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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 as a response to guidelines specified in different national climate-energy laws and plans, which establish targets to reach a low-carbon scenario in 2050. Thus, a TIMES-SUD_{PACA} bottom-up optimization model representing the energy sector of the Région SUD was developed in order to analyze the impact that these policies might have, and to propose different policies that might lead the region to an energy transition. This decarbonization presents specific challenges compared to the rest of France, such as risks for electricity supply due to a non-looped electricity grid that affects the east of the region, a high level of renewable potential, but low local energy production. First results from the model show that decarbonization of the Région SUD energy sector is possible involving the use of local available renewable resources and decreasing energy demand.

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

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 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 as they 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 this context, 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 made the French regions responsible for energy, air and climate issues. 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 they 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. Thus, modelling provides a good opportunity to analyze possible solutions to these challenges. In this way, through a bottom-up TIMES SUD_{PACA} optimization model, it is proposed some different paths that can lead the energy system of the SUD PACA region towards an energy transition that will secure energy supply, develop its local renewable resources, and reduce its emissions.

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

2.1 SUD PACA region's 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 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 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.

By analyzing the territories of the SUD PACA region, there is a big difference between the energy needs of each one of its departments. 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 2500 ktoe and with the lowest consumer, Hautes-Alpes, around 4,000 ktoe, making a difference of 20% and 40% respectively.

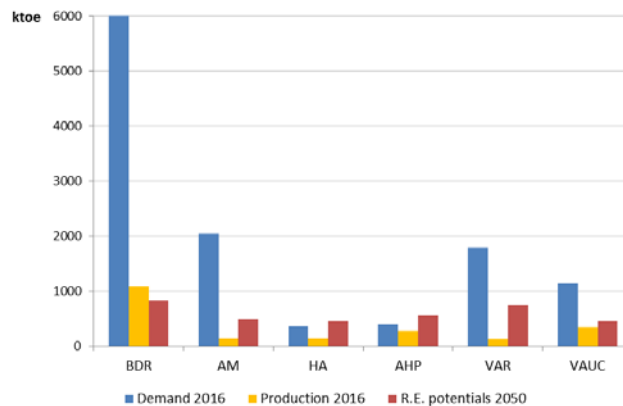


Figure 1: Demand vs. Production vs. renewable potentials

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 are located far from production sources, in fact these zones represents 90% of the energy consumption of each department. This last issue is the case of Alpes-Maritimes, Var, and Bouches-Du-Rhône.

Compared to its high consumption level, the region produces only 18% 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. 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, produces high greenhouse gas emissions, reaching 37 t CO₂eq, 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. The biggest producer, Bouches-du-Rhône, has a difference of around 750 ktoe with the lowest producer, Hautes-Alpes.

2.2 Risk on energy supply

The east part of the region depends on its supply of electricity 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 collapses 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). These risks of failure increase with the constant high level of consumption. A shutdown due to a forest fire, can also affect the network, whose probability increases 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 the 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, increasing the pressure on the use of the network. Seasonal variations in terms of demand are also important facts to take into account.

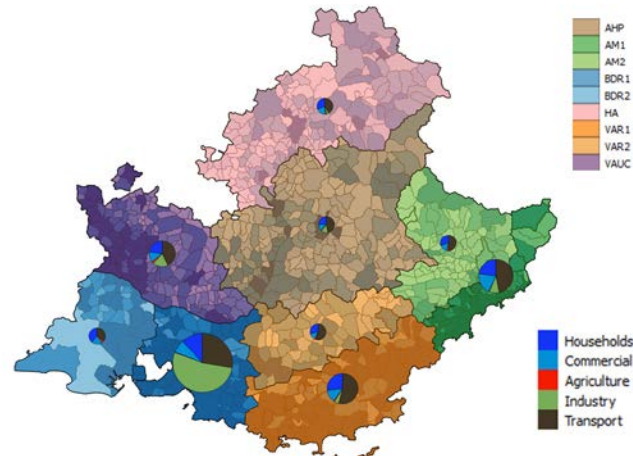


Figure 2: Region SUD PACA's study zones

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.

2.3 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 System", this 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 in nine zones, as shown in Figure 2, that represents its departments Vaucluse, Alpes-de-Haute-Provence, Hautes-Alpes, Bouches-du-Rhône, Alpes-Maritimes and VAR. The last three were separated in 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 that constitutes 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 the energy demand is broken down in eight different economic activities: offices, tourism, commerce, research, community habitat, transport buildings, health and social action, and sport, culture and leisure. This detailed representation has the objective to identify more accurate policies that will help to decarbonize specific sectors. For example, tourism is an activity that represents in some zones around half of total emissions like in AM1 (ADEME, 2012), making it interesting to study the role of some economic activities on energy demand and emissions. Furthermore, the TIMES-SUD PACA model also includes potential technologies that could be developed due to the geographic location of the regions, such as

marine energies, and wind off-shore, that are not yet present but can 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 the SUD PACA region Figure 3. From the model it is possible to get as a result 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 model has as a time horizon 2050 and for the reference year 2016.

