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Modeling low-carbon energy transition in the territories: a TIMES-SUD$_{PACA}$ model to assess a long-term decarbonization strategy for 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 as a response to guidelines specified in different national climate-energy laws and plans, which establish targets to reach a low-carbon scenario by 2050. Thus, a TIMES-SUD$_{PACA}$ bottom-up optimization model representing the energy sector of Région SUD was developed in order to analyze the impact that these policies might have, and to propose alternative policies that might lead the region to achieving its energy transition. The decarbonization of Région SUD presents different challenges than for the rest of France, such as risks to the electricity supply due to a non-looped electricity grid that affects the east of the region, and a high level of renewable potential, but low local energy production. The first results from the model show that with the use of available local renewable resources and a reduction in demand, decarbonization of Région SUD might be possible for some sectors, such as residential and commercial, but that the energy transition of the transport sector will require more accurate policies.

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

NONMENCLATURE

Abbreviations	
AHP	SUD PACA's department: Alpes-de-Haute-Provence
AM1	SUD PACA's department: Alpes-Maritimes high energy consumption zone
AM2	SUD PACA's department: *Alpes-Maritimes low energy consumption zone*
BDR1	SUD PACA's department: *Bouches-du-Rhône high energy consumption zone*
BDR2	SUD PACA's department: *Bouches-du-Rhône low energy consumption zone*
HA	SUD PACA's department: *Hautes-Alpes*
VAR1	SUD PACA's department: *Var high energy consumption zone*
VAR2	SUD PACA's department: *VAR low energy consumption zone*
VAUC	SUD PACA's department: Vaucluse

1. INTRODUCTION

Studies of energy systems developed rapidly following the oil crises of 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 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 modeling 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 as they can provide a significant source of clean energy, even though their intermittent nature introduced a challenge for achieving 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 modeling 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). Modeling intra-national energy systems allows the representation of local available resources in the area under study, and specific local 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 integrate the relation of these systems with their neighbors or with domestic energy systems, at the risk of providing incomplete insights. For example, if Région SUD's energy system is studied as a whole, it is not possible to identify the specific energy developments required by each area within the region.

In parallel, France has developed different laws and plans: first to redefine its national objectives on greenhouse gases, energy production, and air quality, and second to modify the division of territorial competences and make the French regions responsible for energy, air and adaptation to climate change. Consequently, 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 supply security, greenhouse gas emissions, environmental restrictions, and economic structure. These challenges are not evenly distributed around Région SUD, and are particularly localized. For example, the high concentration of energy consumption and greenhouse gas emissions on the coast contrasts with low consumption and emissions in the backcountry, which also harbors a high level of renewable energy sources. Thus, modeling provides a good opportunity to analyze possible solutions to these challenges. One tool that allows this analysis is the TIMES framework as it is possible to break down the energy system of each of the territories in Région SUD with their associated characteristics. In this way, a bottom-up TIMES SUD_{PACA} optimization model can generate different paths to lead the energy system in the region towards an energy transition that would secure energy supply, develop local renewable resources, and reduce emissions.

2. THE SUD PROVENCE-ALPES-COTE D'AZUR REGION

2.1 Energy context

Région SUD with around 5 million inhabitants represents the fourth largest consumer of final energy in France, with 12 Mtoe in 2016, accounting for 8% of national energy consumption. This consumption is characterized by a 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 32% 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 37% 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 (53%), mostly electric. An analysis of the territories of Région SUD reveals a significant difference between the energy needs of each of its *départements*. The biggest consumer, Bouches-du-Rhône, represents 50% 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 2,500 ktoe, and around 4,000 ktoe with the lowest consumer, Hautes-Alpes, making a difference of 20% and 40% respectively. The building and transport sectors in each *département* represent similar shares of total consumption, with an average of 25% for buildings and 45% for the transport sector. Despite this, each *département* has contrasting demands due to seasonal variations resulting from tourist activities, and a high concentration of economic activities and demographics on the coast, which are located far from production sources. In fact, these zones represent 90% of the energy consumption of the Alpes-Maritimes, Var, and Bouches-du-Rhône *départements*.

