A 100% renewable electricity mix? 
Analyses and optimisations

Testing the boundaries of renewable energy-based electricity development in metropolitan France by 2050

October 2015

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Foreword

In 2013, l’Agence de l’Environnement et de la Maîtrise de l’Énergie (ADEME) (French Environment and Energy Management Agency) published its energy and climate scenarios for the period 2030 to 2050, suggesting possible avenues to achieve a four-fold reduction in greenhouse-gas emissions by 2050 by cutting energy consumption by half and deploying renewable energy sources for electricity generation on a substantial scale. Both of these objectives were the basis for targets set by the Président of France and subsequently adopted by Parliament in the Energy Transition Law to promote green growth.

Today we present a study that explores the technical aspects of renewable energy deployment in the electricity system. This is a forward-looking exploratory scientific study, not a political scenario. It is similar to the 2012 National Renewable Energy Laboratory (NREL) study of a 100% renewable energy scenario for the United States. The electricity mixes examined in the ADEME study are theoretical: they are created from scratch and do not take into account the current situation or the path needed to achieve a 100% renewables-based electricity system.

So what is the point of such a study? In putting together an electricity generation mix that relies up to 100% on renewable energy sources, we show that a hypothesis that most stakeholders may have thought inconceivable is technically possible, without underestimating the conditions this would require, whether it is the technical or economic aspects (including the costs to public authorities) or social acceptability. The purpose of this study is precisely to highlight the obstacles and measures to be taken to support a policy aiming for a massive increase in renewables-based electricity generation. It also aims to identify the point beyond which the objective is technically unfeasible or the costs are too great.

Knowing when to question what we think is impossible is what pioneering work is all about. This study falls squarely within the remit of ADEME in its role as a ground-breaker, challenging preconceived ideas and opening a whole range of possibilities. All stakeholders can then re-examine the issue in light of the findings here and adjust their outlook accordingly to build a vision of the future together.

To evaluate the outlook for a 100% renewables-based electricity mix, we launched this study in 2013 with the aim of analysing to what extent the electricity network would be capable of balancing supply and demand on an hourly basis if the share of renewable energy was substantially increased. After two years of work and numerous consultations, it gives me great pleasure to present this completed study. I am extremely proud of the originality of the results and of the analytical rigour and subtlety. An intermediate version published a few months ago aroused a certain amount of interest, as well as fears and criticism. Improved for better understanding with more ample explanations, and substantially supplemented by sensitivity analyses, the study is now complete and gives a clear picture both of the conditions for a 100% renewable energy mix for electricity generation and the inherent limitations of this type of exercise.
The key findings are:

- Several electricity generation mixes are technically possible to satisfy demand during every hour of the year with 80% or 100% of renewables-based power generation.
- Developing demand-side management options for electricity and controlling peak loads are key conditions. Without these, electricity system costs cannot be controlled, whatever the power generation mix including a significant percentage of renewable energy might be.
- Technology costs must continue to fall, especially for the least-mature technologies, to allow a balanced mix of the various options for electricity generation. Lower costs can be achievable through technological progress and by adequate funding for renewable energy research, development and deployment.
- Social acceptance is crucial to create favourable conditions for deployment of a new electricity mix. There needs to be complementarity between decentralised generation and large centralised generation stations, better interconnections underpinned by the electricity network for domestic electricity exchanges, redistribution of the income generated by energy generation and more.

We believe these results to be sufficiently robust to serve as a basis for debate among the stakeholders. Some will probably object that the scope of the study is too narrow, as we do not take into account existing structures and have not programmed the way in which investment will progress. They are right. Others will observe that we have not pushed our analyses to intervals of less than one hour. They are also right and we are well aware of the challenge represented by network stability management, which is not addressed in this study.

Yet, looking out decades ahead can allow a point of departure with a blank (or almost blank) page in order to sketch a lasting, desirable situation. This provides the stakeholders a direction for action in order to make adjustments to choices and important decisions that can enable such a scenario to be realised and to ensure sustainability.