2.4 Scenarios and constraints

The analysis of the energy transition of the region is first analyzed through three different scenarios: The reference scenario, carbon neutral scenario and zero emissions scenarios.

Reference scenario: This scenario takes into account the evolution of the energy system and of demand over the last five years in order to project its possible evolution to 2050. This means an increase of energy consumption demand at an average rate of 1% each year. The proposed evolution of the energy system of the region in this scenario is presented in Table 1. The model chooses from among the different energy technologies to cover demand at the cheapest possible cost, but technologies that are not present in the 2016 energy system are not developed, meaning that wind offshore and ocean energies will not be developed. The development of fossil fuels are constrained to have a maximum activity level as the one presented in 2016 as greater developments of this energies 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; this scenario 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 a maximum activity as the one showed in 2016, which means 50% of the electricity consumed by the region, can come from the network.

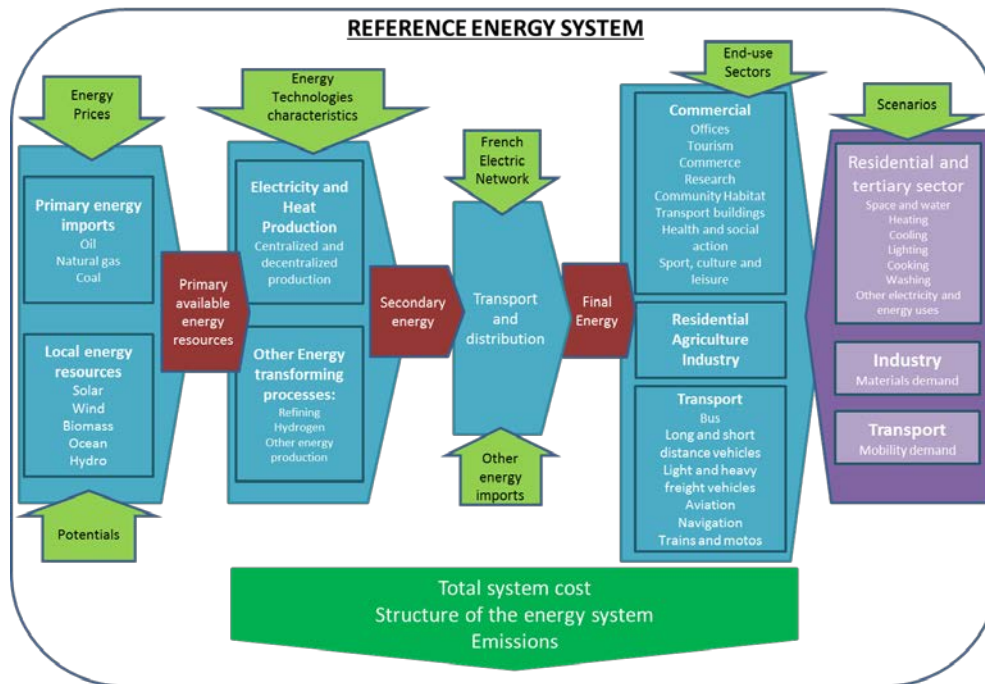


Figure 3: SUD PACA's Reference Energy System

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) which are shown in Table 2. 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 aims 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 later it will 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 get an energy transition and get a carbon neutral energy system in 2050.

2.5 Results and discussion

For the *Reference scenario*, results of 2050 energy production are presented in (Table 1). The use of fossil fuels to produce energy represents around 280 ktoe, 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 in around 65%, and its emissions have decreased in around 70% with respect to 2016.

On the other hand, the development of renewable production has increased significantly, especially solar production that represents around 1300 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 around 800 ktoe. Its share in production has decreased from around 50% of the total electricity production in 2016 to 20% in 2050, and this situation is explained principally because new big hydroelectric power plants are restricted due to environmental constraints to protect biodiversity. In addition, wind production has increased its production in around 7% and represents just 1% of the electricity produced in the region. The higher producer of electricity using wind is the BDR2 zone who has greater potentials to develop this resource. In total, renewables have passed from representing 25% of the total production to 80%, and the total regional production now represents 25% of the consumption of the region in 2050 which is an increase of 10% with respect to 2016. For the departments of Alpes Maritimes and the Var (the territories the most concerned about the electricity peninsula risks), have increased their production from around 6% in 2016 to 15% in 2050 which can alleviate in some extent the risks over the region, but overall the electricity supply keeps depending on the electricity that comes from the national network.