Compared to its high consumption level, the region produces only 18% of the energy it consumes. The domestic 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 remainder. 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 sectors, generates high greenhouse gas emissions, reaching 37 t CO_2eq, mostly concentrated on the coast. An analysis of the production of each *département* shows similar behavior to the consumption patterns. As shown in Figure 1, final energy production is equally uneven in each department. The biggest producer, Bouches-du-Rhône, has a difference of around 750 ktoe with the lowest producer, Hautes-Alpes.

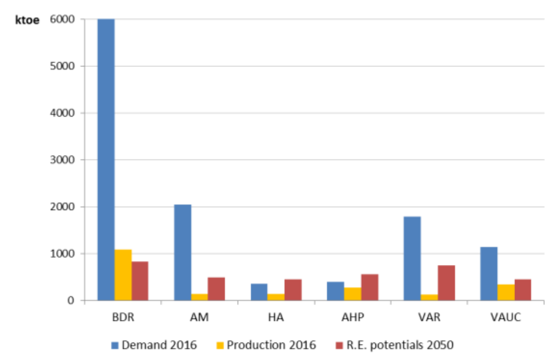

Figure 1: Demand vs. Total Production vs. renewable potentials

2.2 Risk for the energy supply

The eastern part of the region depends on a single, unconnected high-voltage network for its supply of electricity. This network is subject to various risks, such as insufficient capacity to meet high consumption peaks and the risk of network voltage collapse following accidental and sudden breakage of the single high-voltage line, after which the other lines would be insufficient to meet demand (Préfecture PACA). These risks of failure increase with the constant high level of consumption. A shutdown due to a forest fire can also affect the network, the probability of which is increasing due to 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 Région SUD. 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, which increases pressure on network use. 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 low production, dependence on the national electricity grid, concentrated consumption and emissions, underdeveloped renewable energy potentials, and technical, environmental and patrimonial constraints. Modeling the region as a whole can lead to misleading results, as each territory in Région SUD has heterogeneous characteristics that are important to take into account when proposing solutions towards an energy transition.

2.3 Methodology

The modeling of the Région SUD energy system will be developed under the TIMES (The Integrated MARKAL-EFOM System) framework by building a TIMES-SUD PACA model. TIMES 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). In order to better analyze the possible trajectories that can lead an energy transition, the SUD PACA energy system is broken down into nine zones or sub-systems, as shown in Figure 2, which represents the Vaucluse, Alpes-de-Haute-Provence, Hautes-Alpes, Bouches-du-Rhône, Alpes-Maritimes and Var *départements*. The latter three have been separated into two zones: high-energy demand zones (AM1, VAR1, BDR1) and low-energy demand zones (AM2, VAR2, BDR2). TIMES-SUD$_{PACA}$ allows a rich detailed representation of each energy system in each zone in the region in order to depict the specific issues that affect each system. This representation includes, for each zone: 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 big sectors along with their respective associated energy services: transport, residential buildings, tertiary buildings, industry, and agriculture. For the building sector, the energy services are: lighting, heating, cooling, cooking, specific electric devices, etc. Moreover, for the tertiary sector energy demand is broken down into eight different economic activities: offices, tourism, commerce, research, community habitat, transport buildings, health and social action, and sport, culture and leisure. The objective of this detailed representation is to identify more accurate policies to support the decarbonization of specific sectors. For example, tourism is an activity that in some zones represents around half of total emissions like in AM1 (ADEME, 2012), making it interesting to study the impact of some economic activities on energy demand and emissions.

Furthermore, the TIMES-SUD PACA model includes potential technologies that could be developed due to the geographic location of the regions, such as marine energy, and offshore wind, which are not yet present but could be an important source of clean energy in the future. With this detailed representation, it is also possible to show the flow of commodities through the different transforming processes to finally satisfy the energy demand. With this, it is possible to depict the Reference Energy System (RES) of Région SUD in Figure 3. From the model it is possible to obtain the evolution of the structure of the energy system for each *département*; 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 model has as a time horizon 2050 and for the reference year 2016.