Energy transition requires innovation in all sectors, from power generation and consumption to network management and regulation. The changes needed to address climate change issues have to be significant and cannot be simple tweaks to the current systems. Henry Ford was fond of saying that if he had asked people what they wanted, they would have said, “faster horses”.

To put it in a nutshell, everyone has to participate. This includes researchers, experts, public and economic stakeholders, civil society and consumers alike in order to bring about profound change in practices and make substantial deployment of renewable energy technologies possible, based on advanced energy efficiency and radically re-organised electricity networks.
Of course, we should recall that electricity only represents a quarter of total energy consumption in France. The best ways to improve the sustainability of our energy system overall will come about in the context of careful analysis and attention to all the sectors, not by tackling each vector separately (electricity, gas, petroleum products and heat). This study is therefore only a contribution inviting subsequent work to build upon a shared understanding of our energy future.

Bruno Lechevin
Président
l’Agence de l’Environnement et de la Maîtrise de l’Énergie
Context and objectives

This scientific prospective study aims to better understand the functioning of a 100% renewable energy-based electricity system in France. Power generation and consumption must be equalised at every moment. However, some forms of renewable energy such as solar photovoltaic (PV) and wind power produce depending upon the discretion of the weather – when the wind blows or the sun shines. Is it possible to supply the French electricity mix with 100% renewable energy?

Analyses in this study are based on a model used to determine the optimal renewable energy developments by region and to check every hour that the balance between production and demand can be achieved. The horizon of such an electricity generation mix would probably be relatively distant (post 2050). The investment path between today and 2050 is not in the scope of this study. Several prospective scenarios have been constructed and optimised in order to scan a range of possibilities.

Over the last few years, renewable energy technologies have made significant progress. Numerous studies conclude that renewable energy costs will fall sharply by 2050. In this context, it is legitimate to consider the feasibility and the economic impact of an electricity generation mix with a high penetration of renewable energy sources. Such an analysis requires extremely specialised models that can take into account the need to guarantee sufficient electricity supply over a short-time period (typically one hour, over the course of one year and for several climate variables), how the power generation, transmission and distribution assets will be managed across the regions and the circulation of electricity flows.

This study aims to draw together all these parameters. It thus constitutes an innovative technical exercise which, through the hypothesis of a 100% renewable energy-based power generation mix in 2050 (without looking at the path required to achieve this), strives to answer the following questions:

- What limitations emerge if the amount of renewable energy in the electricity mix in France is substantially increased?
- What are the optimal electricity generation mixes to suit various sets of assumptions concerning technological developments, consumption and social, acceptance?
- How are the different renewable energy generation facilities disseminated geographically?
- What are the economic impacts of an electricity system with a high level of renewable energy penetration?

This study uses some of the assumptions from the long-term scenarios prepared in 2012 by ADEME and published in, “ADEME Energy Transition Scenarios 2030-2050” in 2013. These scenarios identified renewables-based generation potential and put forward an ambitious demand scenario. Assumptions regarding storage are taken from previous studies.¹

¹ The Etude sur le Potentiel du Stockage d’Energies study on storage potential in 2030, co-funded by ADEME, Association Technique Energie Environment (ATEE) and the Direction Générale de la Compétitivité (DGCIS) (www.ademe.fr/etude-potentiel-stockage-denergies), and the Power-to-Gas study, co-funded by ADEME, Gaz Reseau Distribution France (GrDF) and Gaz Reseau Transmission (GRTGaz) (www.ademe.fr/etude-portant-lhydrogene-methanation-comme-procede-valorisation-olelectricite-excedentaire).
Methodology and main assumptions

This study is based on a model of the electricity system that both optimises the electricity mix, i.e. the electricity generation and storage portfolio by each type of renewable energy technology and by region as well as inter-regional exchange capacity. The model simulates optimised management of this power mix in hourly intervals over a period of one year. The focus is on renewable energy sources for electricity generation, storage, consumption and commercial exchanges. Other energy sources such as natural gas and heat discussed in this report refer to their use for electricity production.

