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The role of power-to-gas in the integration of variable renewables

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Abstract

Limiting the raise of global temperatures requires a rapid and massive deployment of solution to reduce carbon emissions at all levels. The development of intermittent renewable energy resources has received significant support from governments, and its production will considerably increase. The introduction of this high electrical production presents some challenges, in particular, the allocation of high production in low consumption periods. One of the most promoted solutions to cope with this challenge is the integration of power-to-gas technologies (P2G). In this sense, the European Union, and some of its members have presented their plans supporting the production and consumption of hydrogen. At the same time, it can be noted that the development strategies for these technologies are largely deployed at the local level. To allow local territories to contribute to the decarbonization of the energy system, national governments are extending the application of its energy policy to its territories. This is the case in France that over the last decades, has adopted laws to extend the application of its energy policy at local level, with the objective of ensuring better, faster deployment of its energy transition and reaching the carbon neutrality by 2050. As a result, the French regions have targeted objectives for the development of their local energy resources. The SUD Provence-Alpes-Côte d'Azur Region (PACA) in southern France, in response to these air, energy, environment, and climate change adaptation responsibilities, has targeted as objective to reach the carbon neutrality by 2050, which is concerned by the massive development of solar photovoltaic production as the region has considerable access to solar resources. The region as well has presented a hydrogen plan to support the development of this energy in the region and contribute to the national efforts. This study, conducted with $TIMES_{PACA}$ a bottom-up optimization model representing the energy system of the PACA region, analyzes how P2G technologies contribute to the development of solar resources. Results show that P2G technologies are essential for the decarbonization of the regional energy system and the renewable deployment, what is needed to the national and global decarbonization objectives and is expected to structure the whole hydrogen chain.

Keywords: Long-term modelling, $TIMES_{PACA}$, Low-carbon transition, Renewable energy integration, Power-to-gas, Hydrogen

1. Introduction

The last IPCC report highlights again that in order to limit the rise of temperature to 2°C, or even 1.5°C, it is needed a fast and massive deployment of solutions targeting the reduction of greenhouse gas emissions (Masson-Delmotte et al., 2021). In this regard the European Union has committed to be the first neutral carbon continent by 2050 (European Comissions, 2018). Following these guidelines, many European Union members have updated its environmental objectives, and have targeted the carbon neutrality as well by 2050. This is the case for Germany, France and Spain for example (European council for an energy efficient economy, 2021; Federal Ministry for Environment Nature Conservation, 2016; Ministère de la Transition Écologique et Solidaire, 2020). To reach such objective, it is required the development of different solutions, and the promotion of renewable energies is one of the most prominent one. In this regard, solar and wind technologies have received the support of many different governments. For example, in Germany, solar and wind have increased its power capacity from 53 GW in 2011 to 160 GW in 2020 (Clean Energy Wire, 2021), and in France, these technologies have increased its installed capacity from 10 GW in 2011 to almost 30 GW in 2020 (Ministère de la transition écologique, 2021). Thus, renewable electrical production is increasing significantly, and in a net zero energy system these technologies will account for an important part of the electricity produced in 2050 (IEA, 2021). However, these developments also entail some challenges. First, allocating high renewable intermittent electrical production during high solar, and wind production. This is already producing some effects in the market, such as the presence of negative electricity prices in the wholesale electricity market (in some occasions), which has happened in Germany, France, and Belgium for example (De Vos, 2015). Second, it will be needed to have other energy producing technologies to cover the periods with no solar and wind energy production and guarantee the stability of the electricity network.

A wide range of techniques can be employed to cope with the intermittent nature of renewable energies (i.e. batteries) (Bartolini et al., 2020; Beaudin et al., 2010; Lambert, 2018), but most recently, attention has focused on the development of power-to-gas (P2G) technologies (Estermann et al., 2016; Mazza et al., 2018). The increasing attention on P2G is due to the several advantages that they present. First, P2G technologies act as a large-scale and long-term energy storage for renewable sources (Lewandowska-Bernat & Desideri, 2018). In fact, P2G solutions can profit from the high renewable electricity production during low

electricity consumption periods to produce other energy vectors that can be easily stored and in greater quantities in comparison to other existing energy storage options. Through electrolyzers it is possible to use excess power output from intermittent renewable resources to produce hydrogen (Wang et al., 2019). Hydrogen can be stored in tanks or in geological reservoirs; it can also be blended and injected into the gas network, although its injection is restricted according to the technical conditions of the gas transport and distribution network of the area under study. The French gas network for example, can receive up to 6% hydrogen in volume without the need for major changes in the infrastructure, and up to 20% with a few changes (GRTgaz, 2019). In addition, by mixing CO₂ with hydrogen through a process called methanation, it is possible to produce methane. Synthetic methane would be produced if the CO₂ has a non-biogenic origin (CO₂ from industrial activities), and biomethane if the CO₂ has a biogenic source (biogas purification for example). The biomethane and synthetic methane could be also stored in the existing natural gas network to be consumed when needed, and replacing natural gas which can reduce as well CO₂ emissions (W. Liu et al., 2017). Second, P2G techniques can not only utilize the power from regional renewable energy, but also reduce energy imports and energy reserve consumption ensuring in this aspect energy security (Xing et al., 2018). Third, P2G technologies energy outputs constitute flexible energy vectors that can be employed when needed and can contribute to cope with peak load variations, assuring in this way the stability of the entire energy system. Indeed, the expected increase in use of electricity and gas, mainly by electric-gas vehicles, might impact peak loads if sufficient attention is not paid to distribute the charging load throughout the off-peak period (Mu et al., 2014). This would require fast responses to cover fluctuations due to increase demand. In this aspect, energy storage systems could be deployed to significantly improve the flexibility of power-gas distribution and transport networks to cope with the increase in electricity and gas demand in every period (Gu et al., 2021). Then, with P2G it is possible to profit the most of the capacity of the gas grid to counteract restraints of the power grid, and may also realize the development of a flexible multi-energy complementary system (Clegg & Mancarella, 2016; Doudard, 2019; Xing et al., 2018). Fourth, P2G energies can contribute to further decarbonize the energy system. In fact, hydrogen can be used in some sectors where electricity cannot cover all the energy demand. This is the case for the transport and industry sectors where electricity cannot fully substitute the use of fossil fuels. For freight transport vehicles, it is needed fast recharging energy options that battery vehicles cannot offer for the moment. In the industry sector, electricity cannot fully replace fossil fuels. For example, for the steel industry, electricity cannot be used as a reducing agent for iron production for the moment, and electric arc furnaces (EAF) cannot fully cover steel demand as the availability of scrap (the main raw material in EAF) is limited.

Hence, as P2G technologies offer several advantages to reach decarbonization objectives, governments around the world are setting objectives for its deployment. The European Union (EU) has established a hydrogen strategic roadmap to foster hydrogen development (European Commission, 2020a), targeting for 2030 the production of 10 Mt, which should increase significantly by 2050. Following these guidelines, some of the EU members have also shown their interest in supporting the creation of a clean hydrogen market and have established their own plans. This is the case of Germany, France and Spain for example (Fuhrmann, 2020; Ministère de la Transition Écologique et Solidaire, 2018; Spanish Government, 2020).

To reach all the objectives established in the different national plans, intra-national regional territories can contribute significantly. Indeed, first hydrogen developments will be done locally, and the electrolyzers will be directly connected to the renewable electricity produced by the territory. The outcoming hydrogen would then be used to cover local demands; mainly from industrial activities, and from local buses, and heavy transport vehicles (European Commission, 2020b). As production would be close to demand, this would significantly reduce the need for high hydrogen transport and distribution infrastructures. The local transport infrastructure built would then be extended to cover demands that are at further distances (Le Comité Européen des Régions, 2020). Hydrogen refuelling stations can be provided by local electrolyzers, but their deployment demands an analysis of the specific characteristics of the demand that will be covered, including the requirements for each type of vehicle. Hence, it is likely that the development of the hydrogen ecosystem in Europe will follow a gradual trajectory, at different paces following the sectors and the characteristics of the demand, and that the choice of measures will be different depending on each case, and of each geographical area (European Commission, 2020b). Intra-national regional territories are already showing their desire to contribute to the development of a hydrogen market, and many different local territories have established their plans for the development of hydrogen demand, and production. This is the case, for example, for some regions in Spain, and in France where some of its regions have already adopted plans to develop a clean hydrogen market (Benjumea, n.d.; L'Usine Nouvelle, 2019). Hence, local territories are main actors for the deployment of the hydrogen market.

In this sense, to push its territories to contribute to the decarbonization of its energy system, France has increased its efforts to extend the application of its energy policy at a more local level, with the implementation of different laws and plans. In 2015, the NOTRe law (Nouvelle Organisation Territoriale pour la République / New territorial organization for the Republic) and the LTECV (Loi pour la Transition Énergétique et la Croissance Verte / Energy Transition and Green Growth Act) gave the French regions the necessary jurisdictions to develop their own energy system and policies related to other climate topics. The LTECV also introduced the

Stratégie Nationale Bas Carbone (SNBC/National Low Carbon Strategy) which is the French roadmap to reduce greenhouse gas emissions and fight climate change. It gives guidelines for reaching a low-carbon economy in 2050, defining carbon budgets by economic sector (Ministère de la Transition Écologique et Solidaire, 2020). This strategy was updated at the beginning of 2020, setting an objective of reaching carbon neutrality by 2050, which means reducing carbon emissions by a factor of 6 with respect to 1990.

Consequently, as a response to the guidelines specified in the different national climate-energy laws and plans, the French regions have established objectives for the development of their local renewable energy resources, and also the deployment of hydrogen. This is the case for the PACA region in the south-east of France that has redefined its objectives concerning the decarbonization of its energy system, targeting a low-carbon scenario by 2050. These objectives are set out in the Schéma Régional d'Aménagement, de Développement Durable et d'Égalité des Territoires (SRADDET / Planning, Sustainable Development and Territorial Equality Regional Schemes) (REGION-SUD, 2019). The strategy proposed by the region in the SRADDET targets the massive development of energy production (thermal and electricity) from renewable resources. Just in terms of the new electricity production in 2050, around 86% (47 GW) of the targeted developments come from intermittent solar energy, which would thus represent 73% of PACA's electricity production. The region has as well presented its regional hydrogen plan, in which it proposes to foster hydrogen demand and production (Region SUD, 2020).

