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WP3.5 Modelling and Scenario Development of the TMO Energy System

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Abstract

The WP3.5 of the Interreg RES-TMO project focuses on the development of a decision support tool for the definition of energy, climate and air quality strategies. The method aims at describing, in the simplest and most complete way possible, the various possible options to develop renewable energy production. It consists in: 1) evaluating the characteristics of the energy demand of the Upper Rhine Region (in terms of energy and power); 2) evaluating the resources potentially available in the region (also in terms of energy and power); 3) calculating all the possible scenarios allowing to satisfy the energy demand (always in terms of energy and power) from the available resources so as to estimate the possible needs for energy storage or contributions from outside the region ; 4) grouping the scenarios using similar energy resources in order to show families of scenarios that are clearly distinct from each other; 5) estimating the costs of each family of scenarios by considering the different technologies that could exploit the resources selected in each family.
This report presents the decision support tool developed, and its application to the Upper Rhine region. The application consists in analyzing the energy balance and all the scenarios that have been built for the Upper Rhine Region. The calculation of the wind and solar energy production potentials in the Upper Rhine Region shows that they are sufficient to meet 100% of the electrical demand, or even more. All the scenarios of intermittent energy introduction and mix are detailed with regard to storage and controllable needs, and possible energy exports to other regions. Sensitivity studies have been carried out in order to identify some key parameters that could be used to characterize the technologies that could be deployed in the Upper Region region. All scenarios were computed, evaluated in terms of costs and sorted. The REPM methodology and its results are discussed and compared with the work performed by KIT with the PERSEUS model in other tasks of WP3.

Keywords: Decision support tool; energy strategies; climate; air quality; storage.

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List of abbreviations

CdTe	Tellurure de cadmium
CNRS	Centre Nationale de Recherche Scientifique
c-Si	Crystalline silicon
DTU	Technical University of Denmark
EEA	European Environmental Agency
EPAC	Energy, Air Pollution, Climate Team
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Center
LIVE	Laboratoire Image Ville Environnement
PCA	Principal Component Analysis
PV	Photovoltaïc
PVGIS	Photovoltaic Geographical Information System
REPM	Regional Energy Planning Model
RES	Renewable Energy System
RTE	Réseau de Transport d'Électricité
TECA	Tool for the definition of Energy strategies, Climate and Air quality
UN	United Nation
UNISTRA	Université de Strasbourg
URR	Upper Rhine Region
WRF	Weather Research and Forecasting

1. Introduction

The various sectors of human activity are heavy consumers of fossil fuels, the combustion of which releases into the atmosphere pollutants that are harmful to people's health as well as greenhouse gases. Currently, about 80% of the greenhouse gases are emitted from the combustion of fossil fuels, which contributes to the increase in their concentration in the atmosphere (EEA, 2015). This increase is responsible for global climate disruption, the consequences of which are now clearly visible all over the world: extreme precipitation events, floods, storms, heatwaves, droughts, fires, ice melting, etc (IPCC, 2021; UN, 2015). It is becoming urgent to drastically reduce greenhouse gas emissions to limit climate change as much as possible.

Changing the energy model to limit the use of fossil fuels is an essential strategy for reducing greenhouse gas emissions. This strategy must be based on reducing energy demand (by asking people to be sober), increasing the energy efficiency of technologies, and developing renewable energy production channels (Jacobson, Delucchi, Bauer, et al., 2017; Jacobson et al., 2018; Seba, 2014).

The major advantage of wind and solar energy is that they are, *a priori*, available everywhere on the territory. Their disadvantage is that their energy production is intermittent since it depends on solar radiation and wind. Therefore, the implementation of these energies requires managing this intermittence, either by supplementing the energy production with easily controllable sources, such as the turbines of a hydroelectric dam or a nuclear power plant, or by installing a system capable of storing energy when it is overproduced and releasing it when it is lacking. Other types of renewable energy sources (RES) such as hydro, wood energy, biogas, and agrofuel production routes are easily controllable. They may guarantee continuous energy production as long as water and biomass supplies are assured. However, the disadvantages of such resources are:

- The production of hydroelectric power has almost reached its maximum and offers little potential for development at the scale of the Upper Rhine Region; it should be noted that this sector is sensitive to the effects of climate change, in particular, the increase in droughts that reduce water resources;
- The impact of biomass-based bioenergy production on the environment needs to be further assessed. Indeed, the combustion of biomass emits pollutants such as fine particles that are extremely harmful to health. Moreover, the fermentation of biomass is intended to produce methane, part of which could escape into the atmosphere, which would aggravate climate change because methane is a powerful greenhouse gas.

An infinite number of scenarios can be developed by combining a wide variety of technologies (such as solar photovoltaic or thermal panels, nuclear, gas, or coal power plants, hydro dam turbines, etc.) to produce energy. Each of these technologies uses different resources (renewable and non-renewable) and impacts the environment differently. How to choose the most suitable scenario among this infinity of possibilities?

The most widely used energy management models nowadays employ an approach of estimating the cost of each possible scenario and then selecting the one with the lowest cost. These costs consider the overnight investment required to purchase and implement the technologies to exploit the resources, and the operation and maintenance costs. In the case of controllable resources, the costs of fuels consumed are involved in the estimations. Environmental impacts are considered through specific additional costs that affect some technologies more than others, such as the carbon tax, for example. This approach based on cost optimization has the disadvantage of focusing on a single scenario (that of minimum cost), which leaves the user with too little visibility of other possible options. This is a major handicap insofar as the estimation of the costs of the scenarios is subject to great uncertainties. The costs of the technologies can vary greatly over time and these variations can be very different from one technology to another. However, the prices of fuels such as oil or gas evolve in an erratic way according to the available quantities, the demand on the energy markets or the stock market speculation. For this reason, it is impossible to accurately predict the cost evolution of fossil fuel technologies. For other technologies, the trends are clearer. For example, the costs of nuclear power plants are regularly revised upwards because of the increasingly precise assessment of the cost of their dismantling, as well as the costs of treating and storing their waste. On the other hand, the costs of wind turbines, photovoltaic panels, and certain storage technologies such as batteries are falling exponentially because they are being produced in ever greater quantities, which makes it possible to optimize their manufacturing processes. These costs probably do not yet consider the exact costs of dismantling and recycling these technologies at the end of their life cycle, as well as the costs of the raw materials they are made of (such as rare earth and metals), which are likely to become scarcer in the future. No one is currently able to predict precisely how long these trends will continue. Thus, the cost is certainly an indispensable indicator for guiding energy strategy choices, but it is not reliable enough to exclude options simply because they are more expensive.

The "Energy, Air Pollution and Climate" (EPAC) research group of the Image Ville Environnement (LIVE) research laboratory, mixed unit research of CNRS and University of Strasbourg, has decided to initiate research on a new method for designing and evaluating energy strategies. This new method does not aim to select only the least expensive energy option but to describe, in the simplest and most complete way possible, the different possible options. It consists of: 1) evaluating the characteristics of the energy demand of the region under consideration; 2) evaluating the resources potentially available in the region under consideration; 3) estimating the technical characteristics of different scenarios based on the introduction of intermittent energy sources (solar and wind) as a percentage of the final electricity demand; 4) grouping the scenarios with similar characteristics into clusters; 5) estimating the costs of energy production for each cluster of scenarios by considering the different technologies that could exploit the resources selected in each cluster of scenarios. The method will thus be able to provide a list of scenarios (each scenario being the representative of a cluster) whose characteristics will be sufficiently different so that decision-makers can easily select the option that seems best to them.

This method relies on the REPM (Regional Energy Planning Model) initially developed as part of Ms. Jessie Madrazzo's thesis (Ecole Polytechnique Fédérale de Lausanne, Switzerland & University of Strasbourg, thesis supervisor: Prof. Alain Clappier) to design/analyze energy strategies on Cuba (Madrazo, 2018). Indeed, Cuba offers an "ideal" framework for controlling the developed methodology because this country is an island undergoing an economic embargo. The country's energy supply is difficult so Cubans have been forced to be frugal to reduce energy demand as much as possible. Energy is imported only in the form of fuel, which is easier to estimate than the electricity trade. Finally, Cuba is a tropical country where the solar potential is so high that there are no surface constraints on the use of this resource. The work done in Cuba is still used today as a basis for generalizing the methodology.

The Interreg project RES-TMO (2018-2021) offers a new and more complex context as focusing on a trinational area. It allows the evolution of the formulation of REPM, applying it to the Upper Rhine Region, and comparing its results with the PERSEUS model of KIT. The work benefits of the outputs of the TECA project through the PhD thesis of Mr. Marco Guevara (directed by Prof. Alain Clappier, co-financed by the Doctoral School 413 of the University of Strasbourg and the Fonds de dotation AIR, which started on October 1, 2020) that makes the REPM methodology capable of qualifying the direct and indirect costs of strategies and will

allow building an overall system capable of evaluating the impacts of energy strategies on a multi-criteria basis including economic, environmental and social assessments.
This report presents the work produced in the WP3.5 of the Interreg RES-TMO project. The entire REPM methodology will be detailed although part of it was developed in the framework of the TECA project (part on the costs).

The document is divided into 3 main sections. Section 2 reminds the current status of the energy demand of the Upper Rhine Region. Section 3 details how the solar and wind energy potentials were estimated to be used as inputs of the REPM methodology from hourly meteorological simulations. Section 4 presents the REPM methodology and its application. Section 5 is dedicated to the comparison of the results of the REPM and PERSEUS models and a discussion. Section 6 concludes the work.