Figure 1 - Renewables supply for a daily load curve example in the optimisation scenario

The vertical axis shows the hourly capacity. Power generation from the various renewable sources are combined (one colour per technology) to satisfy demand (black curve). Negative capacity represents export or storage.

In order to take into account regional differences in renewable energy resource potential, e.g. different capacity factors and profiles, this study considers France on the basis of its 21 administrative regions. Technology capacities are optimised for each region, as are inter-regional exchange capacities, allowing network development requirements to be estimated. Optimised management of generation portfolios in neighbouring countries is simulated in hourly intervals in parallel. International exchange capacities and the installed capacity in the power generation mix of other countries are established upstream based on an ambitious European Commission scenario in terms of the share of renewable energy generation (“Roadmap 2050, 80% Renewable Energy”).

In order to put forward an electricity mix which is physically possible to achieve, the maximum resource has been considered per region for all technologies. The potential for each region has thus been assessed in line with the available natural resources and adjusted to take into account local topological and societal constraints. In order to analyse the challenges involved in balancing supply and demand at all times during the year, electricity consumption graphs in hourly intervals have been compiled for 2050 based on profiles per type of use and per sector, and annual volume forecasts taken from ADEME “Energy Transition Scenarios 2050” which assumes significant efforts will have been made regarding demand-side
management by then leading to an estimated annual electricity consumption of 422 terawatt-hours (TWh).²

To meet this annual demand in France, flexible demand ratios have been calculated for various use profiles, resulting in a need for 60 TWh of dispatchable electricity (using different methods depending on the use).

In order to guarantee the robustness of the optimised electricity mix, several meteorological scenarios are also employed. Each of these scenarios corresponds to a historical year, including regional records for temperature, consumption and wind and solar energy resource potential for each region in France as well as each interconnected country. Capacity is optimised for one of these scenarios, deemed to be design-critical as it includes a cold snap lasting two weeks (corresponding to that experienced in February 2012). The resulting mix was then also simulated for six other scenarios and for a year of drought.

Moreover, given the variety of possible technical, political and social developments which may occur by 2050, and the considerable impact of the various assumptions adopted for modelling based on constraints and challenges relative to the electricity supply, fourteen different electricity mixes have been optimised subject to varying degrees of renewable energy penetration (40%, 80%, 95% and 100%):

- A baseline scenario from which various assumptions are modelled.
- Several simulations that consider variations related to societal aspects:
  - moderate demand-side management³
  - low acceptance of network reinforcement
  - one case of moderate acceptance of onshore solar and wind energy installations, and another case of very limited acceptance.
- Several simulations that consider variations related to technical and economic developments:
  - case with more marked progress for technologies which are currently less mature, and a second case with less progress (and higher costs for all renewable energy sectors)
  - access to affordable financing renewable energy development.
- An unfavourable case with both very limited acceptance and a low level of technological progress.
- Four contrasting variations exploited to analyse the sensitivity of the resulting mix to a specific parameter (for example, a particularly dry year, absence of an adequate photovoltaic sector, second-generation wind energy sector not taken into account, no dynamic demand management).
- A case that takes into account sub-transmission network modelling.

² For comparison, France’s annual electricity consumption in 2013 was 442 TWh (“Key Figures for 2014”, ADEME).
³ The moderate demand scenario is based on an extrapolation to 2050 of the annual volume assumptions from the RTE (Réseau de Transport d’Électricité) New Mix scenario.
Table 1 - Summary of the technologies modelled and their main assumptions

For some technologies, the installed capacity is fixed (model input data). National resource corresponds to the maximum capacity that can be installed.