With all this in mind, P2G options emerge as solid contributors to reach the low-carbon energy transition. This is why its integration to the energy systems, and how it would impact them has been discussed at length by the scientific community (Götz et al., 2016).

1.1. Literature review and contribution

Many different studies analysing how P2G can contribute to the decarbonization of energy systems, and how its introduction would impact the energy systems have been published. Most of them focus on one type of energy or just in part of the energy system. One of the main streams of literature correspond to studying P2G storage options as a mean to capture high renewable electricity production. (Moeller et al., 2014) show that P2G is a main part of a cost optimal energy system with renewable energy shares above 75%. However, (Kötter et al., 2016) show that a 100% renewable energy system can be realised with or without P2G as it is possible to use batteries. Nonetheless, a long-term energy storage system such as P2G can reduce the cost of the energy system. A similar finding is given by (Colbertaldo et al., 2019) and (Moeller et al., 2014) which find that the best alternative is the mixed deployment of batteries and P2G technologies rather than batteries or P2G alone. Then, P2G as a storage option might be limited in future energy scenarios,

with deployment levels representing up to 6% of final energy demand in 100% renewable energy systems (Blanco & Faaij, 2018), and one of the best deployment options would be to develop P2G as a seasonal storage technology as energy storage capacity needs might increase (Belderbos et al., 2015). During summer season, to capture up to 90% of excess solar electrical production, P2G capacities up to 19 GW might be needed (Bailera & Lisbona, 2018). Then P2G alone seems not to be the best economical option, and it has to be paired with other storing technological solutions like power-to-heat (Jentsch et al., 2014).

P2G would be further developed if it is looked to replace natural gas demand (Blanco & Faaij, 2018). (Pursiheimo et al., 2017) assessed how P2G technologies could help the integration of variable renewables finding that P2G could be used mainly to produce synthetic gas for the transport and industrial sectors, rather than acting as an energy storage for excess renewable production. Another possibility to promote the production of P2G is through injecting hydrogen into natural gas networks. This would foster initial developments of hydrogen production, allowing to decarbonate some of the gas demand and reduce imported natural gas. In the UK, transforming natural gas networks to hydrogen seems the most economical solution to decarbonize gas consumption (Dodds & McDowall, 2013). However, there is a lack in the literature about assessing how hydrogen injection into natural gas networks would interact with the rest of the energy system, and if it is preferred over direct consumption of hydrogen or not.

Nevertheless, P2G can interconnect electricity and gas networks, and in this regard, some researches assess the balance and flexibility of the integrated gas-electricity network based on the high share of renewable energy sources. In particular, Joint planning strategies would be preferred over sequential planning or single storage planning as it can fulfil the peak charging load while yielding to low investment cost (Gu et al., 2021). (Qadrdan et al., 2015) finds that producing hydrogen from electricity is capable of reducing wind curtailment of high wind production and decrease the overall cost of operating the gas and electricity network in Great Britain. (J. Liu et al., 2021) finds out that P2G is critical in the operation performance of power system, gas network and heating sector in view of reducing decline of gas supply to power system, lessening dependence on gas wells and preventing large drop of node pressure when peak demand arrives.

Some other studies assess how P2G technologies interact with the rest of the energy system, and how they can contribute to decarbonization objectives. Most of these studies perform the analysis through optimization and/or simulation models, and by the bias of different scenarios they evaluate possible trajectories for the deployment of P2G technologies, and focus mainly in the deployment of one product (hydrogen or synthetic methane) (Eveloy & Gebreegziabher, 2018). The geographical coverage goes from international regions, countries, to urban or distributed

levels. Little attention is given to intra-national regions. At the EU scale it is found that electrolysers can help to capture excess power from renewable production which adds flexibility to the power sector and copes with renewable energy's fluctuation (Sgobbi et al., 2016). The hydrogen would help to decarbonize the industry and transport sectors. However, high share of intermittent renewable electricity production would not be a condition to push the development of Power-to-Methane (P2M) technologies, as the flexibility is provided by electrolysers which did not extend to the production of methane (Blanco et al., 2018). For the Baltic countries (Latvia, Estonia, Lithuania) higher renewable production and of hydrogen is possible when all three countries deploy their wind resources (Zoss et al., 2016). Hydrogen then could be mixed with biogas to increase its CH₄ content and it can be used to compensate for fluctuations of the system. At national scale, it has been found that hydrogen can help to decarbonize the energy systems as well, and established that the shift from fossil fuels to cleaner energy is unlikely to be successful without the use of hydrogen technologies to capture the excess solar and wind production (Contreras et al., 1999; Guandalini et al., 2017). While most of the studies discuss how P2G could help to capture excess renewable production, there are some studies considering that P2G can profit from excess nuclear power production (this mostly applies for France) (Scamman & Newborough, 2016). At the intra-national scale most of the research has focus on the German case, as the country has deployed important capacities of renewable energy production (Eveloy & Gebreegziabher, 2018). (Estermann et al., 2016; McKenna et al., 2018; Moeller et al., 2014) discuss the deployment of P2G in intra-national regions in Germany, but they omit the interaction of the electrical interconnection with the rest of the country. This does not allow to evaluate the balance effect that this interconnection might have over the deployment of renewable energies, and over P2G technologies. In fact, (Pursiheimo et al., 2017) discusses that volatility of wind and solar power productions can be balanced by trade. Those studies omit as well how to deal with energy consumption that do not correspond to the territory, such as vehicles coming from other regions and/or from the rest of the Europe. At the local level (urban areas) (Ikäheimo et al., 2022) finds that ending consumption of fossil gas altogether was not possible without investment into P2G or transmission grid expansion. The results show that exploiting P2G can help defer transmission grid expansion and allow cost savings.

The research detailed² in the present paper closes the existing gap in the literature about studying the deployment of P2G solutions at the intra-national regional scale, as a mean to contribute to national and international decarbonization objectives. For this study, a bottom-up energy model is developed for the PACA region at the south-east of France, following the TIMES framework and constructing the TIMES_{PACA} optimization model. The novel modelling approach followed in this study, contributes to the

current knowledge about how to model local energy systems by carefully integrating the specific characteristics in terms of how energy is produced, transported, and consumed in a intra-national regional scale. First, it is well identified the energy demand on which the regional energy policy would not have a direct effect over its decarbonization, which has not been addressed by other researches. Second, the modelling looks to integrate a detailed representation of each of the P2G technologies, and how P2G products are transported and consumed, clearly identifying CO₂ emissions at each of the production, transportation and consumption stages, which allows to better asses the decarbonization potential of each technological option. Injection of hydrogen into the gas grid is specifically assessed and compared with other decarbonization options. The model takes into account as well the electrical interconnection with the rest of the France, and energy trades among the territories of the region are allowed. The model includes a variety of different technologies and energy vectors for each of the different final consuming sectors. In particular, it is included heat pumps (using ambient, and geothermal energy) for the residential sector. This allows to compare the real potential of P2G technologies compared to other possible decarbonization options and energy vectors, which allows to have a complete view of how different energy vectors can cover the different energy services' demand and clearly observe how P2G places in the whole system, which is lacking in some previews researches. Third, through different scenarios, the paper looks to study how P2G technologies can help the deployment of renewable resources at the local scale, and how it would be possible to develop a local green hydrogen market. Finally, the paper shows how developing P2G at the local scale would help as well to reach the French and the European Union's P2G objectives. This paper is a good example of how local energy systems should be modelled in order to better assess the decarbonation pathways of the territories, and how they can contribute to national and international decarbonization objectives. The paper clearly highlights as well that studying the deployment of P2G technologies at the intra-national regional scale is imperative to foster the application of policies that would contribute to a

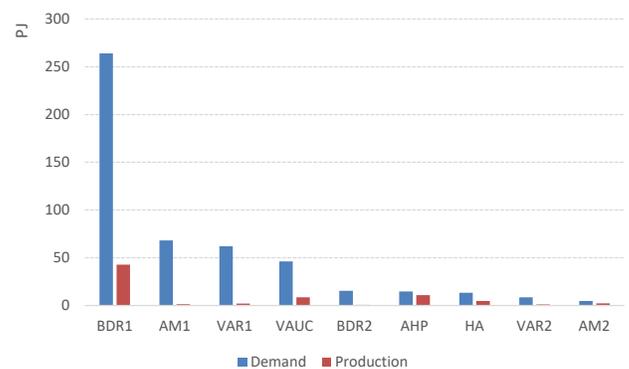


Figure 1 : 2017 final energy demand vs. total regional energy production

fast, and more accurate development of the different P2G options, and to reach a faster decarbonization of the energy systems at national and international level.

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

2.1 Energy context

The PACA region, home to around 5 million inhabitants, is the fourth largest consumer of final energy in France, with 509 PJ in 2017, accounting for around 8% of national energy consumption and CO₂ emissions. 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 particularly high energy consumption of its transport sector, even if it remains comparable to 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 coming from heating (53%), mostly electric. An analysis of the territories of the PACA region reveals a significant difference between the energy needs of each of its administrative areas (*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 105 PJ, and around 168 PJ 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 35% for buildings and 35% 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*.