Production (ktep)		2020	2025	2030	2050
Electricité	Hydroélectricité	3073	3300	3343	3519
	Eolien	45	57	61	82
	Photovoltaïque	596	3015	5745	24143
	Biomasse	0	293	294	297
Thermique	Récupération de chaleur	1199	125	152	334
	Solaire thermique	20	0	0	0
	Biomass	80	191	244	646
	Méthanisation	14	33	53	358
TOTAL		5027	7015	9892	29378
DEMANDE		4%	9%	10%	15%

Table 1: Reference Scenario

Production (MW)		2020	2025	2030	2050
Electricité	Hydroélectricité	3756	3929	3956	4100
	Eolien	557	1068	1597	3305
	Photovoltaïque	6912	9779	11730	46852
	Grandes Centrales Biomasse	141	172	172	172
Thermique	Récupération de chaleur	2 749	3 611	4 300	6546
	Solaire thermique	509	781	998	2065
	Biomass	352	514	650	1283
	Méthanisation	71	162	267	570
TOTAL		12298	16405	19370	64893
DEMANDE		-8%	-11%	-15%	-30%

Table 1: Carbon Neutral Scenario

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

For the *Carbon Neutral Scenario*, the result from implementing the strategy proposed by the region in terms of production and reduction of demand are shown in (Table 2). In this case the use of fossil fuels to produce energy in the region is reduced in 88%, but emissions are not reduced completely due to the use of municipal waste principally to produce heat and they account by 1% of the total energy produced in the region. Renewable energies account for almost the totality of the production 99%, being solar the most important source of energy round 37% followed by wind 35%. Even though its production has increased significantly its total

production did not reach the production proposed by the region. Most of the new solar production is developed in the BDR1 zone and the VAR2 zone accounting 11% and 7% of the 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 the 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 the total production. The total production of the region in this case accounts for 25% of the regional consumption, and the department of AHP and the zone of VAR2 have a surplus of production. The east of the region that is in situation of energy peninsula, the VAR and the Alpes-Maritimes, have increased its production, that now accounts in average for 72% and 13% of their consumption, but most of this production is developed in the zones with low consumption, VAR2 and AM2.

For 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 its share in around 50% and represent just 7% of the total energy demanded by this sector in 2050. The transport sector on the other hand shows a slightly decreased use. From 2016 to 2050, the use of fossil fuels in the transport sector has just decreased by 7%. Biofuels and electricity have both an increase in its use of 4%.

Following the same strategy for the development of the energy system of the SUD PACA region, proposed in the *Carbon Neutral Scenario* but assuming a failure in reaching the objectives for decreasing demand, production in this case will be 11% higher than the one showed in the *Reference Scenario*. This extra production is used to cover the increase in electricity demand principally from the building sector, whose use represents almost 80% of the total energy demand. In this case production is more distributed around the different departments of the region, being the Vaucluse department and Bouches-du-Rhône that represent each one 20% of the region's production. The decrease of the share in production of the department of Bouches-du-Rhône is due to the retirement of the fossil capacity. The east of the region has contrasted situations; the department of VAR has reached a production level that covers around 50% of the demand, but the Department of Alpes-Maritimes has a production that just covers 11% of the demand.

In both scenarios if we let the model decide when to use the electricity that comes from the rest of France or not, it chooses not to and prefers to develop local resources. Moreover, demand of the building sector 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 increase of 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 that consume energy in peak consumption hours. On the other hand, the development strategy proposed by the region was not reached in any of the scenarios principally because the transport sector does not quit the use of fossil fuels and in the three different cases analyzed in the present paper fossil fuels in the transport sector covered more than 90% of the demand, thus more attention to change the structure of the transport sector has to be taken into account.

2.6 Conclusions

A TIMES-SUD_{PACA} energy model has been developed in order to analyze a possible carbon neutral energy system in 2050 through two different scenarios, the *Reference Scenario* that follows past trends for the development of the energy system and the demand increases by 15% and the *Carbon Neutral Scenario* that analyzes the objectives proposed by the region for the development of clean energies and it also proposes a reduction in demand of 30% in 2050. This last scenario analyzes also the case that the 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 the other technologies, but in any situation their development reaches the expected levels of production as those proposed by the region. This situation can be explained as the transport sector keeps choosing fossil fuels as its energy to cover its demand, so it is needed to implement more precise policies to motivate this sector to change its consumption patterns and choose other type of energies. Moreover, it was not possible to reduce completely emissions, but the building sector shows a great potential for the reduction of its emissions by changing the use of fossil fuels for electricity, but this can present higher risks over the network. Indeed, the energy services from the building sector that can change from using fossil fuels to use electricity are the demand of heating and cooking, whose demand increases in peak hours which means that it might increase the stress over the use of the network.

In order to propose a better energy transition for the region it is needed to add constraints for the transport sector to motivate an increase in the use of alternative energies. It is also needed to include new technologies that allow higher flexibility in the choice of energy for the transport sector, for example the integration of hydrogen that can also increase the incentives to develop more renewables production and in this case reach the objectives proposed by the region on its SRCAE.

NOMENCLATURE

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: <i>Alpes-Maritimes low energy consumption zone</i>
BDR1	SUD PACA's department: <i>Bouches-du-Rhône high energy consumption zone</i>
BDR2	SUD PACA's department: <i>Bouches-du-Rhône low energy consumption zone</i>
HA	SUD PACA's department: <i>Hautes-Alpes</i>
VAR1	SUD PACA's department: <i>Var high energy consumption zone</i>
VAR2	SUD PACA's department: <i>VAR low energy consumption zone</i>
VAUC	SUD PACA's department: Vaucluse

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