<table>
<thead>
<tr>
<th>Renewable energy source</th>
<th>Technology</th>
<th>National resource (GW)</th>
<th>Fixed capacity</th>
<th>Dispatchable technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Onshore</td>
<td>174</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Offshore, bottom-fixed</td>
<td>20</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Offshore, floating</td>
<td>46</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Ground-mounted PV</td>
<td>47</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Solar</td>
<td>Roof-top PV</td>
<td>364</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>CSP</td>
<td>0.41</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Hydropower</td>
<td>Run-of-river</td>
<td>8</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Reservoirs (lakes and dams)</td>
<td>13</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Renewable thermal energy</td>
<td>MSW</td>
<td>0.43</td>
<td>yes</td>
<td>no</td>
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<tr>
<td></td>
<td>Wood-fired co-generation</td>
<td>3</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Biogas production and co-generation</td>
<td>–</td>
<td>Fixed energy resource of 8 200 GWh</td>
<td>yes</td>
</tr>
<tr>
<td>Geothermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marine</td>
<td>Tidal power plant</td>
<td>0.24</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Wave</td>
<td>10</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Tidal stream turbine</td>
<td>3</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Notes: GW = gigawatts; PV = solar photovoltaic; CSP = concentrating solar power; MSW = municipal solid waste; GWh = gigawatt-hours.

Our modelling optimises the capacities of the various technologies, summarised in Table 1, based on annualised cost assumptions for their installation and maintenance extrapolated to 2050 from in-depth bibliographic research. Figure 2 compares the levelised cost of electricity (LCOE) for the main technologies for which the installed capacities are optimised. The levelised cost of storage (LCOS) is summarised in Table 2.

4 The main sources are: Appendix 8 of the Court of Auditors report concerning renewable energy; “Energy Technology Perspectives 2014”, International Energy Agency (IEA); the Energy Technology Systems Analysis Program (ETSAP), an implementing agreement of the IEA; “Levelized Cost of Electricity Renewable Energy Technologies – 2013”, Fraunhofer Institut for Solar Energy Systems; “Transparent Cost Database”, National Renewable Energy Laboratory; and “Pathways towards a 100% Renewable Electricity System” SRU (Sachverständigenrat für Umweltfragen, German Advisory Council on the Environment).

5 This refers to the cost of energy in euros per megawatt-hour, taking into account annualised investment costs, yearly maintenance costs, any fuel costs, the amount of energy produced annually by each technology for the different regions and connection costs.
Figure 2 - Levelised cost of electricity by technology with capacity optimised: baseline scenario

<table>
<thead>
<tr>
<th>Storage</th>
<th>Resource</th>
<th>Yield</th>
<th>Average LCOS(^6) (€/MWh)</th>
<th>Discharge time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term(^7)</td>
<td>-</td>
<td>0.81</td>
<td>58</td>
<td>6 hours</td>
</tr>
<tr>
<td>PSHP</td>
<td>P(<em>{\text{min}}) = 7 GW, P(</em>{\text{max}}) = 9 GW</td>
<td>0.81</td>
<td>46 for the first 7 GW</td>
<td>32 hours</td>
</tr>
<tr>
<td>Inter-seasonal(^8)</td>
<td>-</td>
<td>0.33</td>
<td>138</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: LCOE = levelised cost of electricity; €/MWh = euros per megawatt-hour.

Table 2 - Summary of modelled storage and main assumptions

Main technical findings

*Several types of generation mixes can balance supply and demand on an hour-by-hour basis with an 80% or 100% renewables-based electricity supply, including in unfavourable weather conditions. In all cases, wind and PV power provide the bulk of the generation.*

The optimisations conducted for the various scenarios identified several mixes that are able to balance supply and demand for every hour of the year using an 80% or 100% renewable energy-based generation mix by 2050, even under particularly restrictive cases (e.g. insufficient demand-side management or poor social acceptance), as well as in unfavourable weather conditions. The optimised mixes are able to cover demand even during cold snaps, long low-wind periods or particularly dry years. The electricity generation mix under a number of scenarios and variations are illustrated in Figure 3.