Power to gas projects			
Jupiter 1000	2020	1 GW	Electrolyzers
HYGREEN	2025	12 MW	Electrolyzers
	2030	435 MW	
Valhydate	2025	7500 t/an	Waste hydrogen valorization
HynoVAR	2030	7	Hydrogen buses

Table 2: Power-to-gas projects programmed in the PACA region

Compared to its high consumption level, the region produces only around 18% of the energy it consumes (Figure 1). The production of domestic electricity and heat is 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, the remainder coming from the national grid. 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 oil products for its transport and industrial sectors, generates high greenhouse gas emissions, reaching 37 t CO₂eq, mostly concentrated on the coast. An analysis of the production of each *département* shows a similar pattern to consumption. As shown in Figure 1, final energy production is equally uneven in each *département*. The biggest producer, Bouches-du-Rhône, has a difference of around 31 PJ with the lowest producer, Hautes-Alpes.

Sector	2027	2032
Heavy transport	100	630
Utility vehicles	540	2280
Buses	86	260
H2 production (tH2/an)	16000	28800
Hydrogen injected into the gas network (tH2/an)	3000	5400

Table 1: Objectives proposed in the PACA's regional hydrogen plan

2.2 Renewable energies in the PACA region

The region has access to considerable available primary renewable energy resources, some of which have almost exhausted their potentials while others are underdeveloped. The region is the third biggest producer of hydroelectricity in France. This production has almost depleted its hydric resources, leaving a potential to be developed of around 5 PJ (CEREMA, 2015) which represented almost 1% of the energy consumption of the region in 2017. On the other hand, despite being the first territory in terms of availability of solar resources, the PACA region only ranks third in terms of electricity from solar production.

In order to take advantage of the availability of this resource in the territory, the PACA region has set an objective to develop electricity production using solar resources of 54 PJ in 2030 and 216 PJ in 2050. This means that in 2050, solar production alone would cover more than 40% of the total final energy consumed in 2017. If we add the targeted

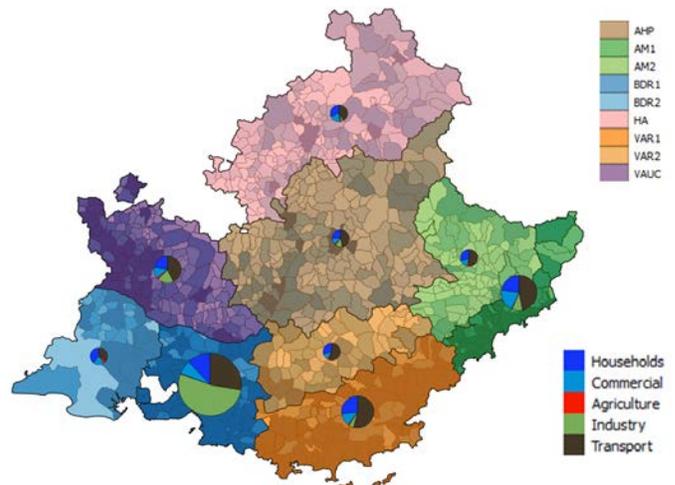


Figure 2: Region PACA's study zones

production from wind technologies in 2050, around 38 PJ, the total production from intermittent sources will represent around half of the energy consumed in 2017. Moreover, the region has set an objective to reduce its final energy demand by 30% in 2050, in which case intermittent electricity production would cover around 73% of the energy demand in 2050. These massive developments in intermittent renewable resources present several challenges for the region. The first one is to identify the best zones to develop intermittent technologies and determine how this will affect the structure of the energy system in each territory of the PACA region. For example, if the new photovoltaic developments are mainly developed in the north of the region, their production will need to be transported to the coast, which concentrates most of the consumption. On the other hand, if the solar developments occur in the south, their production will have to be transmitted to the zones that can capture excess production. Another challenge corresponds to the allocation of high intermittent production in low consumption periods: according to the French network manager (Réseau de Transport d'Électricité, RTE), from 2030, moments of high solar irradiation will produce excess electricity that will be needed to be oriented towards other electricity usages (RTE, 2019).

The region adopted in 2020 the Regional Hydrogen Plan (Region SUD, 2020) on which it strengthens its commitment to achieve carbon neutrality (Table 1). It finds in the deployment of hydrogen an opportunity to push the development of the sector in the region, but also to promote that of solar production, and the decarbonization of its energy consumption. It mainly seeks to introduce hydrogen into the transport and industrial sector and sets targets for 2027 and 2032. The region is as well a territory with several different P2G demonstration projects (Table 2).

3 Methodology

The TIMES_{PACA} model is a decision-making tool developed specifically to evaluate the development of the energy system of the PACA region in the south-east of France until 2050. It has been constructed based on the TIMES framework. TIMES is developed, maintained, and promoted by the Energy Technology System Analysis Program (ETSAP) of the International energy Agency (IEA). TIMES is a bottom-up, partial equilibrium model generator following a linear optimization paradigm, that looks to minimize the total discounted cost of the system through the defined period. TIMES' objective is to cover the exogenous energy services demand (heating, cooling, mobility, etc.) at the lowest net present value (NPV) in a specific time period and respecting the constraints defined by the user (Loulou & Goldstein, 2016). The objective function followed by TIMES is given by the equation:

$$(NPV) = \sum_{r \in R} \sum_{y \in Y} (1 + \alpha(r))^{y - y_{ref}} ANNCOST(r, y) \quad (1)$$

- NPV is the net present value of the total cost for all regions;
- $\alpha(r)$ is the general discount rate;
- y_{ref} is the base year;
- ANNCOST (r, y) is the total annual cost in region r in year y ;

This expression includes: investment costs, fixed and variable costs, the costs of importing and extracting commodities, and taxes.

The TIMES_{PACA} model was created as a tool to facilitate the analysis of the different strategies and policies that can be followed in order to lead the region to a low-carbon energy transition, and to better assess the role that the different technological options can play in reaching this objective. In this sense, the TIMES_{PACA} model has been meticulously developed to integrate the specific

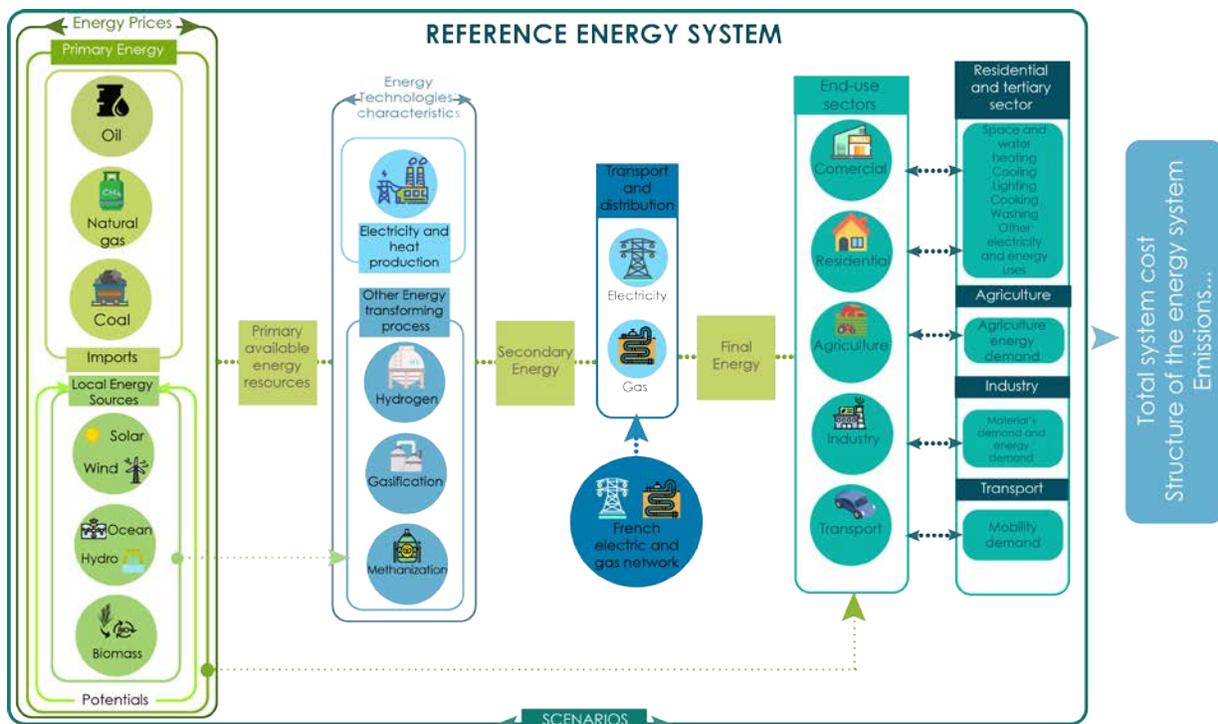


Figure 3: Simplified region PACA's energy system

characteristics that the energy system of its territory presents. Hence, the PACA energy system is broken down into nine zones or sub-systems, as shown in Figure 2, which represent the *départements* of the region: the Vaucluse (VAUC), Alpes-de-Haute-Provence (AHP), Hautes-Alpes (HA), Bouches-du-Rhône (BDR), Alpes-Maritimes (AM) and Var areas. The latter three present an energy consumption concentrated in littoral areas (90% of the consumption of each *département*), so they have been separated into two zones: high-energy consuming zones (AM1, VAR1, BDR1) and low-energy consuming zones (AM2, VAR2, BDR2). In addition, a region called “PACA” has been created in order to represent the French electric and gas network. In other words, this region can take electricity and gas from the French network and send it to the different territories when it is more economical to do so than producing locally. Electricity and other energy costs along with their projected costs towards 2050 are detailed in Annex 2. Moreover, this region is also used as a trade hub for electricity and gas commodities. In this way, the different territories can inject these commodities to the “PACA” region and withdraw them when needed.

TIMES_{PACA} allows a rich detailed representation of each energy system in every zone in the region in order to depict the specific issues affecting them. In addition, 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 in terms of electricity and gas); 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. With respect to the transport sector, it has been broken down into mobility demands for individual vehicles, freight transport, buses, utility cars, etc. Finally, the industry sector has been represented according to the different industrial activities presented in the region. 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. These final sector-specific energy demands have been derived from ATMOSUD’s¹ database. The model is divided into 12 time-slices

representing daytime (13 hours), peak hours, and night (10 hours), and the four seasons.