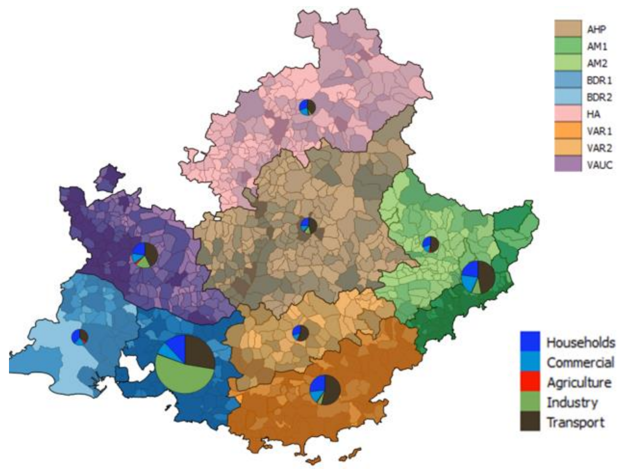

Figure 2: Region SUD PACA's study zones

2.4 Scenarios and constraints

The analysis of the energy transition of the region is first analyzed through two different scenarios: a reference scenario, and a carbon-neutral scenario

Reference scenario: This scenario takes into account the evolution of both the energy system and demand over the last five years in order to project its possible evolution to 2050. This means an increase in energy consumption demand at an average rate of 1% each year. The proposed evolution of the region's energy system in this scenario is presented in **Erreur ! Source du renvoi introuvable.**. The model chooses from among the different energy technologies to meet demand at the cheapest possible cost, but technologies that are not present in the 2016 energy system are not developed, meaning that offshore wind and marine energy will not be developed. The development of fossil fuels is constrained to have the same maximum activity level as in 2016 because more development of these energies is not possible in the region as presented in (Mirakyan, Lelait, Khomenko, & Kaikov, 2009). Although this study was developed in 2009, its remarks are still valid. Moreover, the scenario features no further constraints for emissions; it does not promote any energy, and does not take into account other efforts to reduce energy consumption. In addition, electricity supply from the network is limited to have the same maximum activity as shown in 2016, which means 50% of the electricity consumed by the region can come from the network.

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, Région SUD has redefined the objectives proposed in its Schéma Régional Climat Air Energy (SRCAE, 2018) which are shown in Table 1.

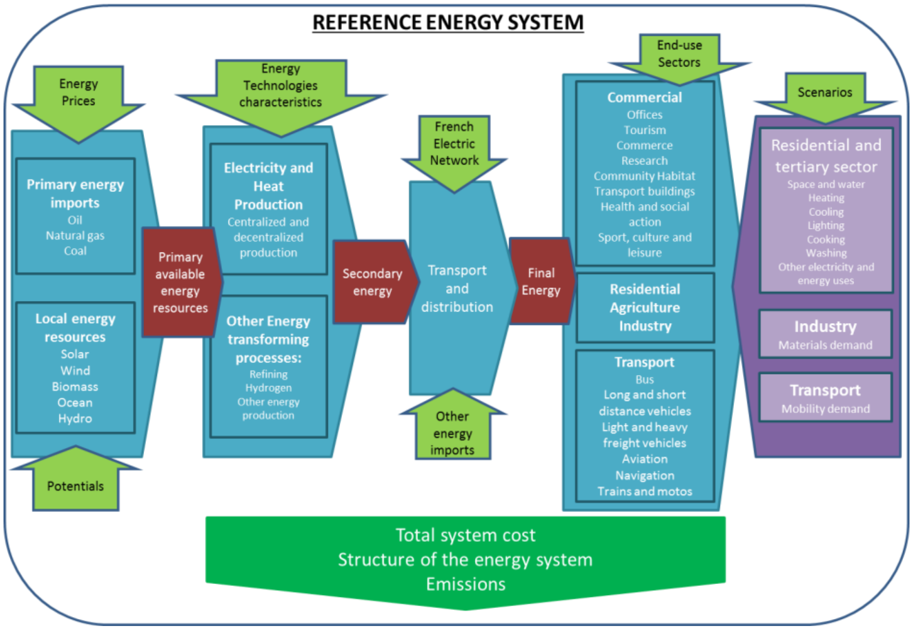

Figure 3: SUD PACA's Reference Energy System

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. 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 energy sector taking into account the demand from the *Reference Scenario* and will later include the demand objectives from the carbon-neutral scenario and compare both situations. The development of the supply side is constrained according to the objectives proposed by the region, and excluding any other technology development. The principal objective of this scenario is to analyze if the proposed strategy will be sufficient to achieve an energy transition and obtain a carbon-neutral energy system in 2050.