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\(^6\) The levelised cost of storage (LCOS) is the equivalent for storage of the LCOE of a producer. It includes the installation costs adjusted to the amount of energy actually discharged (calculated following the optimisation simulation). This is the extra cost of the discharged energy, excluding the stored electricity purchase cost.

\(^7\) For cost projections, the technology was equated with compressed air energy storage (CAES).

\(^8\) Inter-seasonal storage cost projections correspond to pairing up “power-to-gas” (methanation) and “gas-to-power” (synthesis gas combustion turbines) technologies.
Figure 3 - Electricity generation mix in 100% and 80% renewables-based scenarios adapted to various assumptions

The bar charts show installed capacities (GW) and the pie chart shows annual production (TWh) by technology type.9

Baseline scenario – 100% renewables

80% renewables – no constraints

100% renewables – moderate acceptance

80% renewables – moderate acceptance

100% renewables – low level of technology progress

80% renewables – very limited acceptance and low level of technology progress

- Solar power technologies
- Marine power technologies
- Geothermal and thermal renewable energy technologies
- Wind power technologies
- Hydropower technologies
- Conventional thermal energy technologies

9 Wind power including onshore and offshore turbines (bottom-fixed and floating).
The various possible constraints have a significant impact on how the associated optimal electricity mixes are assembled. The main renewable energy sources are wind and solar power in all cases. Depending on the acceptance constraints, the roof-top solar power share, in terms of installed capacity and production, increases compared with ground-mounted installations, as does the offshore wind energy share compared with onshore wind farms. Moreover, where severe acceptance limitations are linked to the network system issues, local generation will often be preferred, even if productivity levels in local resources are not the best. Renewable energy generation mix of 80% generally means the network and storage facilities can be reduced in size unless extremely severe acceptance constraints require the development of marine technologies. Under certain conditions where particularly high demand coincides with very limited social acceptance, achieving a 100% renewables electricity mix may be severely compromised.

According to the assumptions, overall electricity costs vary from €103/MWh\(^{10}\) to €138/MWh\(^{11}\). The parameters which stand out as the most significant for electricity costs are social acceptance, the evolution of technological costs and extent of demand-side management. Keeping a non-renewable energy fraction in the generation portfolio reduces the degree to which cost is affected by these factors and provides some resilience with regard to economic and social constraints.

A comparison of electricity supply costs in 2050 for various scenarios is shown in Figure 4. In the absence of any specific constraints, the difference in costs between the 100% renewables baseline scenario and the 40%, 80% and 95% versions is relatively low (cost falls from €119/MWh at 100% to €117/MWh at 40% renewables level at the scale of the detail of the model). Nevertheless, the additional cost for the higher percentages is significant. To increase from 95% to 100% renewables-based generation, the additional megawatt-hours of renewable energy to be generated would cost about €183/MWh.

It can also be seen that demand and peak load management are important factors to limit the cost of a 100% renewable energy scenario, as these measures make it possible to reduce the cost per megawatt-hour by 5%. Indeed, in cases with insufficient demand-side management (21% increase in annual electricity consumption) and a 40% higher peak load, the electricity system will have to use less cost-effective renewable energy technologies and larger amounts of stored energy to cope with peak loads in winter.

In addition, including severe social acceptance limitations (linked to new developments of transmission and distribution grids and/or onshore renewable energy installations) increases electricity supply costs by 6-7%. These considerable extra costs are due in particular to the need to replace a portion of onshore renewables by marine technologies, which are generally more expensive. For 80% renewable energy penetration, reduced acceptance leads to an increase in cost of only 3%. The composition of the electricity mix can adapt more easily to constraints restricting the deployment of a particular technology.

\(^{10}\) For the least-cost scenario: with "facilitated access to capital" with 100% renewable energy.
\(^{11}\) For the most expensive scenario: "unfavourable" scenario with 80% renewable energy.
Figure 4 - Comparison of electricity supply costs in various scenarios, 2050

The estimates take into account: annualised generation costs; transportation, distribution and storage costs; and fixed costs related to demand flexibility.