Furthermore, the TIMES_{PACA} model includes potential technologies that can be developed in each zone and some other technologies whose development depends on the geographic location of each zone, such as marine energy, and offshore wind. End-use technologies are based on (Assoumou, 2006; Millot, 2020). Hydrogen production can be developed through electrolyzers, biomass gasification or reforming. The modeling of these technologies is based on (Sgobbi et al., 2016). The specific techno-economic data for P2G technologies is detailed in Annex 1.

The modelling of P2G technologies is based on (Bolat & Thiel, 2014; Doudard, 2019), and adapted according to the region’s reality. The CO₂ capture options include the development of carbon capture and storage (CCS) for the steel and cement industry in the BDR1 zone, and for the cement industry in the AM1 zone, as the region presents significant potential for the development of this technology. However, the region does not have access to CO₂ storage options (ADEME, 2020), and thus alternatives need to be anticipated to take advantage of these potentials. For example, the CO₂ captured in these industries (which is non-biogenic) can be used in the methanation process. The combustion of synthetic methane issued from CO₂ from non-biogenic sources would produce 14% less emissions than natural gas according to data from (Meylan et al., 2017). In addition, CO₂ can be captured from biogas purification processes, and can also be used through methanation to produce biomethane whose combustion would be carbon neutral. Biogas can be produced from bio-waste anaerobic digestion. Furthermore, municipal solid waste (MSW) can be used through gasification to produce synthetic gas that can be purified (with or without CO₂ storage) and injected into the gas network as synthetic methane. In addition, synthetic gas or biogas can be directly used to produce heat or electricity.

This detailed representation shows the flow of commodities through the different transforming processes to ultimately satisfy energy demand, depicting in this way the Reference Energy System (RES) of the PACA (Figure 3). A detailed representation of the modelling of the different decarbonization options, integrating specific characteristics of the regional energy system, is presented in annexes 3 to 6. The results of the model include 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, among other things. The model’s time horizon is 2050 and the reference year is 2017.

¹ AtmoSUD is a French association responsible for monitoring the air quality of Région SUD.

4. Scenarios and constraints

Demand projection: The exogenous demands for energy services that will guide the choice of the model in all the different scenarios studied in the present paper are projected as follows. Heating demand in the habitat sector is estimated using the heat requirements per m² of existing and new buildings. The number of new buildings in 2030 is taken from (INSEE, 2019). To establish the requirements of new buildings in 2050, we took the observed trend from 2017 to 2030. The heat consumption of existing buildings is around 50 kWh/m², and 12 kWh/m² for new buildings according to national regulations (Marcheteau, 2020). Cooling demand may be particularly high in 2050 as hotter weather is more likely to occur (ADEME, 2015). In particular, the PACA region features higher temperatures during the year than the rest of France. For the remaining energy service demand from the habitat sector, we employ the driver population growth published by (INSEE, 2017). Mobility demand has been projected using the evolution of kilometers traveled by each type of vehicle in the past ten years. For the industry sector, we assumed a growth rate of 0.5% per year, which means an increase in industrial activity of 18% in 2050 with respect to 2017. The analysis employs four different scenarios: *reference*, *SRADDET*, *autonomy* and *hydrogen scenarios*.

Reference scenario (REF): This scenario considers the actions that the region has implemented (until 2017) and which directly affect the regional energy sector. We further integrate past trends for different energy sectors and services in each studied area over the past ten years, and also consider the region's Climate Air Energy Territorial Plan deployed in 2017 (Région SUD, 2017). This plan in particular supports the development of current power-to-gas (P2G) projects that have been established in the region (Table 3).

These projects will be developed in all the studied scenarios. We consider that the effects of the energy policies of the region since 2005 are visible in the consumption data of the last ten years. In this context, we do not consider the objectives of the region established more recently in the SRADDET (Regional plan for territorial and sustainable development / Schéma régional d'aménagement et développement durable du territoire). The assessment of regional objectives published in 2018 notes that the region is far from achieving most of them, and that while some objectives have been achieved, this is not due to the actions of the region but rather to external effects (Région SUD, 2018). This scenario also attempts to reflect the low level of appropriation of climate issues amongst politicians and economic actors of the PACA region: indeed, according to the High Council for the Climate, "*political and economic actors do not yet appear to be sufficiently aware of the subject [of appropriation of climate issues]*", and the ambitious objectives declared in the SRADDET appear "*to be a declaration of intent based on outward appearances but without any concrete commitment*" (Haut Conseil Pour le Climat, 2020).

In addition, we do not include other objectives established at national level. This scenario is therefore not very ambitious in terms of decarbonization and highlights the enormous efforts to be made to achieve a low-carbon energy transition or even a circular economy. It serves as a basis for building other scenarios and for defining actions to be implemented to guide the region more effectively. The main hypotheses considering the production of electricity are detailed in annex 2.

SRADDET scenario (SR): 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 PACA region has redefined the objectives proposed in its SRADDET. The objectives established by the region in order to reach a carbon-neutral scenario include: first, fostering the development of local available energy resources and reducing fossil-fuel based consumption; and second, reducing final energy demand by 30% in 2050 with respect to 2007. Actions concerning the reduction of consumption imply, for the habitat sector, mobilizing 10% of building renovation potential, and for the transport sector, integrating greater use of public transport and bicycles, and reaching a higher modal share of vehicles, up to 1.35 people per car from 2030 (1.2 people in 2017 (AtmoSud, 2017)).

SRADDET							
	Energy	2017	2020	2025	2030	2050	
Production (PJ)	Biomass	1.41	Max	3.03	4.65	4.65	4.65
			Min	2.88	4.42	4.42	4.42
	Wind onshore	0.42	Max	1.99	4.42	5.57	10.80
			Min	0.99	2.21	2.78	5.40
	Wind Offshore	1.38	Max	2.78	8.56	14.40	28.80
			Min	0.00	-	-	-
	Hydroelectricity	28.65	Max	30.65	32.65	32.65	34.95
			Min	29.12	31.02	31.02	33.20
	Solaire photovoltaïc ground	5.51	Max	8.95	12.72	13.14	58.94
			Min	4.48	6.36	11.83	53.05
	Solaire photovoltaïc roof	-	Max	12.98	32.37	40.94	157.14
			Min	1.30	6.47	36.85	141.43
	Methanisation	1.73	Max	1.99	4.38	7.20	14.78
			Min	1.73	2.19	3.60	13.30
Gaseification	-	Max	-	4.11	7.20	15.20	
		Min	-	2.06	3.60	7.60	

Table 3: SRADDET supply side objectives

The development of the supply side is constrained according to the objectives proposed by the region in the SRADDET (Table 4), and in the regional hydrogen plan which targets objectives for the development of the hydrogen sector up to 2032 (REGION-SUD, 2019; Region SUD, 2020). The principal aims of this scenario are to analyze how the proposed objectives in terms of developing the energy sector can shape the region's energy system, and to determine the role of P2G technologies in the accomplishment of this objective. These two alternatives would help to get some insights as to whether the proposed strategy will be sufficient

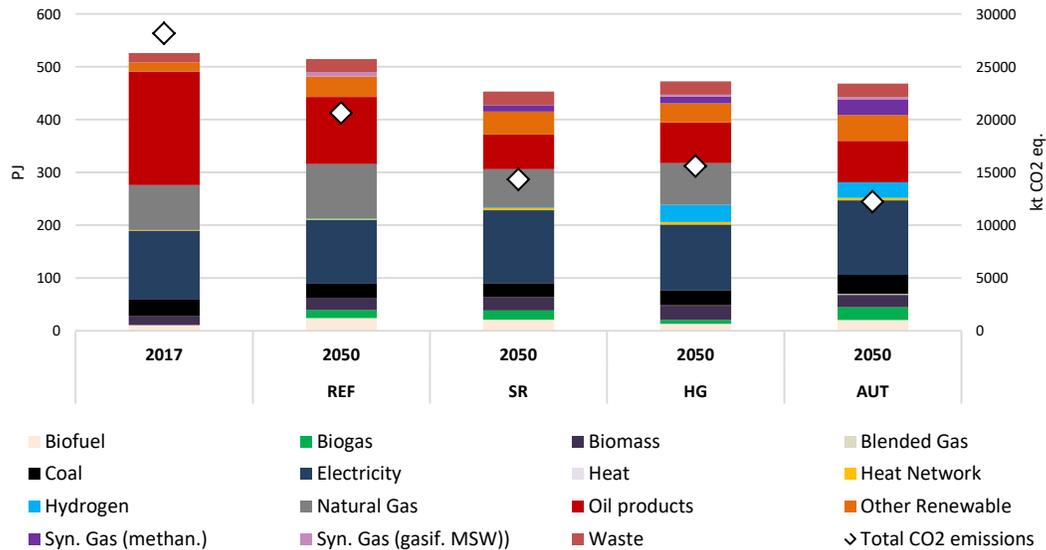


Figure 4: Final energy demand

to achieve an energy transition and obtain a carbon-neutral energy system in 2050.

Autonomy scenario (AUT): This scenario limits the electricity and gas available from the French networks in order to analyze whether the region can cover all of its energy demand by developing its local available energy resources, and to determine the role of the different available technologies in this decentralization process.

Hydrogen scenario (HGS): In order to observe the role that the different P2G techniques can play in the low-carbon transition of the PACA region, this scenario envisions a significant deployment of hydrogen production of minimum 50 PJ in 2050 and a consumption of at least 30 PJ by the transport sector. The main hypotheses concern supply and

demand for each.