2. Upper-Rhine energy demand

For a total consumption of 41.4 TWh in 2018, the electricity demand of the Upper Rhine Region is distributed between three countries : 26% for Switzerland, 35% for France, 38% for Germany. Hourly profile data on the electricity energy demand of the TMO region were collected from different sources :
The demand data of the French side (Alsace) was delivered directly by RTE (Réseau de Transport d'Électricité), the electricity transmission system operator of France ;
The demand for the German side was obtained from the open data source of two different German transmission system operators : Amprion for the Rhineland-Palatinate area and Transnet BW for the Baden-Württemberg part. Since the Upper Rhine Region covers only parts of these two German regions, the electricity demand profiles were downscaled to the studied area ;
The Swiss demand has also been extracted and downscaled from the online Swiss transmission grid operator database.

3. Solar and wind energy production potentials of the URR

The potential of wind and solar energy production were first estimated using the IRENA methodology (IRENA, 2015) to compute the amount of land needed to supply 100% of the demand with solar and wind energy. The hourly wind and solar energy production capacity factors were then estimated using the mesoscale meteorological modeling system WRF (Skamarock et al., 2008).

3.1. Land area required to meet the electrical demand with solar/wind energy

As proposed by the IRENA methodology (IRENA, 2015), the Photovoltaic Geographical Information System (PVGIS) tool (JRC European Commission, 2017) calculates the solar energy that can be received per year by photovoltaic panels of different types and tilts for any geographical point in the world. This energy is calculated for two points at the extreme latitudes of the Upper Rhine Region with the most efficient technology in the South (55.7 GWh/km^2/year), and the least efficient technology in the North (36.5 GWh/km^2/year) so as to estimate the maximum and minimum solar energy that could be produced on the region.
The solar energy received by the photovoltaic panels is transformed into electrical energy. The maximum amount of energy is produced when the radiation reaches the nominal maximum of the average solar panel (typically 900 - 1000 W/m^2) (Figure 9). The losses of the power

generation system with solar panels are estimated at 75% (a typical value recommended by the literature).
The recommended panel power densities for a location in terms of latitude were extracted from Figure 1 : 67 MWp/km² at the URR South point (c-Si technology) and 45 MWp/km² (CdTe technology) at the North point. The technologies were chosen to consider the most efficient technology at the highest sunlight point and the least efficient technology at the lowest sunlight point, and thus the widest range of energy production.
To fully meet the energy demand of 43.5 TWh/year with such potentials would require between 742 km² (using the best technology at the lowest latitude) and 1133 km² of surface (using the least efficient technology at the highest latitude).

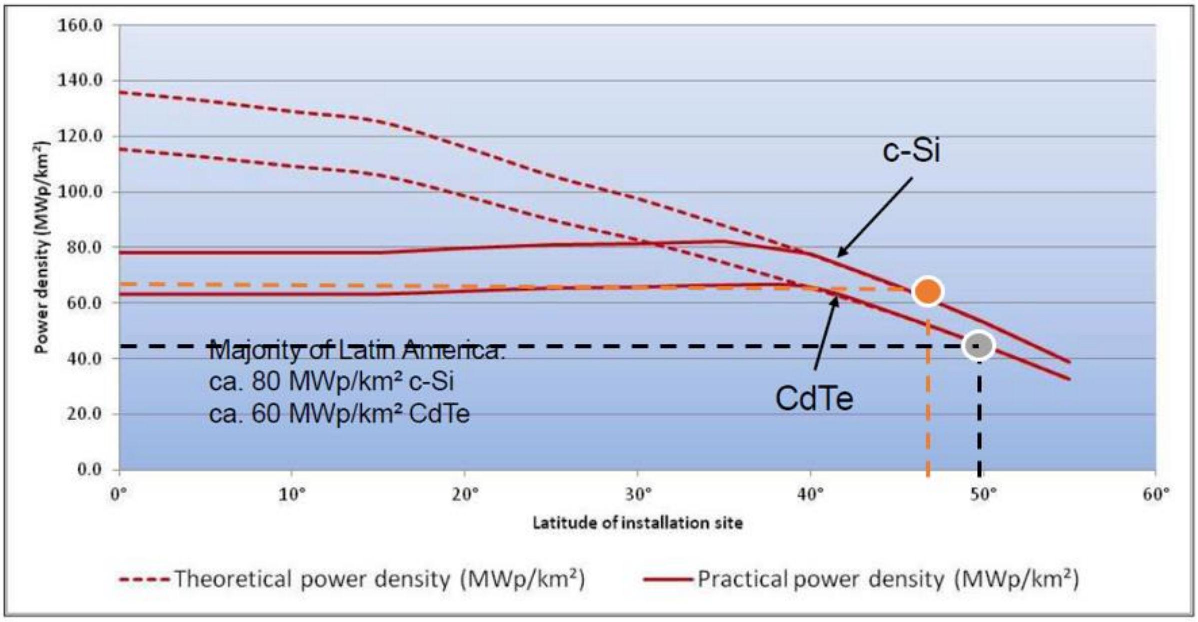


Figure 1 Power density of photovoltaic panels to be installed according to the location of the installation site in terms of latitude. Expressed in terms of nominal power per km2. Source: (IRENA, 2015)

The IRENA (2015) method is also used to calculate wind power generation potential. It consists of combining a frequency distribution of wind speeds with a power curve of a wind turbine (Figure 2). The Global Wind Atlas tool (Technical University of Denmark, DTU, 2021) allows the evaluation of the average wind speed at any geographical point in the world. Two points with extremes in average wind intensity were selected in the Upper Rhine Region. The weakest average wind (4.2 m/s) is observed in the Alsatian plain. The strongest wind (7.8 m/s) is observed on the Vosges ridges.

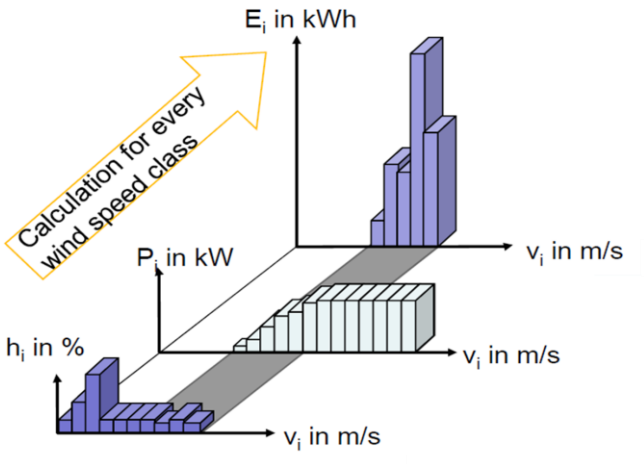


Figure 2 IRENA method for estimating wind energy potentials Ei in kWh (IRENA, 2015; Tiedemann, 2014) from the frequency distribution (hi relative frequency) of wind speeds vi in m/s. Pi the power in kW.

A wind distribution was reconstructed from these two extreme values using the method recommended in the literature (IRENA, 2015; Tiedemann, 2014). This method consists of constructing a frequency distribution of the average wind intensity for a location (Vavg). This distribution is calculated based on the two-parameter Weibull distribution (A and k). The parameter k depends on the nature of the terrain (fixed at 2.5 in Northern Europe) and the parameter A on the average wind speed (A=Vavg/0.9). Figure 3 shows an example of a wind frequency distribution calculated for A=4.67, k=2.5, and Vavg=4.2 m/s.

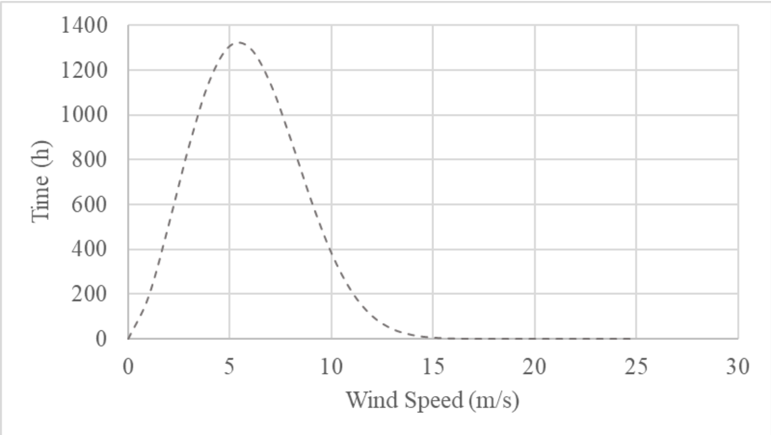


Figure 3 Wind frequency distribution calculated with the two-parameter Weibull distribution (A and k) when A=4.67, k=2.5, and Vavg=4.2 m/s.

The wind distribution is then combined with wind turbine power curves to calculate wind potentials. Figure 4 shows the power curves generated by two types of wind turbines. The 82 m rotor diameter wind turbine (E82-2000) is taken for estimation in this study.