<table>
<thead>
<tr>
<th>Comparison of electricity supply cost in various scenarios, 2050 (€/MWh)</th>
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<tbody>
<tr>
<td><strong>Renewables portfolio cost</strong></td>
</tr>
<tr>
<td>Baseline scenario</td>
</tr>
<tr>
<td>95% renewables</td>
</tr>
<tr>
<td>80% renewables</td>
</tr>
<tr>
<td>40% renewables</td>
</tr>
<tr>
<td>Complex network reinforcement</td>
</tr>
<tr>
<td>Reduced demand management</td>
</tr>
<tr>
<td>Moderate acceptance</td>
</tr>
<tr>
<td>Moderate acceptance - 80% renewables</td>
</tr>
<tr>
<td>Very limited acceptance</td>
</tr>
<tr>
<td>Unfavourable scenario - 80% renewables</td>
</tr>
<tr>
<td>High costs</td>
</tr>
<tr>
<td>Very positive technological progress</td>
</tr>
<tr>
<td>Facilitated access to capital</td>
</tr>
</tbody>
</table>

Lower cost technologies have a significant effect on the overall electricity supply cost. Assuming the reduction in technology costs is 50% less than the baseline scenario means the less-mature technologies such as solar PV incur significantly higher costs (+75% for ground-mounted PV energy and +62% for roof-top PV energy). However, the overall cost of the mix increases to a lesser extent (+14%) by relying on mass development of onshore wind turbines, an industry which is already quite mature and France has substantial wind resource potential.
A mix with a high penetration of renewables requires demand flexibility and the development of storage solutions.

The scenarios implement ambitious demand flexibility solutions, assuming widespread development of smart meters and associated services. This results in a maximum theoretical upward (consumption stimulation) flexibility of 22 gigawatt (GW) and downward (load-shifting) of 8 GW. Demand-side management is activated according to differentiated load-shifting conditions depending on the dispatchable loads (heating, washing, hot water equipment or electric vehicle charging).

Figure 5 - Storage solutions developed for various levels of renewable energy-based electricity generation penetration

The findings highlight the value of developing storage solutions of varying sizes for an electricity mix with a high penetration of renewables (Figure 5). To move from 80% to 95% renewables penetration, fossil-fuel generation is replaced by inter-seasonal storage to cope with the most challenging weather conditions for the system (9 GW with 95% renewable energy and 17 GW with 100% renewables). Without taking into account the possibility of using synthesis gas (syngas) for purposes other than electricity, "power-to-gas" is no longer necessary to balance the electricity system below 80% renewable energy in the mix. Short-term storage, seldom used at a level of 40% renewable energy (2 GW, in particular explained by PV installed capacity in foreign mixes), represents 20% (8 GW) of PV installed capacity from 80% renewable energy upwards.

Moreover, in the event that no dynamic flexibility solutions are set up\textsuperscript{12}, a limited amount of additional daily storage (7.3 GW, or a cost equivalent to that of demand-side management in the residential sector) is sufficient to manage intra-day variations. Given the cost assumptions in the study, short-term storage would thus provide services equivalent to dynamic demand management in the residential sector.

\textsuperscript{12} In this situation, static daily programming (not optimised with regard to the system) of domestic hot water and electric vehicle charging is the only form of management.
Complementarity between technologies is key. The economic optimum depends not only on the energy cost but also on the services rendered to the system.

From the point of view of technology complementarity, Figure 6 shows that the optimum in economic terms involves using both PV and wind power source. Moreover, depending on the particular regions and their wind conditions, the study underlines the value of second-generation wind turbines which enable power production from wind sites with lower levels but less fluctuating wind resource profiles. The system thus benefits from the most cost-effective natural resources specific to each region.