5. Results and discussion

• P2G products for final energy demand

The use of P2G technologies is very limited in the REF and SR scenarios that mainly follow the P2G projects and the regional hydrogen plan (Figure 4). This shows that the objectives proposed by the region are not ambitious enough to encourage the deployment of a hydrogen market or even a synthetic methane market in the long term. On the other hand, in HGS and in AUT, P2G products (hydrogen and synthetic methane issued from methanation) play an important role in the energy mix of the region in 2050 as they represent 10% (45 PJ) and 13% (59 PJ) of the final regional

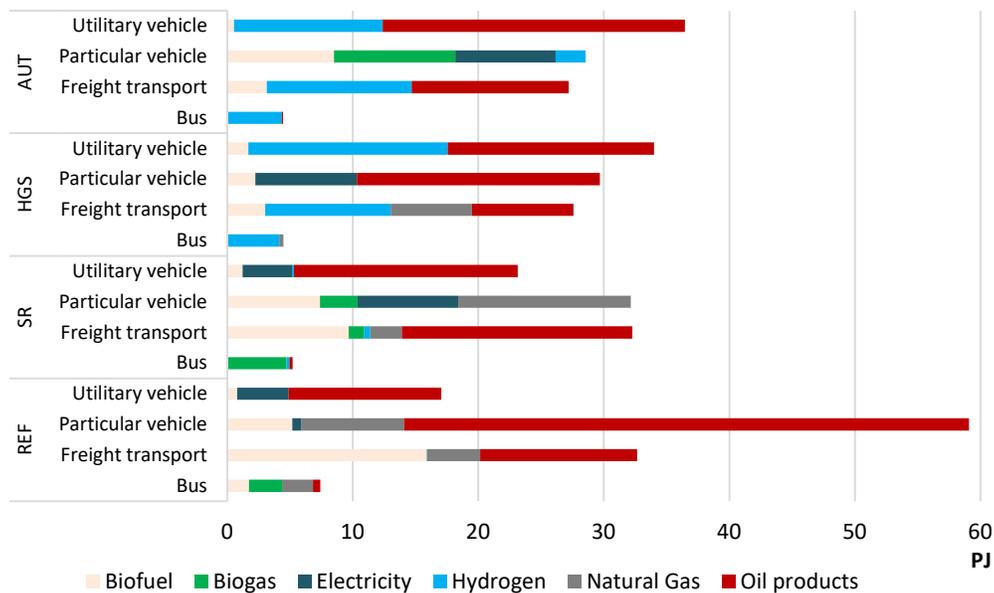


Figure 5: Final energy consumption in the transport sector

energy demand respectively. This use of synthetic methane is higher with respect to the results found in (Blanco & Faaij, 2018). Synthetic methane is mainly used in the industry sector at 80% (27 PJ) in *AUT* and at 54% (12 PJ) for *HGS* (Figure 5). The rest is used in the habitat sector to cover heating, water heating and cooking energy demand. Then P2G products in the habitat sector have a flexibility role, covering the residual energy demand that the other energy vectors have not been able to satisfy. Moreover, the low introduction of P2G products into the habitat sector is explained first because the synthetic methane produced uses CO₂ from industrial activities which cannot contribute to the decarbonization of the sector. Then heat pumps using ambient heat and geothermal energies appear to be more economical options, and finally because of the use of electricity. In fact, in 2050 all the electricity consumed in the habitat sector has been covered by roof photovoltaic production, backed up with batteries. These batteries have stored around 30% of the production and the rest is injected into the electric network (Figure 6). This shows that P2G and batteries can complement each other and be deployed jointly in low carbon scenarios. In particular, it should be a holistic planning that allows to take into account all the energy resources present in the territory and carefully allocate each resource for a specific demand in order to optimize investments.

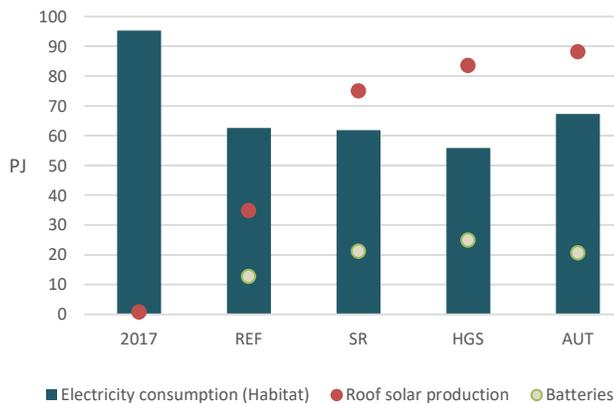


Figure 7: Electricity consumption in the habitat sector vs roof solar production and batteries storage

The high use of synthetic gas in *AUT* is because it is employed to replace the natural gas coming from the French gas network. Hence, replacing natural gas with synthetic methane would encourage the production of synthetic methane. Direct hydrogen use is mainly observed for the transport sector in all scenarios, with a slight use in the residential sector in *HGS* (8% of total hydrogen in 2050). Thus, in the transport sector, in *HGS*, hydrogen is used at 53% for utility vehicles, 33% for freight transport, and 14% for buses, while in *AUT* hydrogen is used at 40% each for utility vehicles and freight transport, 14% for buses, and the rest for private vehicles. These differences can be explained by the fact that the natural gas used for the freight transport sector in *HGS*, is

replaced by oil products in *AUT* which come from private vehicles, see Figure 7.

Therefore, in order to replace the oil products being used by private vehicles in *HGS*, in *AUT* private vehicles use biogas and hydrogen. Considering all of these results, final CO₂ emissions are reduced the most in *AUT*, which achieves a reduction of 57% with respect to 2017, followed by *SR* with a reduction of 49% and then *HGS* with a reduction of 45% in the same period. This shows that the use of P2G products constitutes a very important option for the reduction of greenhouse gas emissions in the region: hydrogen issue from the use of renewable resources, represents a clean energy that can help the decarbonization of the transport sector and complement the use of electricity that has problems to cover energy demand of freight transport vehicles. For the industry sector, hydrogen allows the use of CO₂ for the production of synthetic methane that contributes to the decarbonation of the industrial activities. However, more efforts are needed in order to further reduce the use of fossil fuels in all sectors of activity.

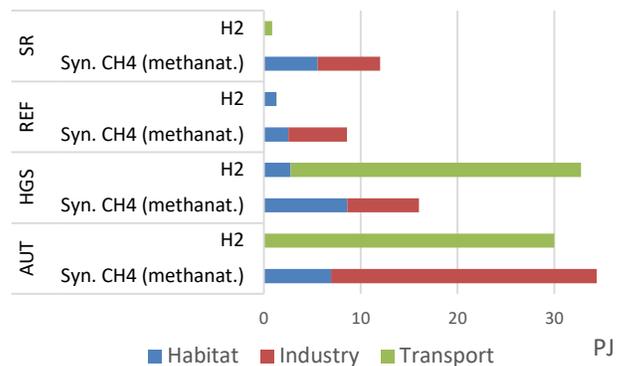


Figure 6: Hydrogen and synthetic methane in final consumption

- *P2G production*

The key energy vector produced by P2G technologies is hydrogen, as it can be used to cover final energy demand, replacing fossil fuels, and to produce synthetic methane. In this regard, the production of hydrogen starts in 2020 following the P2G projects established by the region. Hydrogen production increases in 2030, mainly in *HGS* where the production reaches 5 PJ. In 2050, hydrogen production increases significantly, reaching the highest production in *AUT* with 55 PJ due to the high consumption of synthesis gas in industry and in the residential-tertiary sectors, and of hydrogen in the transport sector. In *HGS*, hydrogen production comes mainly from electrolyzers following the established constraint of a minimum production of 50 PJ which requires the development of 3.2 GW of installed capacity. We established this constraint with the objective of observing the effect that such hydrogen production would have on the production of electricity from the use of solar resources. Thus, this production proved sufficient to cover all of the hydrogen needed in the scenario so that the use of

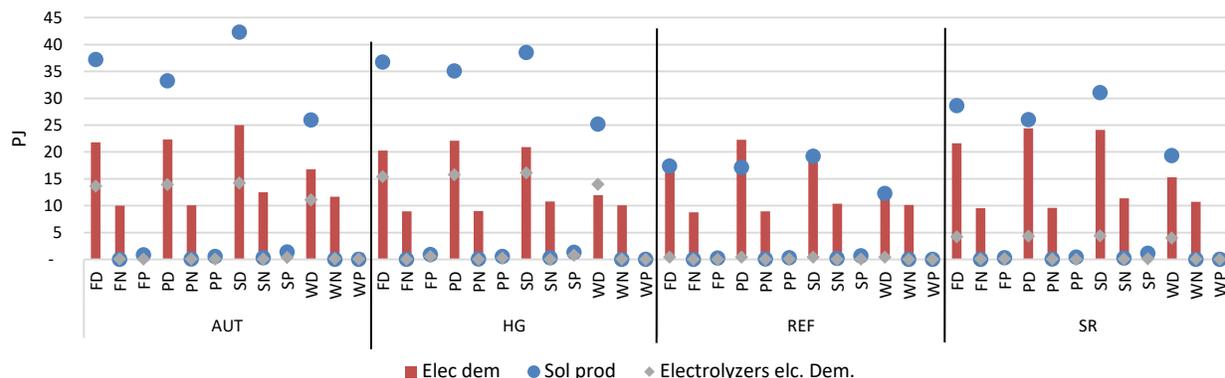


Figure 8: Evolution of the energy production for each study zone of the PACA region

reforming or gasification was not necessary, even when they were available for development. In *AUT* the hydrogen comes 76% from electrolyzers (2.8 GW of electrolyzers), 21% wood reforming (0.6 GW) and 3% MSW gasification (0.06 GW).

Producing this hydrogen requires significant amounts of electricity. In the region in 2050, this electricity is covered by solar photovoltaic production. In *AUT* and in *HG*, the high hydrogen production allows to develop all the easily accessible ground solar potentials (54 PJ). In an *SR* scenario where hydrogen production is not significant, ground solar potentials are developed at 50%. In Figure 8, it is possible to observe that most of the hydrogen production takes place during high solar photovoltaic production in high irradiation periods; indeed, the difference between solar production and electricity demand in high solar production periods almost corresponds to the electricity required from electrolyzers in *AUT* and *HGS*. However, it is also possible to identify that in winter, solar production would not be enough to cover the electricity demand of the electrolyzers, which will require electricity from other sources. In general, electricity production is 8% higher in *AUT* than in *HGS*, with slightly higher solar production of 3% in *AUT* with respect to *HGS*.

