the second quarter of 2019. These low-carbon transition objectives will be taken into account for the development of the SRADDET (which now will include the SRCAE) which is planned to be delivered mid-2019.

Consequently, the SUD – Provence-Alpes-Côte d'Azur region (Région SUD), in the south-east of France, now has to develop a low-carbon transition strategy while taking the opportunity to consolidate its efforts to overcome many of the issues affecting its energy system. Indeed, the region presents some specific characteristics with respect to its security of supply, greenhouse gas emissions, environmental restrictions, and economic behavior. These challenges are not evenly distributed around the Région SUD territory, and the issues affecting its energy system are particularly localized. For example, the high concentration of energy consumption and greenhouse gas emissions on the coast contrasts with the low consumption and emissions in the backcountry, which also harbors a high level of renewable energy sources. Moreover, the east of the region presents an energy peninsula situation, as electricity is supplied through a non-looped electricity network which is subject to high risks that can affect electricity supply. Thus, modelling provides a good opportunity to analyze possible solutions to these challenges. Bottom-up optimization modelling is particularly useful, as it allows a deep analysis of the energy system through a clear representation of each of the energy systems that integrates the whole region with its associated characteristics. Different scenarios can be constructed, providing interesting insights into potential trajectories that might lead to an energy transition for the territory.

2. The SUD Provence-Alpes-Côte d'Azur Region

The Région SUD in southern France had a population of around 5 million people in 2014 and is composed by six *departments*. The biggest *departments* in terms of population and economy are Bouches-du-Rhône [13][2] which represents 40% of the population in the region, followed by Alpes-Maritimes [06] and the Var [83] which together account for 43% of the total population. These areas are characterized by the fact that their population and economic activities are concentrated on the coast. The rest of the departments located inland, are the Vaucluse [84] with 11% of the population, Alpes-de-Haute-Provence [04], and Haute-Alpes [05] both representing 6% of the population of the region. Concerning the energy consumption of Région SUD, it represents the fourth largest consumer of final energy in France, with 12 Mtoe in 2015, accounting for 8% of national energy consumption (ORECA 2016). This consumption is characterized by the predominance of fossil fuels and a large share of petroleum products. This is explained by structural characteristics, namely a larger industrial sector than in the rest of France (consuming 37% of regional energy), and the energy consumption of the transport sector, which is also particularly high, even if it remains comparable at the national level (around 35% of total regional energy consumption). With one-third of the region's energy consumption, the residential and tertiary sectors are also significant, the largest energy use being characterized by heating (75%), mostly electric. Concerning the territories of the Région SUD, the biggest consumer, Bouches-du-Rhône, represents 45% of the final energy consumed in the region due to the presence of a large high-energy industry and its high population. The difference in consumption with the second highest consumer, Alpes-Maritimes, is around 2500 ktoe and with the lowest consumer, Hautes-Alpes, around 4,000 ktoe, making a difference of 20% and 40% respectively. The building and transport sectors in each department represent similar shares of total consumption, with an average of 25% for buildings and 45% for the transport sector. Despite this, each department has contrasted demands due to seasonal variances, namely due to tourist activities, and a high concentration of economic activities and demographics on the coast, which is located far from production sources. This last issue is the case in the Alpes-Maritimes, Var, and Bouches-Du-Rhône.

Compared to its high consumption level, the region produces only 11% of the energy it consumes. The electricity and heat productions are mainly derived from renewable primary resources, 43% from hydraulic origin and 13% from biomass, including wood. Concerning electricity, the region produces around half of its requirements, importing the remaining amount. The Région SUD concentrates 15% of French hydropower production (RTE, 2018), thus ranking third in the country. For photovoltaics, it

[2] The figure in brackets indicates the administrative number of each *department* in France.

also ranks third regarding power connected to the grid, but wind installed capacity and production are almost negligible. Even though the region does not possess fossil fuels, the electricity production based on these commodities is 36% of the total production, principally from natural gas. The total consumption of fossil fuels, mainly of oil products for its transport and industrial sector, produces high greenhouse gas emissions, reaching 47,147 kt CO_2eq, mostly concentrated on the coast. An analysis of the production of each *department* shows similar behavior to the consumption patterns. As shown in Figure 1, final energy production is equally uneven in each department, but the difference in production from one territory to another is not as big as the gap in consumption. The biggest producer, Bouches-du-Rhône, has a difference of around 750 ktoe with the lowest producer, Hautes-Alpes.