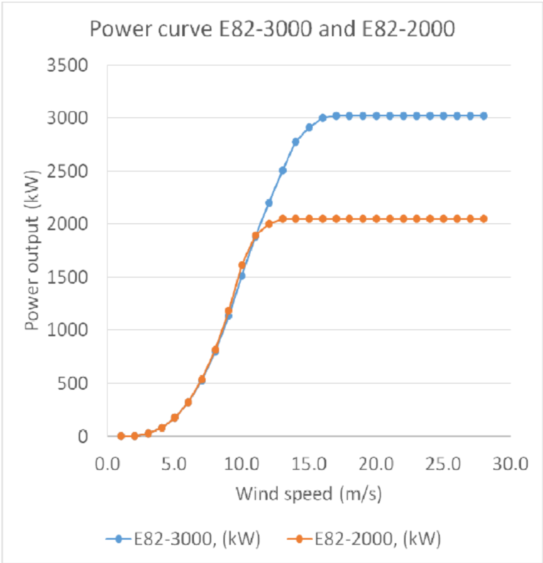


Figure 4 Power curves generated by two types of wind turbines with 82 m rotor diameter (E82-2000 and E82-3000) Source: (IRENA, 2015).

The wind energy potentials are used to calculate the number of wind turbines needed to satisfy 100% of the electricity demand. The land area needed to install such a wind farm is the ground configuration recommended (Figure 5) by the IRENA method (IRENA, 2015; Tiedemann, 2014). Thus, to produce 43.5 TWh/year, 4656 wind turbines would be needed if the average wind intensity is 7.8 m/s or 14839 wind turbines if the average wind intensity is 4.2 m/s, which would require an area of 1042 km² or 3320 km² respectively.

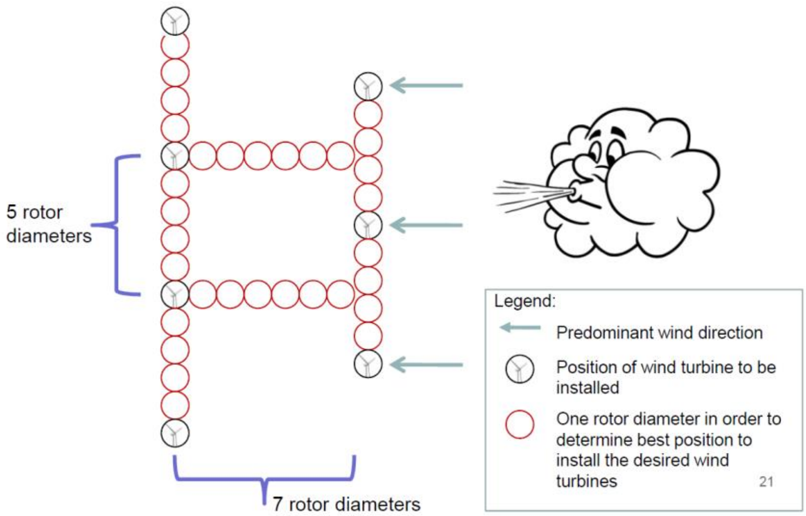


Figure 5 Recommended configuration for wind farm installation to reduce wake effects Source: (IRENA, 2015; Tiedemann, 2014).

The IRENA method allows us to conceptually estimate the land surface required to install the PV panels or wind turbines to produce the electricity consumed by the Upper Rhine region in one year. In this case, the maximum and minimum possible values of the land surface are computed according to the maximum and minimum solar and wind generation potentials observed in the region. Figure 6 shows the results in terms of land area required to meet 100% of the energy demand with solar or wind energy.

Figure 6 Land area needed to meet 100% of the electricity demand with solar or wind energy sources (considering minimal and maximal potentials), compared to the total area of the RES-TMO region (surface of the gray circle which is equal to the surface of the region on the map).

The results show that between 3.45% and 5.26% of the surface of the Upper Rhine region would need to be occupied by solar panels to meet 100% of the electricity demand while between 4.84% and 15.42% of the surface of the region would be needed for wind turbines. Figure 7 generalizes these surface estimations for an increasing amount of solar and wind energy produced. The upper limits of the available land surface for PV panels and wind turbine installation have been estimated by WP2.

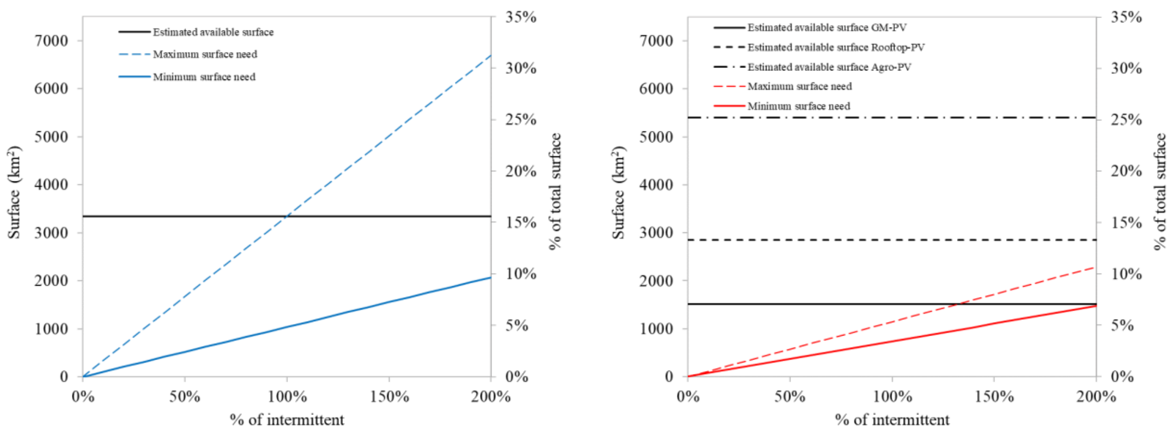


Figure 7 Surface (km²) required as a function of wind (left graph, blue curves) or solar (right graph, red curves) energy introduction as a percentage of the electricity demand of the Upper Rhine region. The solid curves correspond to favorable conditions for intermittent energy production. The dotted curves correspond to less favorable production conditions. The vertical axes correspond to the land surface (left axis) and the percentage of the total land surface (right axis). The horizontal black lines correspond to the limits of usable surface for the installation of wind turbines and solar panels in the Upper Rhine region.

3.2. Evaluation of solar and wind power generation capacity factors

The wind and solar energy production potentials were also spatially and temporally evaluated from wind speeds and solar radiation simulated by the Weather Research and Forecasting (WRF) Version 4.1 meteorological model (Skamarock et al., 2008) installed on the computational servers of the Strasbourg Computing Mesocenter.

The year 2018 was simulated for three nested domains centered on the city of Strasbourg. The horizontal resolutions used were 3km x 3km for the smallest domain (d03) covering the URR region, 9km x 9km for the medium domain (d02) covering almost all of France and Germany, and 27km x 27km for the largest domain (d01) covering all of Europe (Figure 8).

The WRF simulations provide hourly vertical wind and solar radiation profiles over the Upper Rhine Region on a 3km x 3km grid at several altitudes (33 levels from 0m to 19761m, the first 4 levels correspond to altitudes above the ground surface of 0m, 24.4m, 80.0m, and 150.6m).

The hourly wind speed and solar radiation profiles were extracted from specific locations in the region: 60 locations for solar and 75 for wind. The number of locations was established assuming the same number of wind farms and solar PV plants per km² in the three parts of the Upper Rhine region (i.e., the french, swiss, and the german parts) taking as reference the current density of installed wind farms and solar PV plants in the german part (0.006 Farms/km²). The location of these points was defined by distributing them in the areas with similar characteristics to the areas in which there are currently installed solar and wind infrastructure in the whole region.

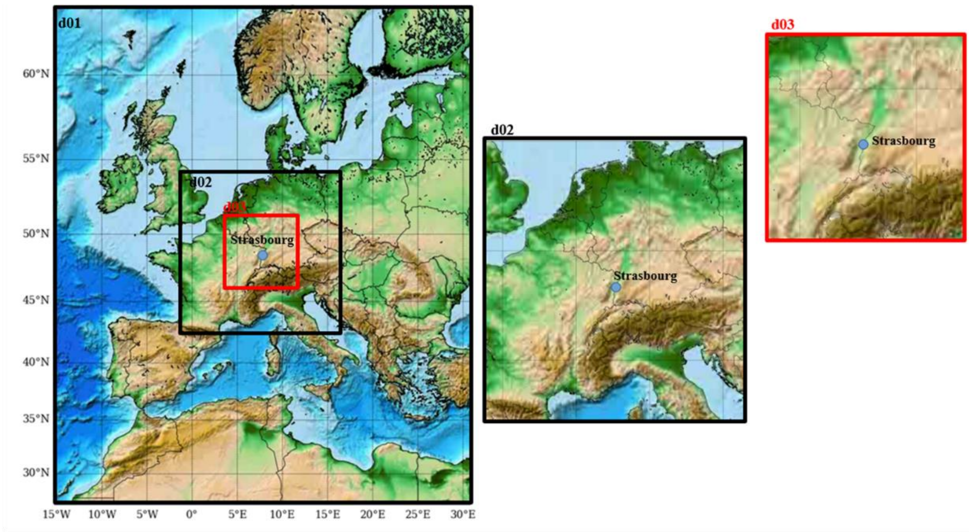


Figure 8 Configuration of the simulation domains of the weather forecasting model (WRF) to be used for the estimation of solar and wind energy potentials of the URR region.