The main hydrogen production zone in all scenarios is AHP, using centralized large-scale alkaline electrolyzers, as this allows for economies of scale. As a result, this zone becomes a net importer of electricity (being net exporter in 2017) as its production only covers around 70% of its total electricity demand of around 60 PJ (electrolyzers and final electricity demand). Then low consuming zones have become net electricity exporter and this shows that, for the region it is needed a coordinated planning of energy developments in order to reach decarbonation objectives and better profit of the resources present in the region. PEM electrolysis technologies are not chosen in any of the scenarios. What drives production in this area is mainly the presence of the saline cavity which serves for hydrogen storage. Indeed, more than 50% of the production in each scenario is stored in these cavities during day-time production, and is then used in the other periods. This illustrates the importance of this storage option in the region's energy low carbon transition as it allows increased flexibility of the system. In addition, in all

scenarios, the hydrogen that is used in the transport sector is delivered for final consumption, first through pipelines, and then taken to a filling station in trucks. In *SR*, where there is a hydrogen production of 13 PJ, the production comes from medium-sized electrolyzers and takes place in the VAUC and AHP zones, each representing 36% of the production, the rest is produced in the BDR2 zone.

As mentioned previously, there is a significant production and consumption of syngas in the different scenarios. The production of this energy takes place through methanation and gasification, which starts from 2040. Thus, methanation, using industrial CO₂, accounts for most of the production in all scenarios. This methanation takes place in the zones where the CO₂ has been captured, zone AM1 for the cement sector and BDR1 for the steel industry; synthesis gas is also mainly consumed in these zones. Gasification for the production of syngas also uses MSW, and in all scenarios, the potentials of MSW are predominantly used for the production of either hydrogen or syngas gas. These resources are therefore very important for achieving the region's energy transition objectives. Moreover, we target them because in the reference scenario we can already observe the use of these resources through gasification for the production of synthesis gas. A carbon tax would further push the development of clean energies in this scenario.

Another important finding in this study is that blending and injecting hydrogen into the natural gas network is negligible. This is explained because it is preferred to foster hydrogen consuming technologies in order to have greater energy demand rather than just consuming small quantities of hydrogen through the gas network. Developing small capacities of hydrogen might not be sufficient enough to create and foster an hydrogen market. A similar situation is observed with the use of synthetic gas. Moreover, there is no use of P2G technologies to produce electricity as the absence of renewable production is covered by the use of batteries, and by the production of electricity through biogas and wood based power plants. Finally, the electricity coming from the french network has been reduced completely in all scenarios, except for *HGS* where just 5 PJ have been used in 2050 (60 PJ in 2017).

Facing the high cost of deploying P2G technologies would imply to apply policies targeting the use of P2G products for specific uses. Then hydrogen should be targeted for the transport sector, and syntetic methane for the industry sector in order to reeplace natural gas. This would allow greater specialisation and reduction of costs. Moreover, the PACA region cannot target higher CO₂ taxes than those proposed by the French government, so in order to promote the development of P2G technologies there should be established subsidies to final consumption of P2G products.

- *Biogas*

It is important to make a point about biogas production as its purification for injection into the gas network would generate biogenic CO₂, which can be mixed with hydrogen to produce biomethane, whose use would substitute some of the remaining fossil fuel use in *HGS* and *AUT* reducing emissions even further. In this sense, biogas reaches a high production of 21 PJ in 2050 in *SR* and 21 PJ in *AUT*, with the main producers being the BDR1 and VAUC zones. Of this production, 89% has been purified and injected into the gas transport network, but less than 1% has been purified with CCS (which has been mixed with waste hydrogen to produce biomethane). This provides an additional opportunity for the region for further decarbonation of the energy sector, as capturing the CO₂ from biogas purification, for example in *AUT*, would allow the additional production of around 12 PJ that can replace the fossil fuels used in the industrial sector (11 PJ). Nonetheless, this would require an additional 15 PJ of electricity needed for electrolyzers production, which can foster even higher electricity production from renewable resources in the region.

- *Contribution of the region to national and international hydrogen deployment objectives*

The region accounts for around 8% of the French energy consumption and CO₂ emissions. Then the development of hydrogen is inevitable for the decarbonation of the French and regional energy system, but most importantly, developing local hydrogen can contribute further to this decarbonization as the distance between the production site, the AHP zone, and the consumption sites (high consuming zones: BDR1, AM1, VAR1) is not very significant. In fact, it is possible to create a hydrogen valley in the region where it is possible to profit from high local intermittent renewable production to produce hydrogen that are localized close to consumption sites (Jorgo Chatzimarkakis, Levoyannis et al., 2021). If hydrogen can be stored and used close to the production sites, its cost would be reduced significantly (IEA, 2019). Then transporting hydrogen from other regions might not be the most economically available options, mainly because of the geographical structure that the region presents with mountainous areas in the north that limits the interconnection with the rest of the France. However, this should be studied deeper through

geographical information systems, to allow a more complete integration of local geographical characteristics. Then, producing and storing hydrogen in the AHP zone and transporting it for consumption in high consuming areas in the south, might be a strategy to consider in order to foster the development of a hydrogen market. Hydrogen valleys would be key hubs for the emerging hydrogen economy (Jorgo Chatzimarkakis, Levoyannis et al., 2021), which applies for the region and the rest of France.

In addition, hydrogen might be a very important energy carrier for the region as it allows to profit from the carbon capture potentials present in the territory through methanation to produce synthesis methane. These potentials would not be developed otherwise, as the region lacks storage options (ADEME, 2020). Furthermore, developing the consumption of hydrogen for regional vehicles in high consuming zones would be essential for developing hydrogen in France, as the vehicles presented just in the region's high consuming zones represent 5% of the French vehicles fleet. Moreover, as the energy consumption of the transport sector is highly concentrated in the BDR1, AM1 and VAR1 zones, this might present further incentives to develop hydrogen refueling stations and other infrastructures that will have high utilization rates which might present even better conditions for the development of hydrogen. Hydrogen allows as well to further developed solar resources, as shown in *AUT* and in *HG*.

Finally, the hydrogen produced by the region in 2050 in *AUT* and *HG* would represent around 5% of the objectives established by the European Union for 2050 (10 000 Mt H₂), and half the objectives stablishes by the French government in the National hydrogen plan, for the development of electrolyzers in 2030 (6 GW). It is compared the results obtained for 2050 with the 2030 objectives as there are not specific objectives stablished for 2050. In this sense, developing hydrogen locally, is required to develop a hydrogen market, which will help the decarbonization of the regional, and French energy system. This requires then a coordinated action between local and national governments.

6. Conclusion

This study looks to contribute to the analysis of the development of P2G solutions at the local level (intra-national regional scale) as a mean to contribute to national and international decarbonization objectives, contributing in particular to the current reflection that exists about the development of the transport and distribution of P2G products, hence, the remarks of the paper will help to structure of the sector. For this study, a bottom-up energy optimization model has been constructed in order to analyze the possible evolution of the energy system of the PACA region in France. The novel modelling approach followed in this study integrate specific characteristics of the regional energy system in terms of how energy is consumed and

produced, and it allows to clearly identify how emissions are produced at each stage of the energy system. The paper then explores how the development of P2G technologies can help the development of renewable energies and the decarbonization of the regional and French energy system. The study is realized through four different scenarios: a reference (REF) scenario that analyzes the evolution of the energy system following past trends, a SRADDET (SR) scenario that integrates the energy policies established by the region, a hydrogen scenario (HGS) that pushes hydrogen production, and an autonomy scenario that attempts to completely limit the electricity and gas coming from the French network in order to analyze the effects over the regional energy system.

The results show that P2G technologies can further push the development of solar resources and allow, through electrolyzers to capture excess solar electricity production in low electricity consumption periods. In fact, in high solar irradiation periods, solar photovoltaic production corresponds almost to the electricity demand from electrolyzers. However, in the case of higher electricity demand, and in winter, solar electricity production might not be enough to cover electrolyzers demand, hence it would be required additional electricity capacities. The hydrogen produced through electrolysis can significantly contribute to the reduction of greenhouse gas emissions from the regional energy system by integrating the use of hydrogen into the transport sector where electricity cannot cover all its energy demand. In particular, hydrogen can be used for freight transport vehicles, as there is no other energy vector that can allow their decarbonization. Synthetic methane presents an important potential to replace the use of fossil fuels in the industry sector, in particular when it is looked to replace natural gas. Its use is not significant in the other sectors as there are more economical and cleaner options to be developed. The synthetic methane produced has been developed using CO₂ from industrial activities, then it will still produce emissions at consumption. Injection of hydrogen to the gas network in this study has been negligible, and it has been preferred to foster greater hydrogen production than just promoting small hydrogen consumption through the gas network. In addition, batteries seem to complement the development of P2G technologies and help the decarbonization of the habitat sector. This is particularly important as it shows that a holistic planning and analysis of the possible decarbonation options have to be performed in order to better assess the potential of the different technologies and resources to decarbonize the entire energy system. This would allow to have a clearer perspective of which resources develop and for which demands.

The flexibility needed to allow high share of renewables has been provided by electrolyser and batteries to capture excess renewable production, while to cover periods with low renewable production it has been used wood and biogas based power plants altogether with batteries. Electricity use from the French network has been reduced completely.

Furthermore, it is possible to further reduce regional greenhouse gas emissions in the region by promoting the capture and use of CO₂ from biogas purification when producing biomethane. This CO₂ could be mixed with hydrogen to produce biomethane that can be used to replace the oil products demanded by the industry sector. There is a potential to produce biomethane using biogenetic CO₂ of around 12 PJ. Fostering the development of P2G technologies in the region is key to reducing emissions, as hydrogen is a key energy vector that can allow the decarbonization of the transport sector, and the production of synthetic methane and biomethane.