Some technologies with a more baseload profile, such as geothermal electric production, or which are dispatchable, such as wood-fired co-generation, see their extra cost compensated by the benefit they offer to overall system operation. They are thus used to their maximum potential. However, their share in the overall mix remains low, given the constraints linked to their site-specific nature and thus are determined exogenously in the modelling.13

Depending on the cost assumptions adopted and how well the production profiles match, the optimum energy ratio is four-times more wind power than PV technologies from 80% renewables levels upwards. This ratio drops if wind power development is restricted by lower social acceptance. In this case, PV power can account for 40-50% of the assumed wind power generation.

Moreover, subject to costs being significantly reduced, there is a place for marine generation technologies in an optimised 100% renewable energy mix. This would allow the electricity system to benefit from the more stable profile (in weekly increments) of marine resources.

Our analyses confirm that energy costs are not the only criteria to be taken into account when selecting which technologies to include in an optimised generation portfolio. The services rendered to the system by the different technologies, i.e. how well the electricity production profiles correspond to non-dispatchable demand on an hourly, daily or monthly level, and the flexibility of dispatchable technologies, are also fundamental criteria when developing a generation mix that ensures reliability, affordability and sustainability of the power generation mix.

13 These resources are taken from ADEME (2013) “Energy Transition Scenarios 2030-2050”, which, in particular, assumes that biomass is used in preference for direct use, which maximises its yield.
The pie charts show the breakdown of the energy generated in each region.

The findings highlighted in this executive summary summarise the main messages from the core study. They are not, however, a full summary of the comprehensive analyses conducted. Other themes were addressed such as sensitivity analyses highlighting the importance of certain technologies (e.g. optimisation of a case without PV or without second-generation wind power), an estimation of reserve capacity needs, and an assessment of the built surface area required or the impact of funding levels on renewable energy installations.
Limits and outlook

While this study strives to model numerous parameters of the electricity system, it has its limits, linked to the methodological framework in which it was conducted. The analyses carried out do not aim to be a comprehensive feasibility study. They are simply designed to answer the questions raised in the objectives. The following points therefore reflect the scope inherent to the methodology adopted:

- Even if modelling the network in hourly intervals is a common practice for this type of forward-looking exercise, it does not allow the electricity network's fine dynamics and stability to be assessed, in particular with regard to transient phenomena such as a sudden frequency drop in the event of an exceptional incident.
- The mixes studied achieve an hourly balance between supply and demand but would undoubtedly lead to significant changes in terms of network operation, which have not been examined in this study.
- The study analyses various optimal electricity mixes in the long term without taking into account the existing situation. Therefore it does not examine the investment path needed to move from the current electricity system to the mixes studied.
- At this stage, additional costs in the distribution networks have not been considered. Current costs have simply been extended. Subsequent work on these points may supplement the analyses.
- Costs are assessed from the community point of view and do not reflect opportunities a project sponsor may have due to specific regulatory measures. Breakdown of the electricity supply costs (e.g. energy portion / capacity portion / fixed portion of TURPE (acronym for the public electricity network tariffs), CSPE tax (acronym for the public service contribution portion of the electricity tariffs) which only partially reflects reality and the disparity of costs to the public authorities may mean certain projects are cost-effective for their sponsor but not optimal for the public authorities.
- Externalities such as the impact on employment, social benefits associated with the emergence of a renewable energy technology sector (increased know-how, export), energy security (independence criterion) or environmental elements (e.g. impacts of greenhouse-gas emissions, pollutants and accidental risks) are not addressed.
Supplementary documents