The profiles of wind speeds and solar radiations were used to compute hourly wind and solar capacity factor profiles from the curves presented in Figure 9. They are averaged to obtain a single average hourly profile of a solar capacity factor and a wind capacity factor for the entire Upper Rhine region.

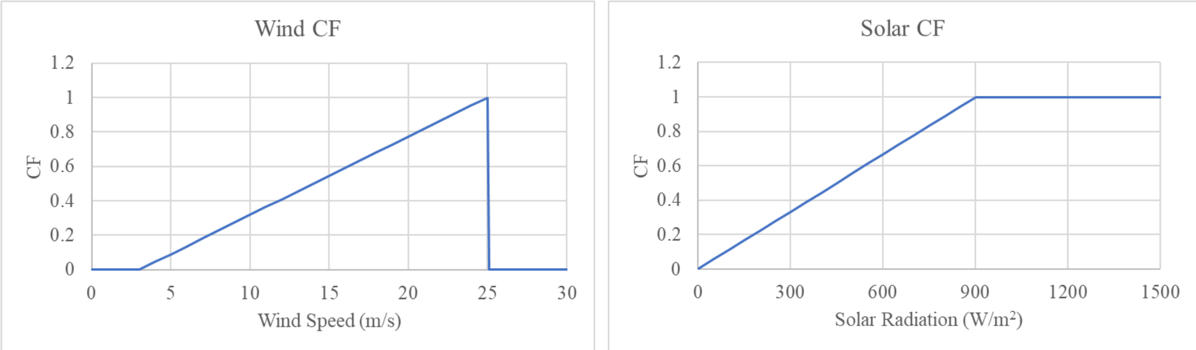


Figure 9 Generation capacity factors (dimensionless) of wind (left) or solar (right as a function of, respectively, wind intensity (m/s) or solar radiation (W/m2). Source: (Al-Khazzar, 2017; Jacobson, Delucchi, Cameron, et al., 2017; Madrazo, 2018).

4. The regional energy planning model (REPM)

The IRENA method has shown that wind and photovoltaic energy productions are quite feasible alternatives for the Upper Rhine region to meet the entire current demand for electrical energy. Nevertheless, these energy productions vary according to the solar radiation and the wind intensity and do not follow the variations of the electric demand. The mismatch between demand variations and wind and solar sources requires either storing energy when it is produced in excess and destoring it when it is lacking, or using an additional energy resource that can easily modulate its production to follow demand variations.

A wide variety of production technologies (such as photovoltaic or thermal solar panels, nuclear, gas, or coal power plants, hydroelectric dam turbines, etc.) or storage technologies can be mobilized to meet demand. These technologies use different resources, renewable or not, and thus impact the environment differently. How to choose the best scenario for a region among the infinite combinations of technologies and resources possible?

The methodology developed at LIVE does not aim, like traditional methods, to select only the economically optimal energy option, but to describe, in a complete way, all possible options. The method relies on the REPM (Regional Energy Planning Model) model initially developed in the framework of Ms. Jessie Madrazzo's thesis (Ecole Polytechnique Fédérale de Lausanne, Switzerland & University of Strasbourg, thesis supervisor: Prof. Alain Clappier) to design/analyze energy strategies in Cuba (Madrazo, 2018). This REPM (Regional Energy Planning Model) model simulates energy flows between 5 interconnected elements (Figure 10): Energy demand, energy production by intermittent sources (solar and wind), energy produced by controllable sources, energy storage, and exports (or surplus). Energy demand and intermittent generation are hourly data that the user must estimate upstream. This data is used by the model to calculate storage, controllable, and exports each hour so that the demand is always met.

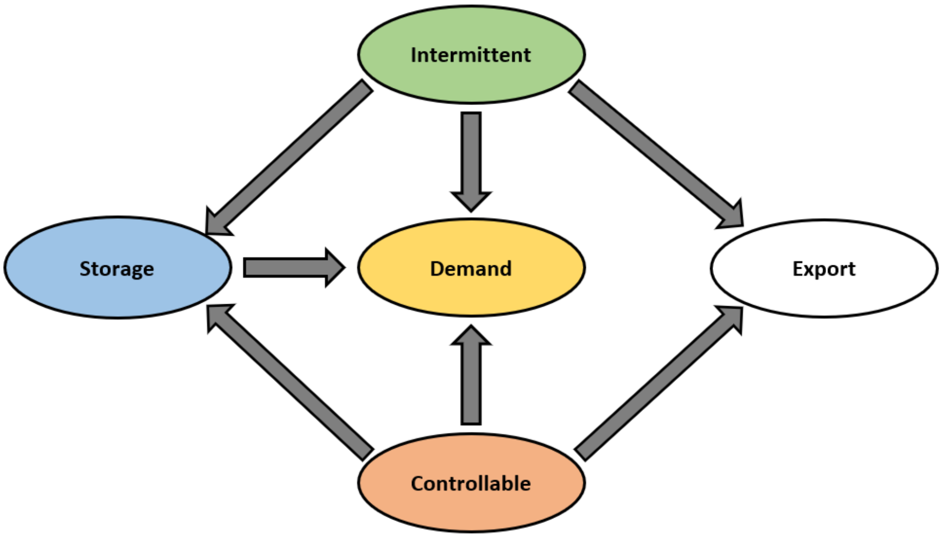


Figure 10 Energy system diagram of the REPM model.

The following sections will not describe the entire strategy evaluation methodology. Here we will only elaborate on how all possible energy scenarios are calculated from the REPM model. Section 1.4.1. describes the REPM algorithm. Section 1.4.2. presents the results obtained from the application of the REPM model on the Upper Rhine Region to build the set of possible scenarios. The rest of the work consists of "sorting" these scenarios in such a way as to reveal families of scenarios that are clearly distinct from one another and quantify them in terms of costs. The objective is to present the results in a sufficiently synthetic manner so that decision-makers can easily select the option that seems best to them. One challenge is to identify the parameters that will allow us to sort out the scenarios and quantify them in terms of costs. These parameters are mostly referring to the characteristics of the technologies: What is the minimum and maximum power they should deliver? What energy should they store and for how long?

4.1. REPM Algorithm

Based on the desired percentage of intermittent energy in the annual electrical energy demand, and the chosen solar/wind mix, the REPM model first calculates the total solar photovoltaic panel capacity, and/or wind turbine capacity required. Then, knowing hour by hour the nominal power of the technologies as well as the capacity factors of solar and wind energy production, REPM calculates the hour by hour intermittent energy production (I). This hourly intermittent energy production (I) is compared to the hourly energy demand (D), and an energy balance is performed at each hour, which results in the calculation of all energy flows between the different components of the energy system (Figure 11).

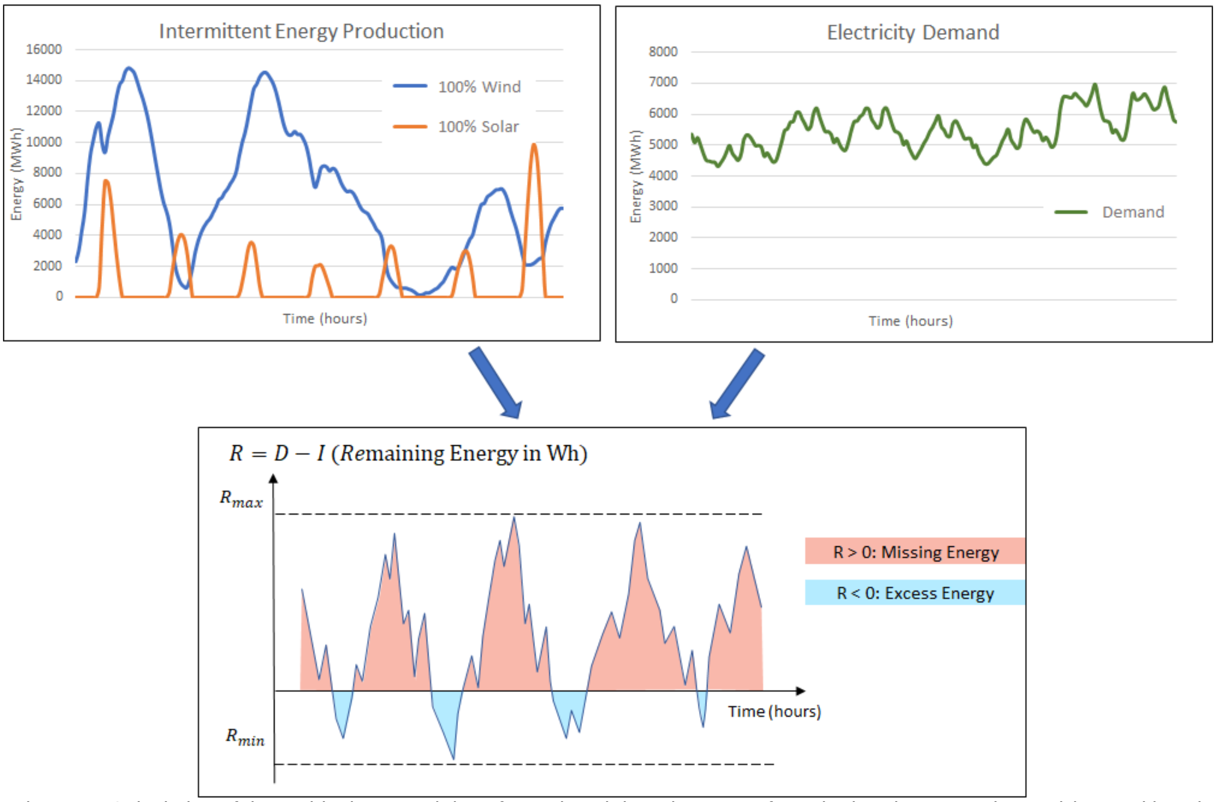


Figure 11 Calculation of the residual energy (R) performed each hour by REPM from the hourly energy demand (D, MWh) and the hourly intermittent energy production (I, MWh).