It is highlighted as well that developing hydrogen locally would be more beneficial as it can foster the development of local resources, and reach a deeper decarbonization of the transport, and industry sector. In particular, the distance between the hydrogen producing zones, and the consuming zones is not very important, reducing in this way transport costs, which can help the development of hydrogen in the region, and in France. This also applies for the use of CO₂, and the consumption of synthesis methane, as the capture and consumption of these commodities has mainly taken place in the same territory (high consuming zones: BDR1 and AM1). Deploying consuming hubs in high energy consuming zones would also be beneficial for the development of a hydrogen market as infrastructures would have higher usage rates. Then the development of hydrogen will happen first at the local level, which will be further developed to national and international scales.

This study contributes also to the analysis of how local regions in the world can tackle the development of their renewable energy systems, in particular how to analyze the integration of intermittent renewable energy resources, and how P2G technologies can help them to reach the decarbonization of their energy system and contribute to the national and international decarbonization objectives. In this way, the study of local energy system is inevitable to better assess the development of decarbonization options that will contribute to the national and international low carbon energy transition.

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Annex 1: Tecno-economic costs of P2G technologies

P2G technologies' data		Investment costs			Variable costs	Fix costs	Source
		2017	2030	2050	2025	2025	
Electrolyzers (€/kW)	Proton Exchange membrane	1500	950	750		45 (M€/GW)	(Sgobbi et al., 2016)
	Alkaline large	625	377	377	0.06	41.5 (M€/GW)	
	Alkaline medium	1779	444		0.06	89.9 (M€/GW)	
	Alkaline small	1940	512		0.9	136.7 (M€/GW)	(Doudard, 2019)
Gasification – Prod. H2 (€/kW)	Centralized wood/MSW	2453			0.86	122.5182	(Sgobbi et al., 2016)
	Decentralized wood/MSW	3814			1.7	76.2042	
Reforming (€/kW)	Wood reforming	519	519		0.18	20.77 (M€/GW)	
Biogas (€/kW)	Methanisation€/MWh				60		(Doudard, 2019)
	Purification	500	450	405			
	Epuration biogas (€/t)				9		
	Pyrogasification - wood	3000		2500			
	Pyrogasification-MSW (€/MWh)				40		
	Methaner	3267	447	263			
Energy storage (€/kWh)	Biomethane injection	354	267	193			(Sgobbi et al., 2016)
	H2 - Underground centralised	2.7				0.3 (€/kWh)	
	H2 - Tank centralized	13				0.8 (€/kWh)	
	H2 - Tank decentralized	7.5				0.4 (€/kWh)	

Annex 2: Hypothesis about energy prices

€/GJ	2017	2020	2030	2050	Source
Oil	8.23	10.64	19.35	22.37	(Commissariat Général au développement Durable, 2020a)
Gasoline	14.62	18.90	34.34	39.70	
Diesel	12.54	16.21	29.46	34.05	
LPG	20.83	26.93	48.94	56.57	
LFO	12.32	15.92	28.94	33.45	
HFO	8.49	10.97	19.94	23.06	
Bio fuel	21.24	27.47	49.92	57.71	(IFPEN, 2019)
Natural gas	9.50	13.06	16.11	18.65	(Commissariat Général au développement Durable, 2020c; European Comission, 2016)
Electricity frome french electric network	31.8	29	29	29	(Commissariat Général au développement Durable, 2020b)
Biogas from french network	22	20	16.67	16.67	(Ministère de la Transition Écologique et Solidaire, 2019)

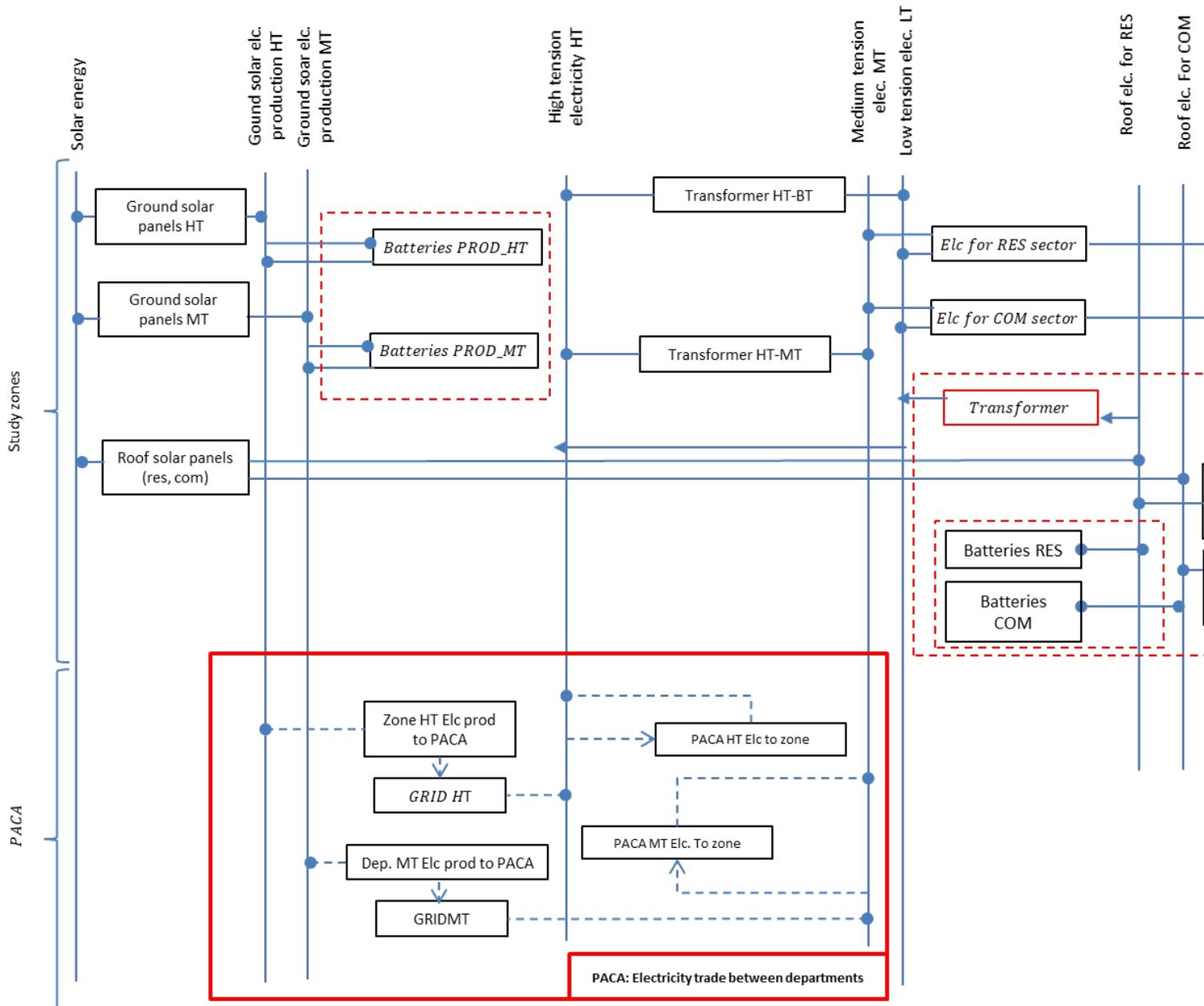
Annex 3 : Hypothesis applied for the end consuming sectors for each of the studied scenarios

2050		REFERENCE	Hydrogène	Décarbonation SR	SRADET	
Habitat secteur	Buildings renovation	Mobilisation of potentials	-50%	80%	100%	
	Electricity		Keeps its share in cooking, heating and water heating demand (~30%)	Keeps at least its share in cooking, heating and water heating demand (~30%)		
	Biomass		Max 13 PJ	Max 13 PJ		
	Gas	Total gas available for consumption in the sector	10% more gas (with respect to 2017) disponible pour consommation dans le secteur (sum of different type of gas : natural gas, biogas, blended gas, synthetic gas)	10% more gas (with respect to 2017) disponible pour consommation dans le secteur (sum of different type of gas : natural gas, biogas, blended gas, synthetic gas)		
		Biogas	max 20 PJ	Can replace the part of natural gas in the sector		
		Blended gas	max 60% of available gas	Can replace the part of natural gas in the sector		
	Geothermal		max 4 PJ	Max 8 PJ		
	Aerothermal heat pumps		max 53000 units per year	max 53000 units per year	max 53000 units per year	Max 58 000 units per year
	Solar	Residential	min +10% per year with respect to 2017	min +20% per year with respect to 2017		
		Commercial	max 1.25 PJ	max 2.5 PJ	max 2.5 PJ	max 2.5 PJ
	Oil products	Energy available for consumption	equal to 2017	-80% with respect to 2017		
	Heat Network	Max energy delivered through the network	20 PJ	Max 20 PJ		
Transport	Gas		max 15% of energy consumption of the sector	max 30% of energy consumption of the sector		
	Biogas		min 10% of the gas available for consumption		min 15% of the gas available for consumption	
	Particular vehicles	Electricity	~30% of vehicles	max 80% of private vehicles in 2050		
		Oil products	-40% of the energy consumed in 2017	-40% of the energy consumed in 2017	No new oil products consuming particular vehicles from 2040	
		Gas	min 10% of the energy consumed by particular vehicles		min 15% of the energy consumed by particular vehicles	
	Modal shift/modal share	People by vehicles	1.2	1.5 in 2050		1.35 from 2030
		Bicycles / scootering	Hydrogen bicycles	Max 5% of particular vehicles mobility demand in 2050		
			can cover up to ~6% of private vehicles mobility demand in 2050	can cover up to ~15% of private vehicles mobility demand in 2050		
	Bus	can cover ~10% of private vehicles mobility demand in 2050	can cover up to ~20% of private vehicles mobility demand in 2050			
	Buses/Freight Transport	Gas	min 20% of the consumption		min 15% of the consumption	min 15% of the consumption
Biofuel		max 20 PJ				
Hydrogen			min 30%			
Industry	Heat recovery		Keep the share of electricity in the sector	Keep the share of electricity in the sector		
Network	Electricity		-15% with respect to 2017		Max 10 PJ	
	Gas		max +10% with respect to 2017			
CO2 Tax			€100/tCO2			