On the other hand, the territory presents interesting potential in terms of primary renewable energy production that could help to cover some of the weaknesses of security of supply. In terms of solar, hydraulic, and wind potential alone, the region amounts to 9,244 MW, producing around 16,000 GWh/an, which could cover most of the electricity that is not produced locally and be delivered through the national network. Most renewables potentials are limited due to environmental and patrimonial constraints. The right axis on Figure 1 shows the technical potential production that renewable energies present in each of the departments of the Région SUD in 2050. The renewable energy potentials depicted in Figure 1 include solar photovoltaic (on buildings around 400 ktoe and on the ground 700 ktoe), on-shore wind at around 300 ktoe, hydraulic at 94 ktoe, biogas at 400 ktoe, wood at 700 ktoe, and power-to-gas at around 900 ktoe. These potentials are also very unequally distributed around the region, and the highest potentials are located far from consumption hubs, which would lead to greater usage of the network, thus increasing the risks affecting it.

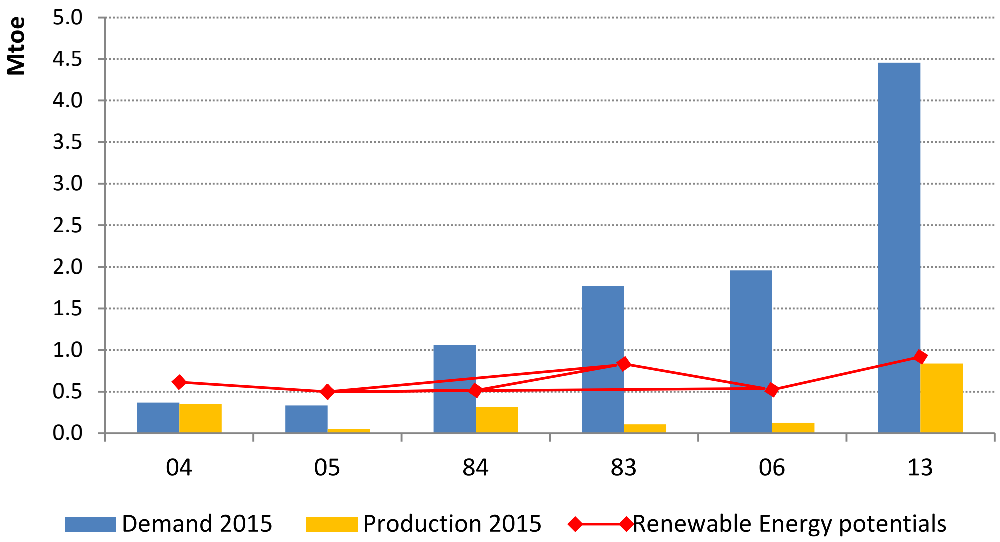

Figure 1. Comparison of energy systems of *departments* in the SUD PACA region

Alpes-de-Haute-Provence [04], Haute-Alpes [05], Vaucluse [84], Var [83], Alpes-Maritimes [06] Bouches-du-Rhône [13]

Moreover, the east part of the region is in an “electric peninsula”, in other words its supply of electricity is dependent on a single, unconnected high-voltage network. This network is subject to various risks, such as the insufficiency of the network to meet high consumption peaks or network voltage collapse following an accidental and sudden breakage of the single high-voltage line, after which the other lines would be insufficient to meet demand (Préfecture PACA). This risk of power failure is expected to occur approximately once every three to four years and increases with the level of regional consumption. A shutdown due to a forest fire, as in 2001, 2003 or 2005, is one of the risks of rupture for example. It should be noted that forest fires are more frequent during long periods of drought. Serious damage to the south axis due to sticky snow, landslides, technical failure of pylons or other accidents can also lead to a blackout in the eastern part of the Région SUD. Various solutions to increase interconnections and secure the power grid have been analyzed, such as the construction of a second line, but technical and environmental constraints have not yet resulted in their development. Other concerns affect the Région SUD energy system. One of these is that the electricity produced from hydro resources, which in itself is low compared to electricity consumption, can be affected by long periods of absence of rain, increasing the pressure on the use of the network. Seasonal variations in terms of demand are also important facts to take into account.