For this, the REPM model calculates the quantity R=D-I (Demand-Intermittent) for each hour. This R (the residual energy) corresponds to the amount of energy that remains to be delivered to meet the energy demand once the intermittent energy share is consumed. R takes positive values when the intermittent source is not sufficient to fully meet the demand and negative values when the source produces more than the demand requires. The excess energy can then be stored in order to be released at another time when the energy demand is no longer supplied by intermittent energy (the question of the choice of the period of release of the stored energy is discussed later). If during this same period, the storage is not sufficient either, then the controllable is used to fill up the energy needs. Without any storage infrastructure, the positive R values correspond directly to the necessary controllable. The hourly balance of storage and controllable/export needs allows us to understand the size of the necessary infrastructure over a year.

REPM is thus able to calculate various parameters concerning storage: the storage capacity (maximum energy to be stored, in Wh), its power (in W), and the sum of the energy flows (in Wh) entering and leaving the storage. REPM also characterizes the controllable (Wh/yr) which can be either produced by local, controllable energy sources (such as a nuclear, thermal, or bioenergy plant, etc.) or imported from other regions. The model calculates the total energy as well as the capacity (i.e. the power in W) required by the technologies that must ensure the production of the controllable. Several parameters are used to characterize the controllable capacity:

- Cmax: Maximum controllable capacity to be installed to meet the demand;
- Cmin: Minimum controllable capacity that cannot be stopped;

- γ: The ratio between Cmin and Cmax, such that Cmin = γ Cmax (example: a thermal power plant cannot be completely shut down; it remains in operation at γ = 20% of its total capacity);
- Cth: The desired controllable capacity in the energy mix (Cmin<Cth<Cmax).

In some scenarios, if the intermittent and controllable energy sources can produce in excess (i.e. produce in total over the year more energy than is needed to meet the demand), the surplus energy is considered by REPM as possible exports to other regions.

The REPM model considers the energy losses (η as a fraction with a value between 0 and 1) affecting the different energy flows. They are due in particular to the transport of energy and its conversion during storage.

The results of REPM will often be represented as in Figure 12, with:

- On the x-axis, the set of scenarios described by their percentages of intermittent energy introduction (%INT). Curves can also show other characteristics of the scenario, such as the percentage of a mix between solar or wind energy, or a scenario with or without storage.
- On the ordinates, the amount of energy to be produced, stored, or the capacity/power (in W) of an infrastructure to be provided. As REPM simulations model a full year, the calculated energies will always correspond to annual data over 8760h (365days*24hours).

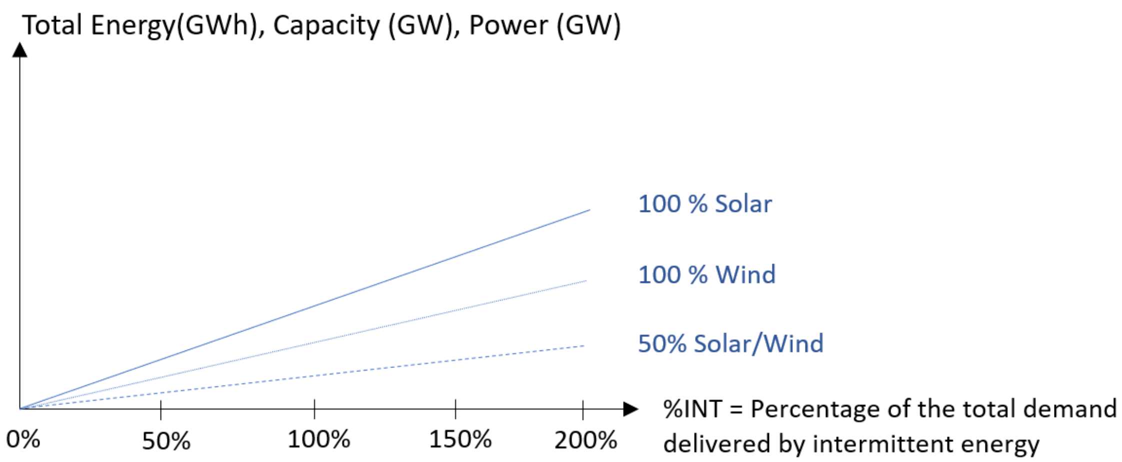


Figure 12 Standard graph used to present the results of the REPM model.

Thus, each of the graphs presented will not represent the result of a single scenario but the results for a set of possible scenarios. Percentages of intermittent energy introduction %INT varying from 100% to 200% correspond to scenarios going from zero solar and/or wind energy produced in the mix up to an overproduction of 2 times the electricity demand (i.e. overproduction) from intermittent energy sources.

Storage management by a "Peak shaving" method

The question of returning stored intermittent energy at a time when the demand for electrical energy can no longer be met poses a fundamental problem: When is it most appropriate to return stored energy to the energy system? As soon as intermittent energy production is no longer sufficient to meet the demand for electrical energy? or later? The answer to this question is not trivial.

A first test consisted in effectively returning stored energy to the energy system as soon as intermittent energy production is no longer sufficient to meet the demand for electrical energy. This work shows that such an energy system could not do without controllable power even with significant participation of the intermittent sources. It allows us to study the controllable energy sources and to better understand the operation of nuclear, thermal, bioenergy production facilities, etc. Most of these facilities cannot be completely shut down, so a minimum level of operation must be maintained. The REPM model, therefore, considers that the controllable energy is constrained between two limits that allow us to characterize the technologies capable of producing the controllable:

- The maximum level (Cmax, in W) will give information on the power needed for the controllable, which allows us to estimate the size of the installations and their investment cost.
- The minimum (Cmin, in W) is the minimum level that the facilities will continue to provide in all situations, which allows excluding or including possible choices, such as technologies that are unable to stop their production in scenarios where Cmin would become very low or zero. This minimum level is estimated as a proportion of the maximum level Cmax, i.e. Cmin = γ Cmax, $\gamma \in [0,1]$ dimensionless).

The energy balance should be analyzed as follows (to support the reasoning, Figure 13 shows a typical graph of the residual energy R = D - I):

- When Cmin*1h < R < Cmax*1h, the intermittent energy production is not sufficient to meet the demand but the controllable can contribute;
- When R > Cmax*1h, the intermittent energy production is not sufficient to meet the demand and the controllable can no longer contribute;
- When R < Cmin*1h, the intermittent energy production, associated with the controllable, delivers excess energy. In the same way as before, the excess energy can then be stored in order to be released at another time if the energy demand can no longer be met by intermittent energy.

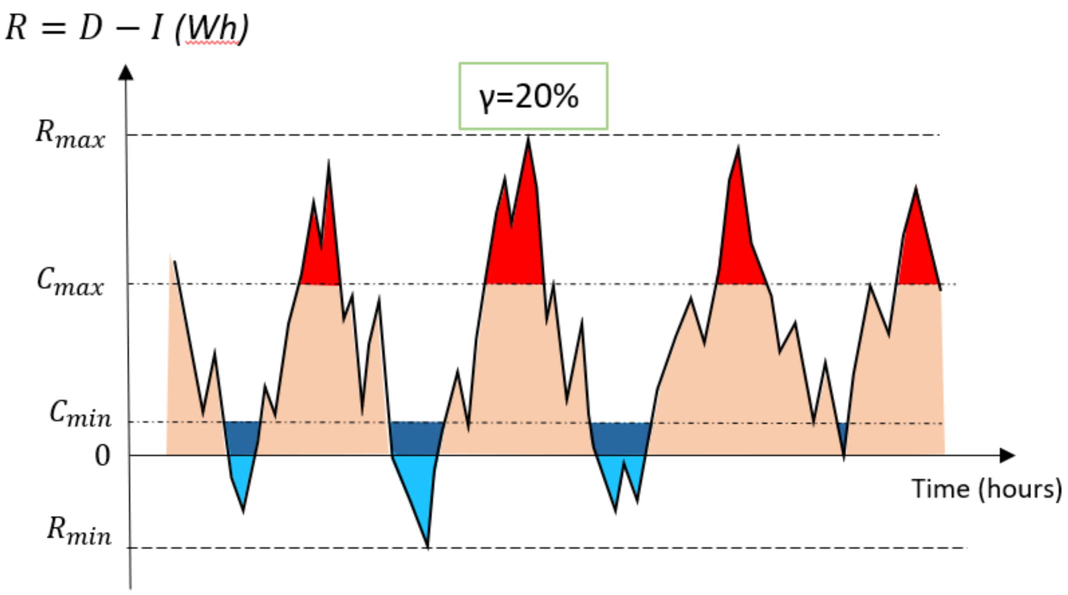


Figure 13 Load duration curve of residual energy (R = D - I) calculated by the REPM model to distinguish different situations of under or overproduction of the energy system.