Production (MW)		2020	2025	2030	2050
Electricity	Hydraulic	3,258	3,300	3,343	3,519
	Wind	53	57	61	82
	Photovoltaic	1,583	3,015	5,745	24,143
	Biomass	293	293	294	297
Thermal	Heat recovery	103	125	152	334
	Solar Thermal	0	0	0	0
	Biomass	150	191	244	646
	Biogas	20	33	53	358
TOTAL		5,459	7,015	9,892	29,378
DEMAND		4%	9%	10%	20%

Table 1: Reference Scenario installed capacity

Production (MW)		2020	2025	2030	2050
Electricity	Hydraulic	3,756	3,929	3,956	4,100
	Wind	557	1,068	1,597	3,305
	Photovoltaic	6,912	9,779	11,730	46,852
	Biomass	141	172	172	172
Thermal	Heat recovery	2,749	3,611	4,300	6,546
	Solar Thermal	509	781	998	2,065
	Biomass	352	514	650	1,283
	Biogas	71	162	267	570
TOTAL		12,298	16,405	19,370	64,893
DEMAND		-8%	-11%	-15%	-30%

Table 1: Carbon Neutral Scenario installed capacity

2.5 Results and discussion

For the *reference scenario*, the results of 2050 energy production are presented in Figure 4. The use of fossil fuels to produce energy represents around 280 ktoe, which is 8% of the total energy produced in the region, and 97% of this production comes from BDR1. The share of fossil fuels in the energy production has decreased by around 65%, and its emissions have decreased by around 70% with respect to 2016.

around 800 ktoe. Its share in production has decreased from around 50% of total electricity production in 2016 to 20% in 2050, and this situation is mainly explained by restrictions on new big hydroelectric power plants due to environmental constraints to protect biodiversity. In addition, wind production has increased by around 7% and represents just 1% of the electricity produced in the region. The highest producer of electricity using wind is the BDR2 zone, which has the most potential to develop this resource. In total, renewables have gone from representing 25% of total production to 80%, and the total regional production now represents 25% of the region's consumption in 2050, which is an increase of 10% with respect to 2016. The Alpes Maritimes and Var *départements* (the most concerned by electricity peninsula risks) have increased their production from around 6% in 2016 to 15% in 2050, which could to some extent alleviate the risks over the region, but overall the electricity supply still depends on electricity from the national grid.

In terms of demand, emissions have increased by around 32%. This increase is principally due to the use of fossil fuels in the transport sector, which accounts for 94% of energy demand in this sector in 2050 and shows a decrease of 4% with respect to 2016. In addition, biofuels account for 4% of final energy demand and electricity accounts for 2%. On the other hand, the residential and the commercial sectors have decreased their 2050 emissions by around 75% as 45% of new heating and cooking devices use electricity and 20% use wood. Fossil fuels represent just 8% of total demand, which is a decrease of 75% with respect to 2016.