When analyzing the energy system of the region as a whole, it is possible to identify clear challenges to overcome such as the low production, dependence on the electricity national network, concentrated consumption and emissions, underdeveloped renewable energies potentials, and technical, environmental and patrimonial constraints. Modelling the region as a whole can lead to misleading results as each territory that constitutes the Région SUD has heterogeneous characteristics. Hence studying cooperation between energy systems in the lower geographical areas (by *department* or even by breaking them down into smaller areas like coast and countryside) is an exercise that could lead to very interesting insights.

3. Methodology

The modelling of the Région SUD energy system will be developed under the TIMES framework by building a TIMES-SUD_{PACA} model. TIMES stands for “The Integrated MARKAL-EFOM[3] System”, which was developed under the IEA’s Energy Technology System Analysis Program (ETSAP). TIMES is a bottom-up model generator using a partial equilibrium under a linear optimization paradigm, with an objective to satisfy the exogenous demand of energy services at the lowest possible discounted cost for the development of the energy system in a time period and under constraints defined by the user (Loulou & Goldstein, 2005).

TIMES-SUD_{PACA} allows a rich detailed representation of each energy system in the six *departments* that constitute the region in order to depict the specific issues that affect each system. This representation includes: primary available energy resources; transformation, transportation and distribution processes with their respective technical-economic costs (including the electrical interconnection between the region and the rest of France); and end-use energy demands. Demand is represented in five different sectors: transport, residential buildings, commercial buildings, industry, and agriculture, with their respective associated energy services. Examples of energy services in the building sector are: lighting, heating, cooling, and specific electric devices, etc. It also includes potential technologies that could be developed, and the energy carriers that are consumed or produced with their respective required investments. In other words, it establishes the relation and flow of commodities that through the processes convert commodity carriers into energy services, thus producing the Reference Energy System (RES) which is presented in **Erreur ! Source du**

[3] MARKAL stands for Market Allocation model, presented for the first time in (Fishbone & Abilock, 1981). EFOM stands for Energy Flow Optimization Model, (Finon, 1974; Van der Voort et al., 1984).

renvoi introuvable.. Finally, the model gives as results: the evolution of the structure of the energy system for each department; the investment needed for this evolution; the operating cost of the developed technologies; the energy flows among the represented technologies; the energy consumed by type of commodity; and the related emissions. The time horizon for this model is 2050 and the reference year is 2015.