The second test, which is currently being analyzed, aims to return stored energy to the energy system as soon as the controllable exceeds its maximum limit (Cmax). This method, known as "peak-shaving", is ultimately aimed at avoiding controllable peaks. Figure 14 shows the distribution of R values by the number of hours.

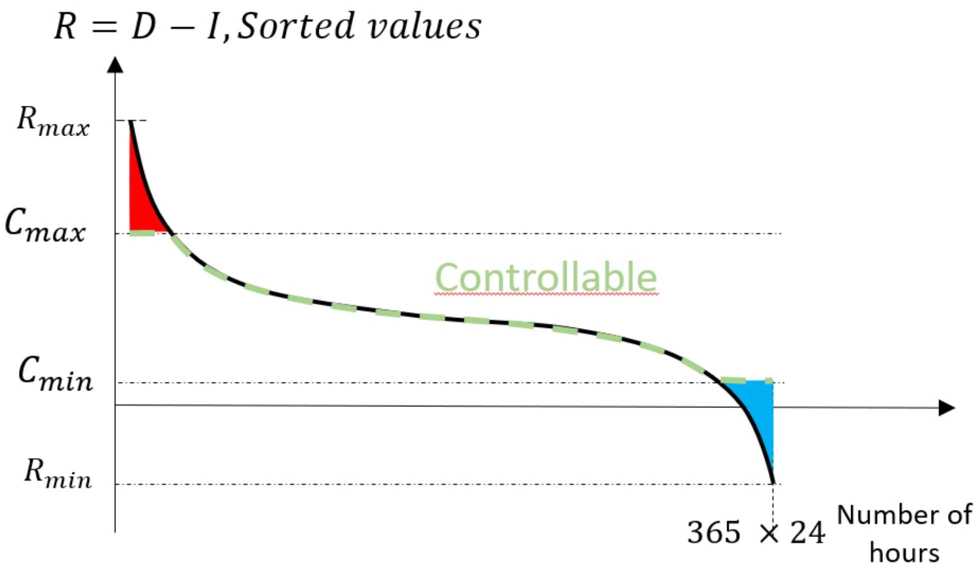


Figure 14 Distribution of residual energy in hours.

It is considered that the energy demand must be met every hour. The missing energy (intermittent and controllable) during the consumption peaks (red surfaces in Figure 15) must be supplied by previously-stored energy (blue surfaces in Figure 15), which amounts to constraining the system so that the areas of the red surfaces are equal to the area of the blue surfaces.

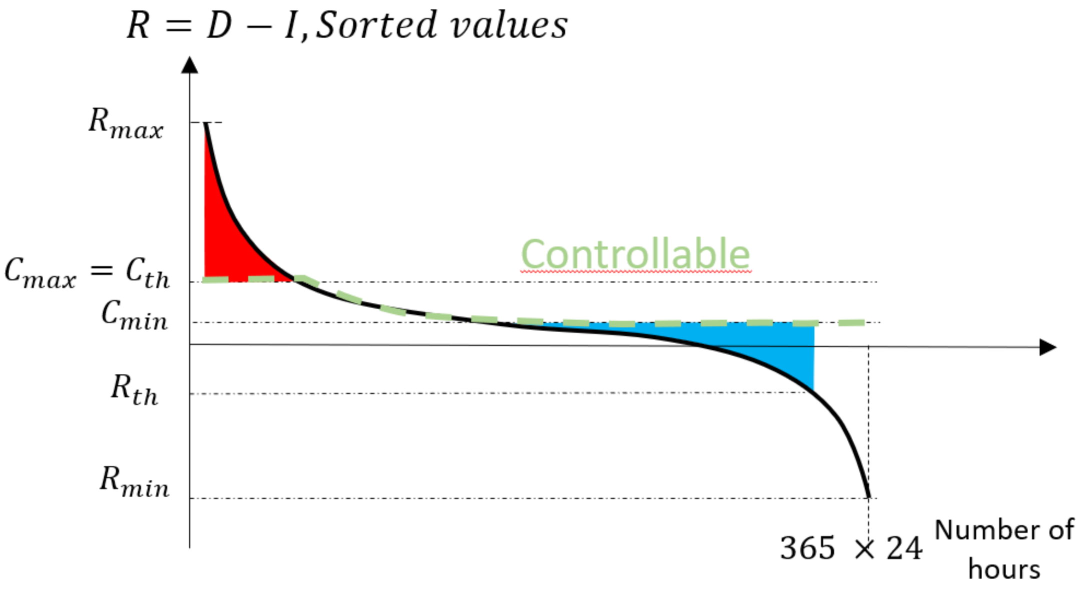


Figure 15 Distribution of residual energy in hours.

Thus the REPM model is constructed to search, starting from a fixed γ (Cmin = γ Cmax, γ∈[0,1]), for the value of Cmax, which will equalize the areas of the red and blue surfaces. This calculation is used to size the controllable and the amount of energy to be stored. In the case where intermittent energy is importantly introduced into the energy system and this energy could fully meet the demand, it is necessary to be able to limit the storage demand (otherwise the storage can increase as much as the intermittent energy production). To address this, two additional parameters Rth and Cth were introduced:

- Cth (for "controllable threshold") is a minimum value that Cmax can never exceed. This value allows us to generate scenarios where a certain amount of controllable energy is imposed in any situation, even when solar and wind resources are the most important.
- Rth ("R threshold") is the value of R above which the excess energy produced is not stored but counted as export of energy. This threshold value allows us to generate scenarios where energy is produced in excess. The value of Cmax has reached Cth and the amount of energy produced is greater than what is needed to keep the controllable equal to Cmax. It is useless to store all the excess energy, Rth acts such as a limit on the storage capacity.

In practice, γ, the percentage of intermittent energy (%INT), the percentage of solar/wind %Solar/Wind), and Cth are the parameters whose value can be varied so that the REPM model generates all possible scenarios. In order to size the storage infrastructure capacities needed in the region to meet the electrical energy demand, the REPM model differentiates two energy system regimes (Figure 16):

- **Regime 1:** when the total energy demand is greater than the total intermittent energy production, Σ D > Σ I, Cmax and Cmin are defined such that Cmax = γ Cmin: the REPM model looks for a pair of values of Cmax and Cmin allowing to size the controllable and storage to fully meet the electrical energy demand.

- **Regime 2:** when Σ I > Σ D and Cth=Cmax, excess energy can be stored, and a threshold R (Rth) is calculated. Below Rth, the excess energy is no longer stored but exported.

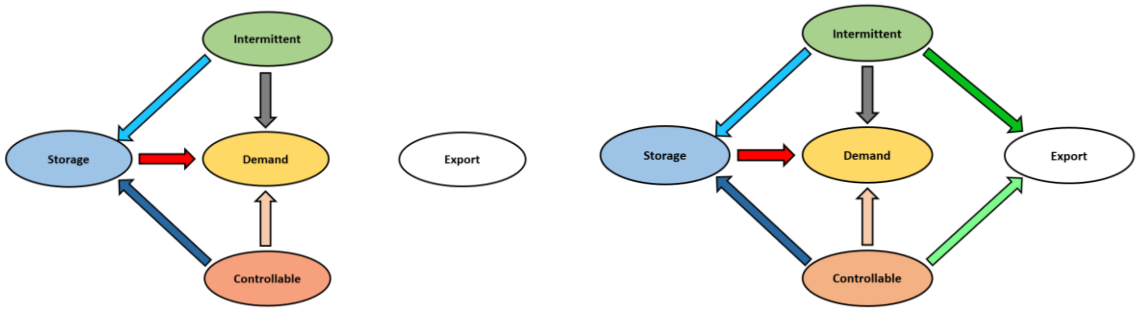


Figure 16 Representation of the energy flows within the energy system during regime 1 (left) and regime 2 (right).

Figure 17 shows the current operation of the REPM model.

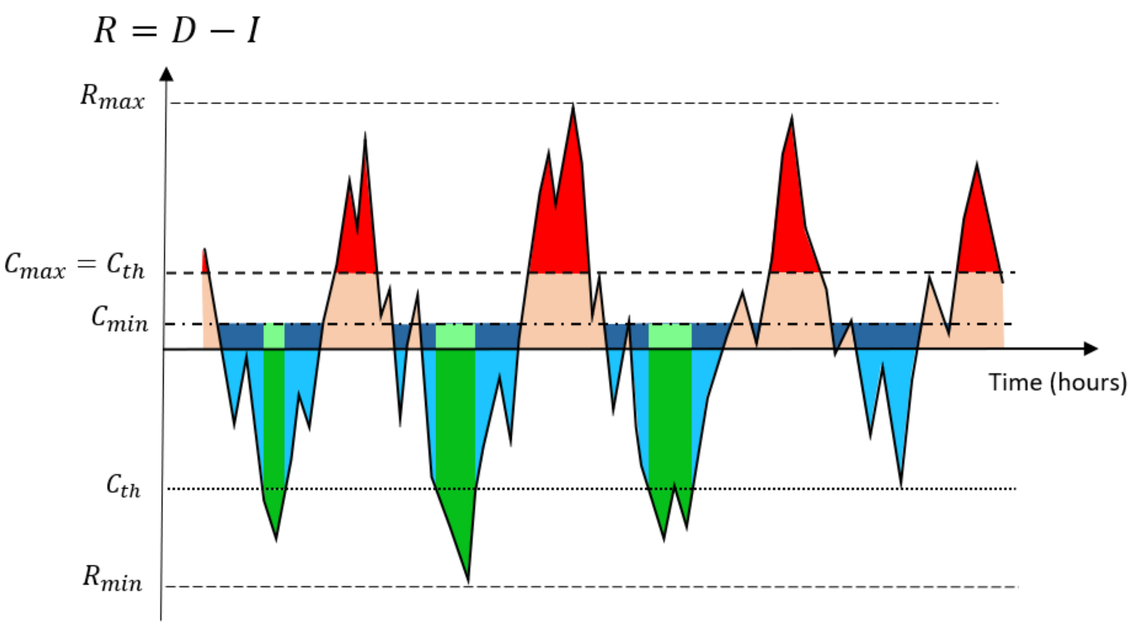


Figure 17 Typical graph of residual energy (R = D - I) calculated by the REPM model, allowing us to distinguish different situations of under-or overproduction in the energy system. The colored areas represent flows as described in Figure 16: red areas correspond to flows from storage to demand; pink-salmon areas from controllable to demand; dark blue areas from controllable to storage; light blue areas from intermittent to storage; dark green areas from intermittent to export and light green areas from controllable to export.