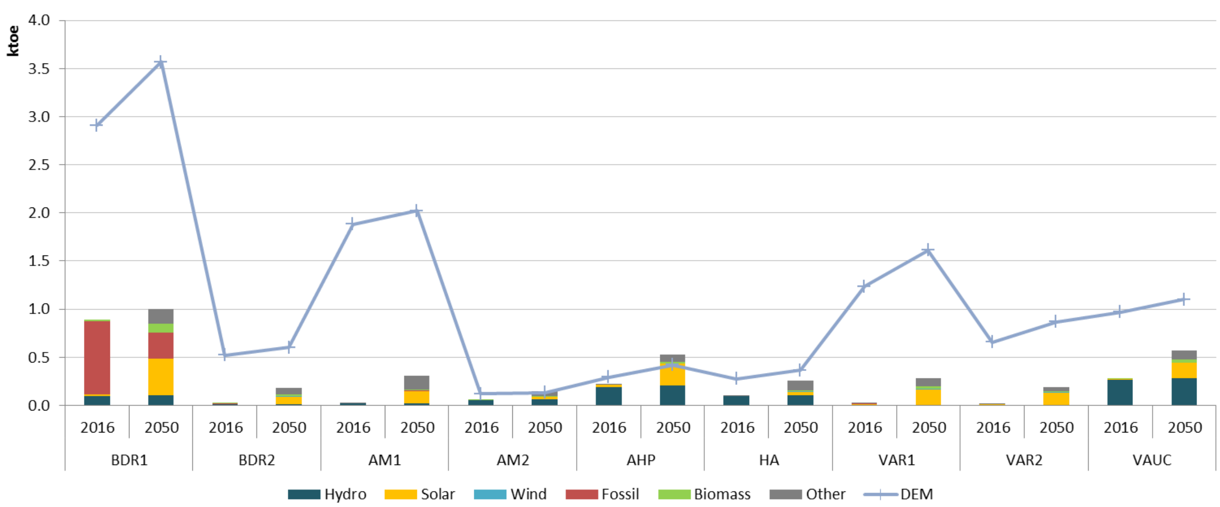

Figure 4: Evolution of the energy production for each *département* of Région SUD – Reference scenario

On the other hand, the development of renewable production has increased significantly, especially solar production, which represents around 1,300 ktoe and accounts for around 38% of the energy produced in 2050, and almost 50% of the renewable production. Most of the new production comes from the BDR1 zone representing 25% of the new production, followed by the AHP department representing 16% of the total production. Moreover, hydroelectricity has maintained an average production of

For the *carbon-neutral scenario*, the results of implementing the strategy proposed by the region in terms of production and reduction of demand are shown in Figure 5. In this case, the use of fossil fuels to produce energy in the region is reduced by 88%, but emissions are not reduced completely due to the use of municipal waste principally to produce heat, which accounts for 1% of the total energy produced in the region. Renewable energies account for almost the totality of the production at 99%, with solar being the greatest source of energy at round 37%, followed by wind at 35%. Although solar production has increased significantly its total production has not reached the production proposed by the region. Most new solar production is developed in the BDR1 zone and the VAR2 zone accounting for 11% and 7% of total solar production respectively. In addition, the new wind production is developed mostly in the VAR and in the VAUC departments representing principally 11% and 6% of total wind production. On the other hand, hydro shows a similar evolution as the *reference scenario*, but in this case its production accounts for 21% of total production. The total production of the region in this case accounts for 25% of regional consumption, and the AHP *département* and the VAR2 zone have a production surplus. The east of the region which is in situation of energy peninsula, the VAR, and the Alpes-Maritimes, have increased production, which now accounts on average for 72% and 13% of their consumption, but most of this production is developed in the zones with low consumption, VAR2 and AM2.

On the demand side, the building sector uses mostly electricity to cover its energy services and accounts for 81% of the energy used by this sector, which has doubled with respect to 2016. This means that fossil fuels have decreased their share by around 50% and represent just 7% of the total energy demand from this sector in 2050. The transport sector on the other hand has slightly decreased its use. From 2016 to 2050, the use of fossil fuels in the transport sector has only decreased by 7%. Biofuels and electricity have both increased in usage by 4%, which means that it is not really possible to reach a carbon-neutral scenario.

distributed around the different *départements* of the region, i.e. in the Vaucluse and Bouches-du-Rhône, each of which represents 20% of the region's production. The decrease in the production share for the Bouches-du-Rhône is due to the phase-out of fossil capacity. The east of the region has contrasted situations: the VAR has reached a production level that covers around 50% of demand, but the Alpes-Maritimes' production covers just 11% of demand.

In both scenarios, if we let the model decide when to use the electricity that comes from the rest of France, it chooses not to and prefers to develop local resources. Moreover, building sector demand shows that it might be possible to get rid of the use of fossil fuels, as in both scenarios the use of fossil fuels is reduced drastically, but the increased use of electricity might increase the risks over the use of the network as the principal energy services that use electricity are heating and cooking, which consume energy at peak consumption times. On the other hand, the development strategy proposed by the region has not been reached in any of the scenarios, principally because the transport sector does not stop using fossil fuels and, in the three different cases analyzed in the present paper, fossil fuels in the transport sector cover more than 90% of demand. Thus more attention should be paid to changing the structure of the transport sector.