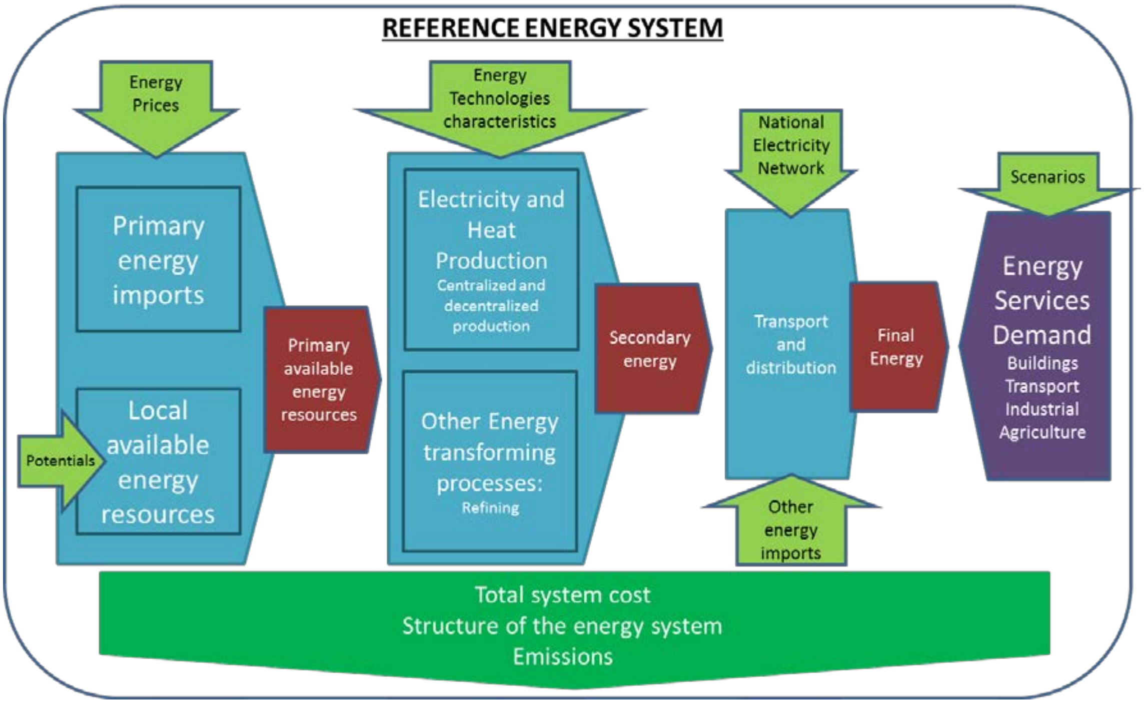

Figure 2: Reference Energy System

4. Scenarios

The Région SUD, like the other regions in France, operates under the framework of the LTECV law, which provides guidelines for the establishment of local objectives, resulting in different trajectories for energy transition in each territory. "*The objectives of the law are to ensure the energy transition of territories and thus prepare the post-oil period and establish a robust and sustainable energy model to meet the challenges of energy supply, changing prices, depleting resources and the imperatives of environmental protection*"[4]. In order to identify the different possible paths to an energy transition for the SUD PACA region, two scenarios will first be investigated.

Business-as-usual scenario (BAU): This scenario takes into account the evolution of the energy system over the last five years in order to project its possible evolution to 2050. The model chooses from among the different energy options to cover demand at the cheapest possible cost. It features few restrictions limiting fossil fuel development because significant developments are not possible in the region as presented in (Mirakyan, Lelait, Khomenko, & Kaikov, 2009). Even though this study was developed in 2009, its remarks are still valid. Moreover, it features no further constraints for emissions, does not promote any energy, and does not take into account other efforts to reduce energy consumption. According to previous annual trends, energy consumption demand decreased

[4] https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte

at a rate of 1% each year, but electricity demand grew at a positive rate of 1% due to increased access to electric services for all sectors.

Carbon Neutral scenario: In this scenario, to accompany France in its efforts to reach a carbon-neutral energy system in 2050 and to strengthen its commitment to cope with climate change, reduce greenhouse gas emissions, and improve the quality of life of its citizens, the Région SUD has redefined the objectives proposed in its Schéma Régional Climat Air Energy (SRCAE, 2018). The established objectives to reach a carbon-neutral scenario include: first, fostering the development of local available energy resources and reducing fossil-fuel based production; and second, reducing final energy demand by 30% in 2050 with respect to 2007 (Table 1). The increasing renewable production and decreasing demand in this case aim to complement each other in order to reach a carbon-neutral scenario. This scenario will first analyze how the objectives involving production affect the electricity sector without taking into account objectives that alter demand, in order to later include the demand objectives and compare both situations. Therefore, this scenario will analyze the impact of these policies on the energy systems of the different territories in the region and provide interesting insights as to whether they will be sufficient to achieve a carbon-neutral scenario.

Table 1. Principal objectives affecting the electricity system of the SUD PACA region detailed in the SRCAE

	2020	2030	2050
Hydroelectricity (ktep)	780	780	835
Wind onshore (ktep)	71	133	258
Wind offshore (ktep)	22	344	688
Solar (ktep)	760	1292	5162
Large biomass power plants (ktep)	91	111	111
Demand	-8%	-15%	-30%

Other scenarios will be developed with further construction of the model and according to any insights obtained after the upcoming meetings with regional actors.

5. Results and discussion

To date, a first version of the TIMES-SUD$_{PACA}$ model representing the electric system of the Région SUD has been developed and, in a first instance the *BAU* and the *Carbon Neutral scenario* have been analyzed. This first model does not intend to break down the electricity system of the region into *departments* as the region will be first studied as a whole and then compared with the results of the model that include the energy systems of each department.

For the development of the TIMES-SUD$_{PACA}$ electric system model, the *BAU* and *Carbon Neutral* scenarios were implemented, taking into account only the objectives and other constraints that affect demand and consumption in the electricity sector. For the demand side, the *BAU* scenario establishes that electricity demand will increase by 1% per year until 2050 for each of the electric services according to previous annual trends, and the same goes for supply.