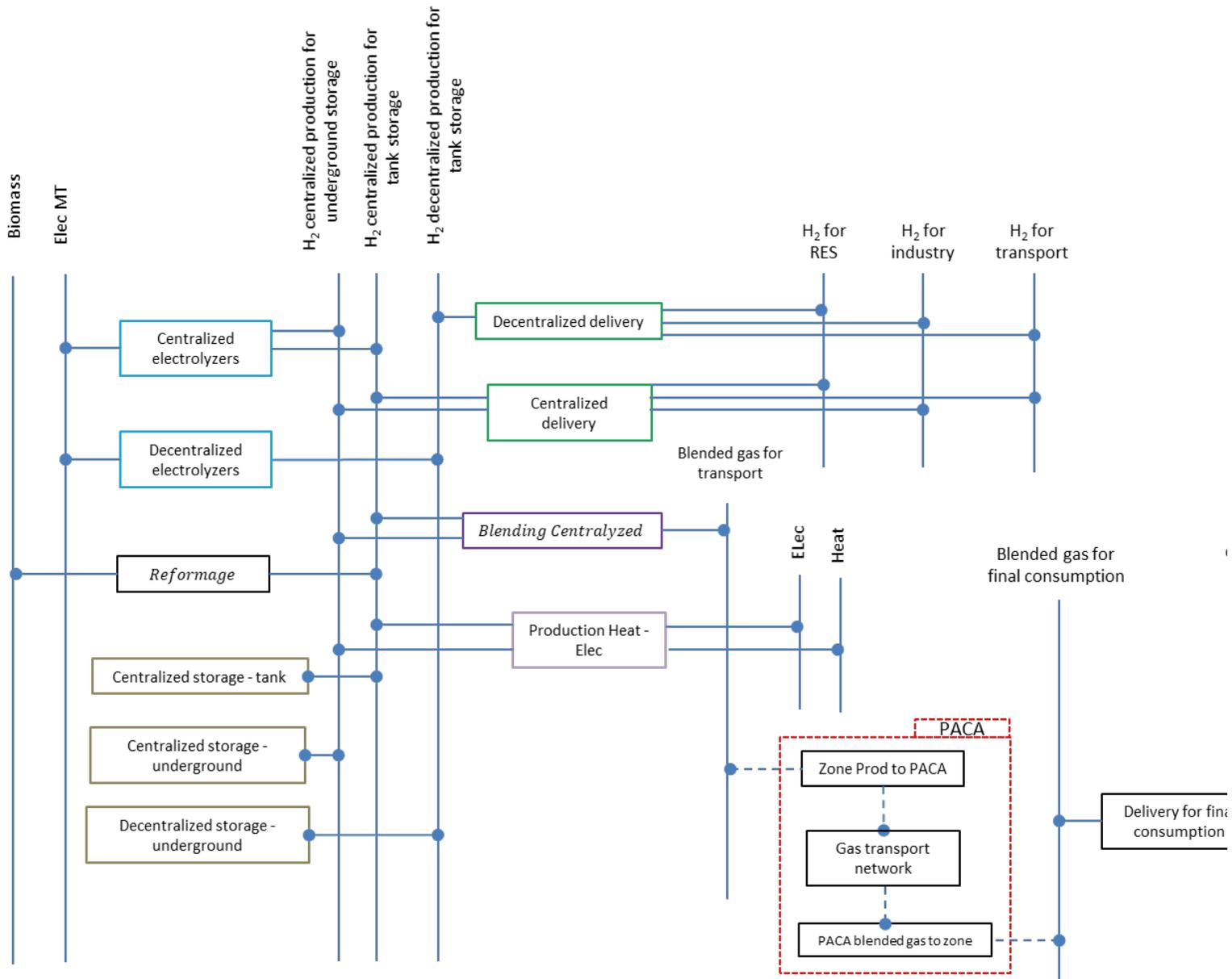
Annex 4: Hypothesis applied for the electricity production sector for REF, HG and AUT

2050		Growth rate	REFERENCE		Hydrogen		Autonomie		
Electricity production	Biogas	Maximum development (PJ)	6%	0.84	4.9	Max 30 PJ	Can replace natural gas	Max 30 PJ	Can replace natural gas
		Minimum development (PJ)	1%		1.16	2.32	Doubled with respect to the reference scenario	2.32	Doubled with respect to the reference scenario
	Biomass	Maximum development (PJ)	2%	1.43	2.75	2.75		2.75	
		Minimum development (PJ)	0%		1.43	1.43		1.43	
	Wind	Maximum development (PJ)	2%	0.42	0.81	0.81		10 PJ	
		Minimum development (PJ)	1%		0.59	0.59		0.59	
	Hydro	Maximum development (PJ)	1%	28.65	35	35		35	
		Minimum development (PJ)	0%		29.13	29.13		29.13	
	MSW	Maximum development (PJ)	1%	1.53	2.3	2.3		2.3	
		Minimum development (PJ)	0%		1.53	1.53		1.53	
	Solar	Ground	Max 10%	1.47	47.52	100%	of potentials (easily accessible potentials)	100%	of potentials (easily accessible potentials)
			Min 5%		30.26	min 90%	of potentials	30.26	of potentials
		Roof	Max 10%	0.77	80.46				
			Min 5%		3.85			3.85	
Ocean	GW				1		2		
Fossil	Max	0%	35.54	35.54	No new power plants				

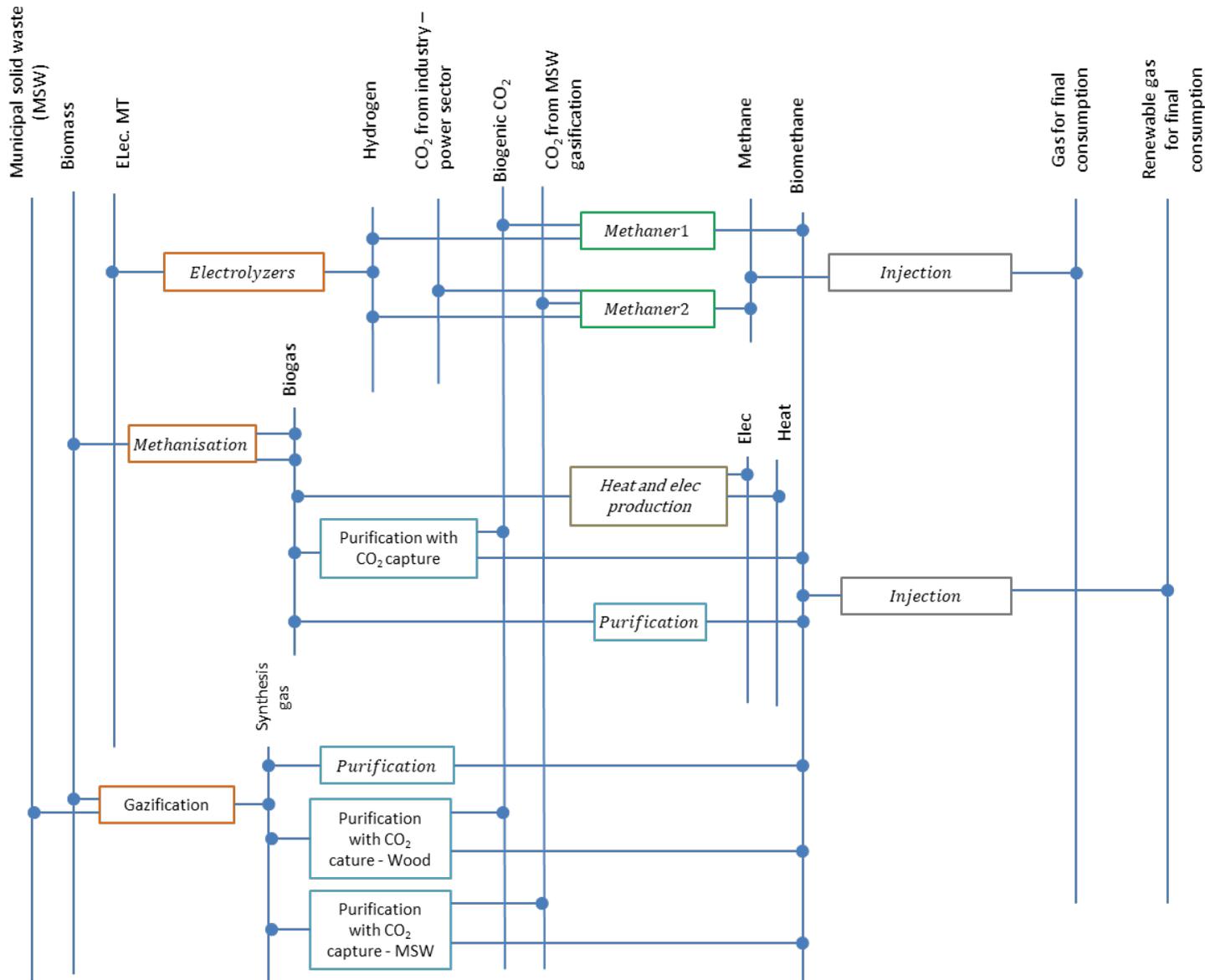
Annexe 5: Modeling of solar energy production



Annexe 6: Modeling of hydrogen production



Annexe 7: Modeling for methanation, biogas, syngas, and methane production



Annexe 8: Modeling for the transport and distribution for the different gas products