4.2. All possible scenarios over the URR

This section presents the results obtained by the REPM model for the URR.

Several scenarios are simulated by varying all identified parameters over the full range of technically possible values:

- The percentage of intermittent energy introduction (%INT), from 0% to 200% every 10%;
- The mix between solar and wind energy: 100% solar (100% Solar), 100% wind (100% Wind) and 50% of each (50% Solar/Wind);
- With or without storage to be developed in the study area;
- The value of γ (Cmin = γ Cmax), from 0% to 100%, every 20%;
- The value of Cth, from Cth = 0 GW (no controllable energy will be produced when wind and solar production is sufficient) to Cth = 4 GW (the maximum controllable energy will never go below 4 GW, whether solar and wind production is sufficient or not).

Varying these different parameters allows us to traverse the entire field of possible scenarios. The results are first presented for a fixed Cth and a variable γ and then for a fixed γ and a variable Cth.

Results obtained without a previously imposed controllable capacity

Figure 18 shows the result of the simulations of the different scenarios for a value of γ = 20%. If the energy system includes storage, the need for controllable decreases linearly with the introduction of intermittent energy in the energy mix up to ~120%. Complete independence of the system from controllable energy sources occurs with an intermittent energy production reaching between 120% and 130% of the total demand (an overproduction must be provided in order to compensate the energy losses taking place between the different elements of the system). If the energy system does not include storage, the need for controllable decreases much less rapidly, and does not cancel out, even when overproducing intermittent energy up to 200% of the total demand. It should be noted that a 50% Solar/Wind mix allows for a greater reduction in controllable energy production.

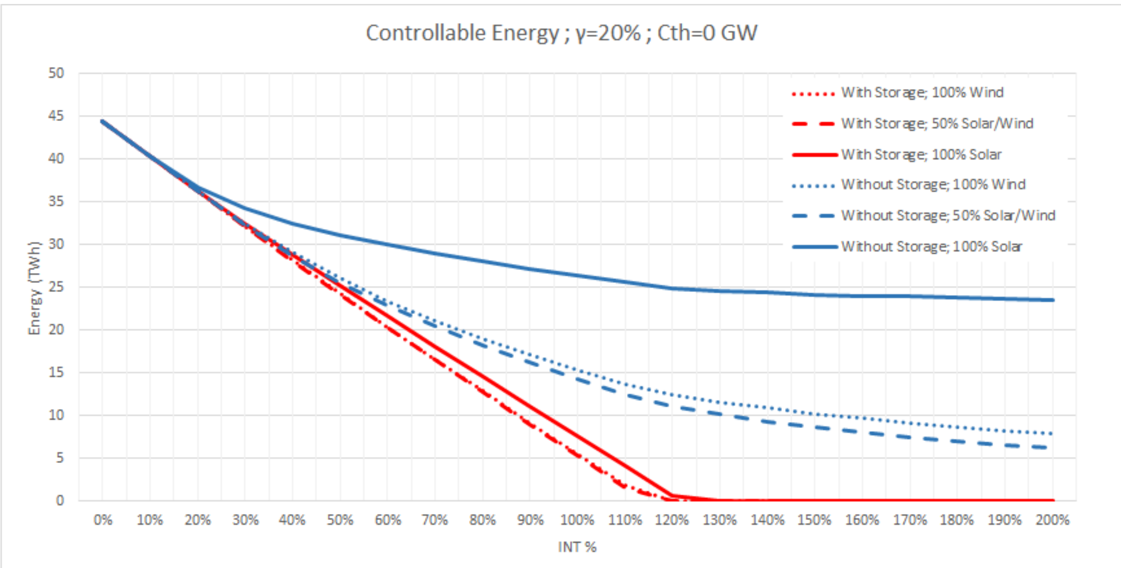


Figure 18 Necessary controllable energy according to various scenarios of energy introduction (%INT), solar/wind mix (100% Solar - solid lines, 100% Wind - dashed lines, 50% Solar/Wind - dashed lines), with (red curves) or without storage (blue curves).

Figure 19 shows similar results in terms of the maximum controllable power to be provided: These results confirm that without storage, the system cannot do without controllable energy, regardless of the percentage of intermittent energy. Indeed, during certain hours, the wind and solar potentials are so low that they are not sufficient to meet the demand despite an oversized capacity of intermittent sources. In this case, a 50% Solar/Wind mix does not allow for a significant reduction in controllable power requirements. With storage, the need for controllable power decreases almost linearly with the introduction of intermittent energy in the energy mix up to ~120%.

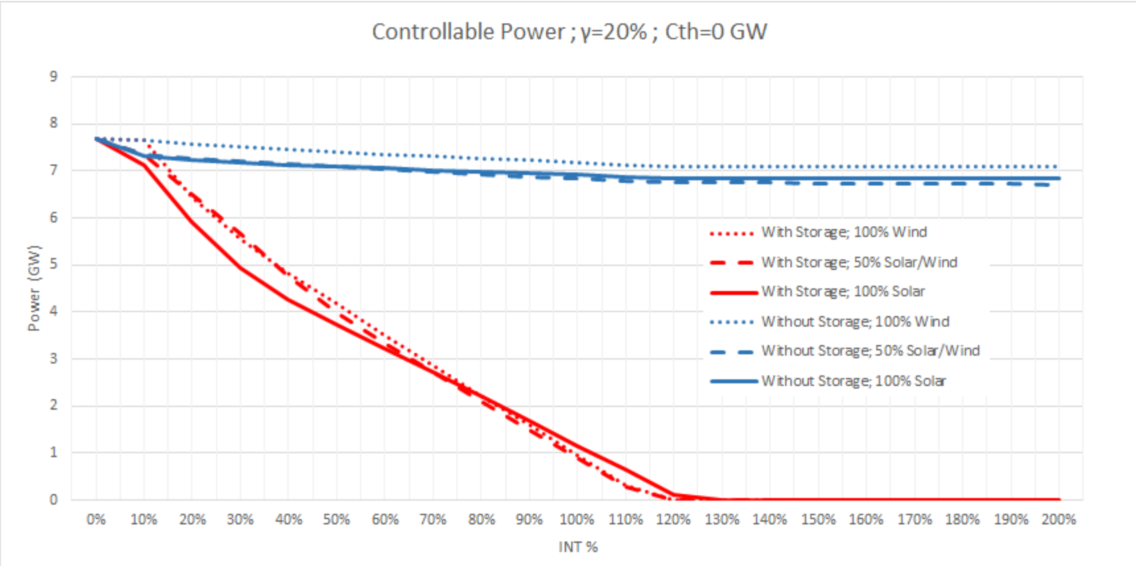


Figure 19 Maximum controllable power required according to various energy introduction scenarios (%INT), solar/wind mix (100% Solar - solid lines, 100% Wind - dashed lines, 50% Solar/Wind - dashed lines), with (red curves) or without storage (blue curves).

Figure 20 describes the storage requirements for each scenario. A need for storage capacity appears as soon as 10 to 20% of intermittent energy is introduced into the energy system. This need then increases almost linearly until it reaches its peak between 120% and 130% which corresponds to the point of independence of the system in terms of controllable, then a decrease in the need for storage capacity is observed due to the overproduction of intermittent energy. We can note that wind energy production requires a much lower storage capacity than solar photovoltaic energy production.