2.6 Conclusions

A TIMES-SUD$_{PACA}$ energy model was developed in order to analyze a possible carbon-neutral energy system in 2050 through two different scenarios, a *Reference Scenario* that

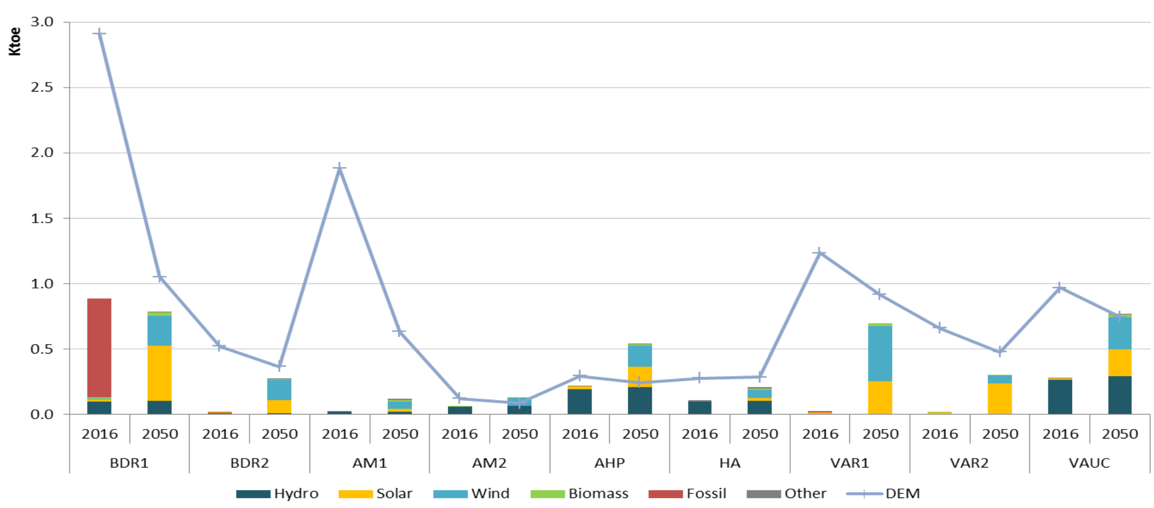

Figure 5: Evolution of the energy production for each *département* of Région SUD – Carbon neutral scenario

Following the same strategy for the development of the energy system of Région SUD proposed in the *carbon-neutral scenario* but assuming a failure to reach the objectives of decreasing demand, production in this case will be 11% higher than in the *reference scenario*. This extra production is used to cover the increased electricity demand, principally from the building sector, whose use represents almost 80% of total energy demand. In this case, production is more widely

follows past energy system development trends in which demand increases by 15%, and a *Carbon Neutral Scenario* that analyzes the objectives proposed by the region for the development of clean energies and also proposes a reduction in demand of 30% by 2050. This latter scenario also analyzes a case in which demand fails to be reduced and follows the trends shown in the reference scenario.

The results from the model show that renewable technologies can be developed in the region. Solar and wind technologies can be developed to a greater extent than other technologies, especially in the BDR1 and Var1 and Var2, but in any situation their development reaches the same levels of production as proposed by the region. This situation can be explained by the fact that the transport sector keeps choosing fossil fuels to cover its demand. The implication is that more precise policies should be implemented to motivate this sector to change its consumption patterns and choose other types of energies. Moreover, although it was not possible to completely reduce emissions, the building sector shows great potential for reducing its emissions by exchanging fossil fuels for electricity, although this could present higher risks over the network. Indeed, energy services other than? the building sector that could change by exchanging fossil fuels for electricity are demand from heating and cooking, which increases at peak times and thus could increase the stress over the network.

In order to propose a better energy transition for the region, constraints should be applied to the transport sector to motivate its increased use of alternative energies. New technologies should also be included that allow greater flexibility in the choice of energy for the transport sector, for example the integration of hydrogen which can also increase the incentive to develop more renewables production and in this case reach the objectives proposed by the region in its SRCAE.

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