In this way, the model gives as a result the possible paths that the energy sector can follow. First, in the BAU scenario, the use of fossil fuels is reduced by around 70% in 2050, representing 3% of electricity production, and its emissions account for 3.5 Mt CO_2 which is a reduction of around 50%. On the other hand, the development of renewable production increases, especially solar production, which represents around 2,000 ktoe and accounts for around 32% of the electricity produced in 2050, and almost 60% of the renewable production (Figure 3). Moreover, hydroelectricity and wind represent around 15% and 4% respectively for electricity production, while the use of biomass represents just 5%. Furthermore, renewable electricity production has increased considerably, going from representing around 25% of the electricity production in 2015 to around 55% in 2050. The rest of demand is covered by use of the network, which in 2050 represents 39% of the total electricity supply, and thus a reduction of 15%. Total local production increases from 45% to around 60%, which means that it is possible to increase local production to substitute fossil fuel use, and reduce the use of the national network at the same time, which decreases the risks affecting it and improves the security of supply.

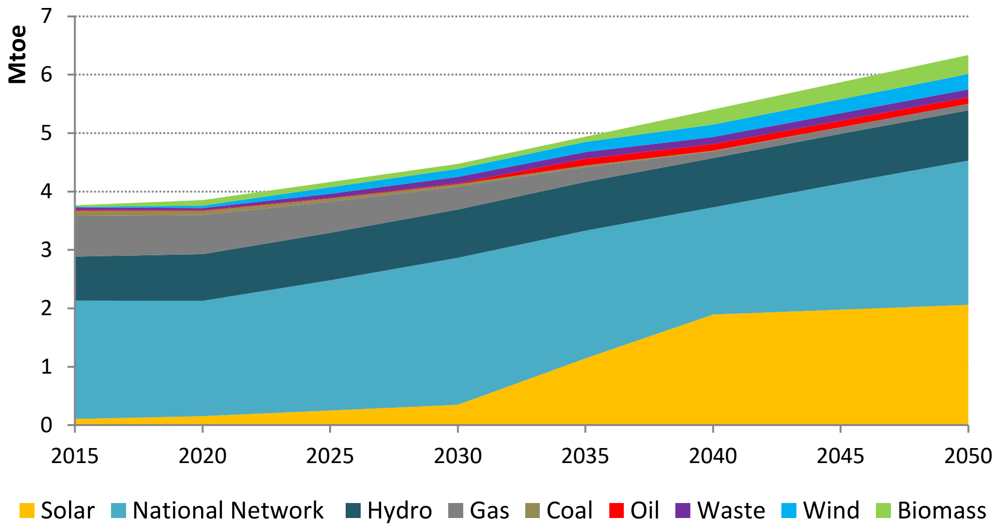

Figure 3: Electricity Supply in the BAU scenario

The carbon-neutral scenario starts with a presentation of how the objectives with respect to production (not taking into account objectives involving demand) can affect the electricity sector. Demand in this case follows the same trends as presented in the BAU scenario. As shown in Figure 4, there is no production of electricity based on fossil fuels, and renewable energy production accounts for around 65% of the total electricity consumed, the rest being covered by the national network. Solar production in this case represents around 35% of the total production and is the highest source of renewable energy, followed by wind and hydro, each representing around 15% of total production. In this case, as renewable energies are deployed faster, the use of the national network is reduced to 33% of the total electricity supply in 2050, a reduction of around 6% compared to the BAU scenario. With these results it is possible to identify that with the right policies it might be possible to decarbonize the electricity sector even with an increase in demand.

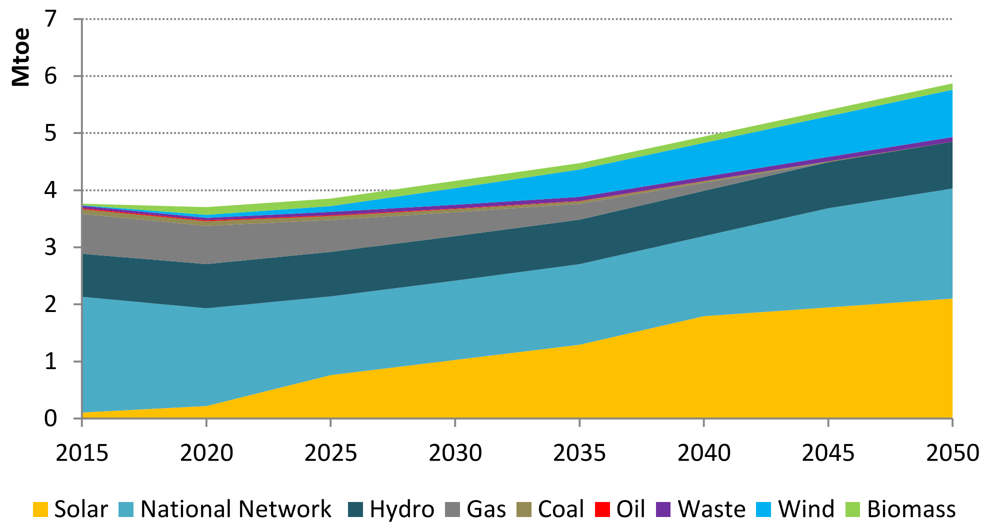

Figure 4: Electricity supply in the carbon-neutral scenario taking into account only production objectives