The documents listed below were developed for this study. They provide details of the assumptions and other aspects that support our analyses. These annex studies are available in conjunction with the main report on the ADEME website (in French) at: [www.ademe.fr/mix-electrique-100-renouvelable-analyses-optimisations](http://www.ademe.fr/mix-electrique-100-renouvelable-analyses-optimisations). The terms in French in the reference column are used throughout the report to direct readers to sources for further information.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
<th>Source</th>
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<tr>
<td>[Consommation]</td>
<td>Energy demand scenarios</td>
<td>Energies Demain</td>
</tr>
<tr>
<td>[Coûts]</td>
<td>Technology costs</td>
<td>Artelys</td>
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<td>[EolienPV]</td>
<td>Solar PV and wind resource potential graphs and estimates</td>
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<td>[Gisements]</td>
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<td>Artelys</td>
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<td>[Marché]</td>
<td>Qualitative analyses concerning the market rules and cost-effectiveness of the facilities</td>
<td>Artelys</td>
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<td>[Modèle]</td>
<td>Inventory of existing generation facilities optimisation-simulation model</td>
<td>Artelys</td>
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<td>[Réserve]</td>
<td>Standard days Establishment of reserve capacity</td>
<td>ARMINES-PERSEE</td>
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Consult the internet animation with a breakdown in hourly intervals of the 100% renewable energy electricity mix at: [http://mixenr.ademe.fr/en](http://mixenr.ademe.fr/en).
ADEME, authors and contributing partners

Having played a central role in environmental issues for two decades, ADEME – the French Environment and Energy Management Agency – is active in the implementation of public policies in the areas of the environment, energy and sustainable development. ADEME provides expertise and advisory services to businesses, local authorities and communities, government bodies and the general public, enabling them to establish and consolidate their environmental action. As part of this work, the agency helps finance projects from research to implementation in the following areas: waste management, soil conservation, energy efficiency and renewable energy, air quality and noise abatement.

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This study was conducted by ADEME with the participation of the Directorate General for Energy and Climate (DGEC). Participants include:

- Anne-Laure Dubilly, engineer in the Networks and Renewable Energies Department, ADEME.
- David Marchal, deputy head of the Networks and Renewable Energies Department, ADEME.
- Jean-Michel Parrouffe, head of the Networks and Renewable Energies Department, ADEME.
- Damien Siess, deputy manager of the Sustainable Production and Energy Department, ADEME.
- Eric Vidalenc, economist in the Economics and Long-Range Planning Department, ADEME.

ADEME entrusted a consortium composed of Artelys, ARMINES-PERSEE and Energies Demain with implementation of the study. (Profiles of these partners are below.) This work was carried out by:

- Project management (Artelys): Laurent Fournié; project manager: Alice Chiche.
- Energy system modelling, hourly supply and demand balance simulations, energy system optimisation, economic calculations (Artelys): Nathalie Faure, Régis Bardet and Jean-Christophe Alais.
- Modelling and analysis of energy demand (Energies Demain): Jean-Baptiste Biau, Ugo Piqueras and Colombe Peyrusse.

To guarantee scientific soundness and robustness, the assumptions, methodologies and results were examined by a scientific committee composed of national and international experts in the energy field in industry and academia (Réseau de
Transport d’Électricité (RTE), International Energy Agency (IEA), Institut du Développement Durable et des Relations International (IDDRI), Météo France, German Advisory Council on the Environment (SRU) and Total). We are extremely grateful to the members of this scientific committee for their active participation and judicious suggestions. In addition, the study benefited from a discussion committee comprised of industry stakeholders on three occasions and their significant contributions helped to strengthen the study throughout its course.

*   *   *

Artelys is a company specialising in optimisation, forecasting and decision-making support. With about 100 studies and software projects in the energy field, Artelys has become a reference in optimisation and technical and economic analysis of large-scale energy systems. Artelys has developed a software suite, “Artelys Crystal”, dedicated to the economic optimisation of management and investment for energy systems.

The ARMINES-PERSEE Centre, the joint centre of the ARMINES and MINES ParisTech (specifically the ERSEI group – le groupe Énergies Renouvelables et Systèmes Électriques Intelligents) has developed expertise in modelling variable renewable energy generation and its integration into the electricity system over the last 25 years. More recently, issues concerning the integration of renewable energy generation into the electricity market have been integrated in the centre's field of expertise.

Énergies Demain has been developing tools for several years which are used to reconstruct and forecast energy demand at all levels from municipalities to the whole of France. Modelling is carried out for each separate use and for each type of user. The "bottom-up" approach selected is based on an estimation of unit needs, the level of equipment and usage modes.
ABOUT ADEME

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