Finally, as seen in Figure 5, with these preliminary results, total decarbonization and autonomy of the electricity sector is possible when integrating into the model the objectives detailed in the SRCAE involving supply and demand. Solar production in this case represents around 50% of electricity production, hydroelectricity accounts for 30% of production, and wind has a share of around 20%. The use of the national network is completely reduced from 2030 thanks to efforts to bring down demand, and zero carbon emissions are reached in 2040, thus supporting the accomplishment of national objectives regarding the decarbonization of the electric system.

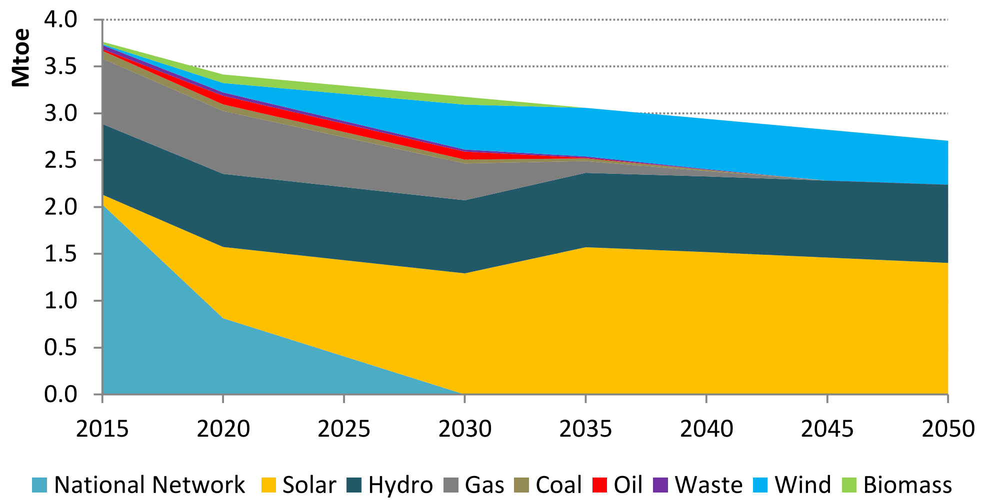

Figure 5: Electricity supply in the carbon-neutral scenario taking into account demand and supply objectives

6. Conclusion

An electric TIMES-SUD_{PACA} model was developed in order to analyze a possible carbon-neutral electric system in 2050 through two different scenarios: *Business as Usual* and *Carbon Neutral*. From the BAU scenario the model shows that inadequate policies for promoting renewable energies could lead to a non-carbon neutral electric system. On the other hand, if the objectives described in the SRCAE are accomplished, total decarbonization of the electric system is possible, even in the case where electricity demand increases; however, in order to decrease the risks over the electricity network, it would be necessary to work on decreasing demand.

These results concern only the electric system of the whole Région SUD, and do not represent the challenges and characteristics that affect the different territories comprising the region. The inclusion of these factors could lead to different and more accurate insights, which is one of the future (and already advanced) steps for the development of this model. Aa full representation of the Région SUD's energy sector broken down into its territories is also a future research area of interest that will be included in this analysis of how the Région SUD can achieve decarbonization of its entire energy sector.

7. Acknowledgement

This research is primarily funded by ADEME and the Région SUD and supported by SCHNEIDER ELECTRIC as part of a doctoral program. The work is also supported by the Modeling for Sustainable Development Chair, driven by MINES ParisTech and Ecole des Ponts ParisTech, supported by ADEME, EDF, GRTgaz, RTE, SCHNEIDER ELECTRIC, TOTAL and the general directorate for energy and climate at the ministry of ecological and solidarity transition. The Modeling for Sustainable Development Chair gratefully acknowledges the support received for this study. The views expressed in the reports and any public documents linked to the research program are attributable only to the authors in their personal capacity and not to the funders.

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