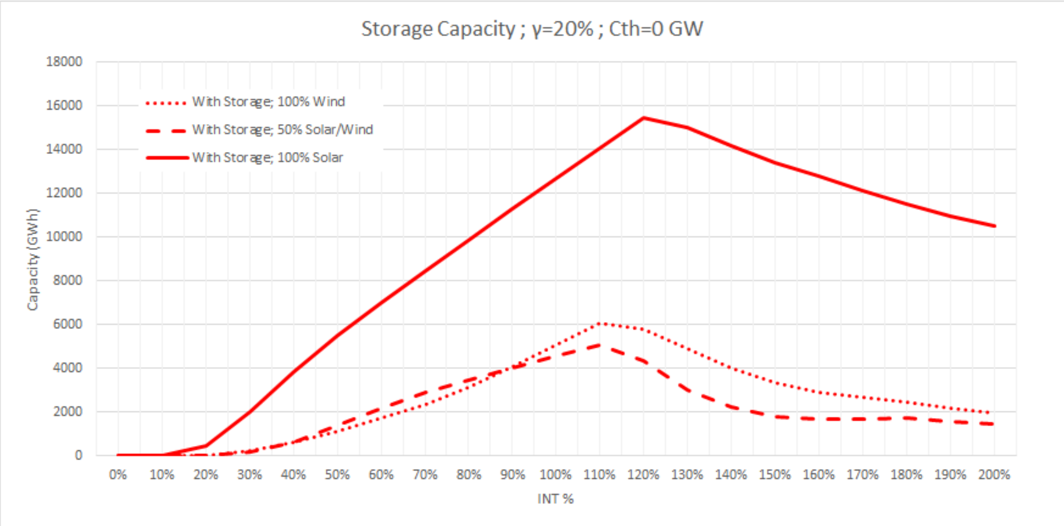


Figure 20 Energy to be stored according to various energy introduction scenarios (%INT), solar/wind mix (100% Solar - solid lines, 100% Wind - dashed lines, 50% Solar/Wind - dashed lines).

Figure 21 shows the results of the simulations for various values of γ, and for a 50% Solar/Wind mix with possible storage in the region. The results show that while the amount of controllable energy needed by the energy system is only slightly influenced by the value of γ, the maximum controllable power needed is much more influenced for scenarios with less than 120% renewable energy. The higher γ is, the lower the controllable power requirement, but the higher the storage requirement.

As a reminder, the REPM model seeks, for a value of γ, to determine the values of Cmin and Cmax so that the quantity of energy to be stored can fully meet the energy demand. The larger γ is (Cmin close to Cmax), the more the controllable is used, and the more storage mobilized to store controllable, but the less the energy system needs high power from this controllable. The value of γ does not actually change the controllable energy needed by the energy system. Simply this energy is either directly used to meet the demand without going through the storage (γ=0), or is totally stored and re-delivered by storage (γ=100%), or partly to meet the demand and partly stored (0<γ<100). The value of γ finally constrains the share of controllable energy that can flow into storage: the larger γ is, the more storage capacity is needed.

Moreover, the higher the percentage of intermittent in the mix, the higher the amount of stored energy, and thus the lower Cmax (i.e. the higher the stored energy, the less the system needs to call on the controllable, thus the lower Cmax). Cmax decreases until it reaches Cth. As here Cth=0, Cmax decreases to 0, as does Cmin. When Cmax gets closer to 0, the value of Cmin is not so much impacted by γ, Cmin becomes very small anyway.

Results obtained with previously imposed controllable capacity

In order to analyze the impact of a decision to impose in the energy mix a controllable quantity, Cth, Figure 22 shows all the results obtained for all the scenarios with a Cth value varying from 0GW to 4GW, with γ = 20% for a 50% Solar/Wind mix. The greater the amount of controllable energy into the energy mix, the less storage capacity the energy system needs.

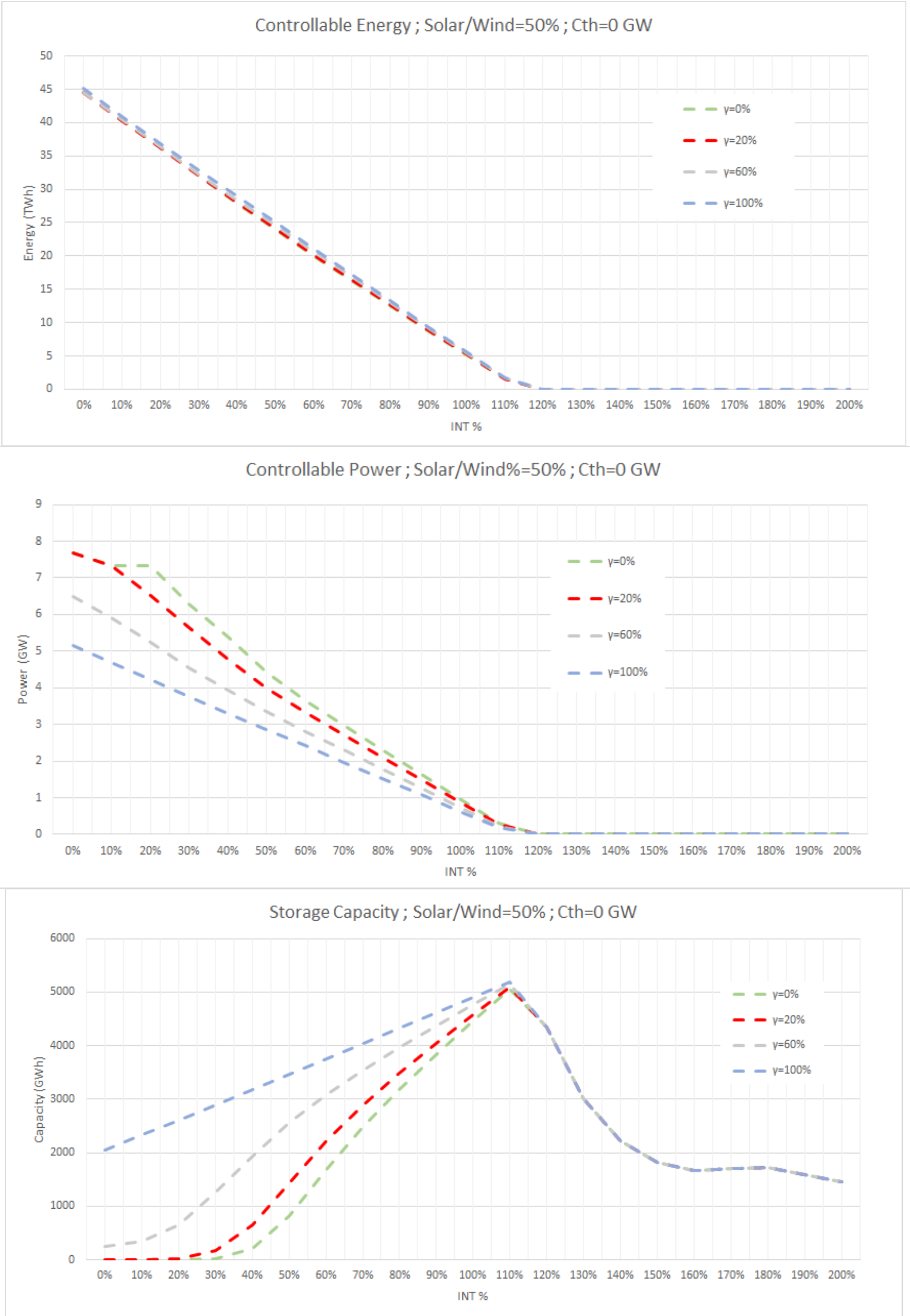


Figure 21 Required controllable energy (a), maximum required controllable power (b), storage capacity (c) as a function of various energy introduction scenarios (%INT) for a 50% solar/wind mix with storage, for various γ values.

Figure 22 Required controllable energy (a), maximum required controllable power (b), storage capacity (c) as a function of various energy introduction scenarios (%INT) for a 50% solar/wind mix with storage, for various values of Cth. γ = 20%.

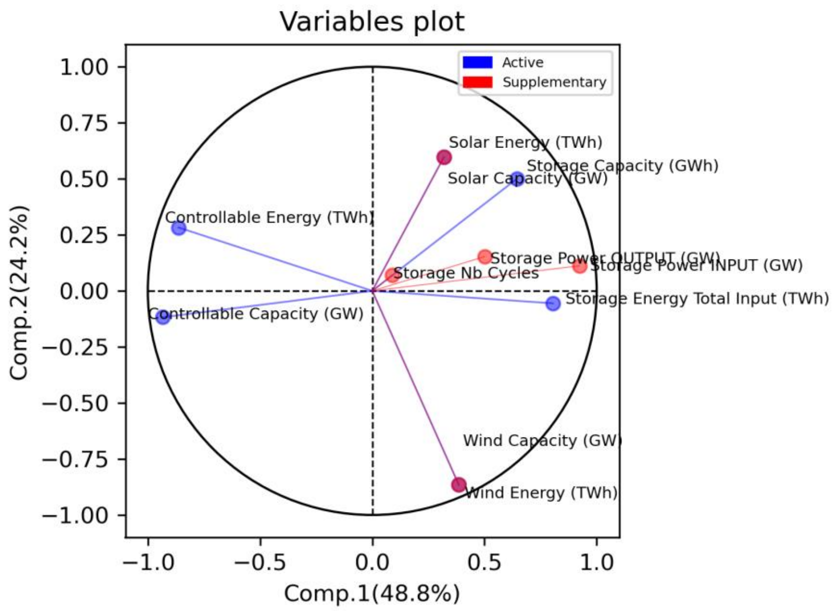
4.3. Grouping the scenarios over the URR

REPM is generating a large number of scenarios varying the percentage of intermittent energy, solar/wind percentage and Cth (in the following analysis the value of γ and $\eta_{StoToDem}$ are fixed equal to 20%). Each of these scenarios is characterized by the capacity and the energy produced by the intermittent sources (solar and wind), the capacity and the energy fluxes of the storage and the capacity and the energy produced by the controllable sources. A methodology was developed to present all the scenarios and summarize their main characteristics.

In a first step, a Principal Component Analysis (PCA) is used to underline the correlations between the different characteristics of the scenarios. It shows that the scenario characteristics can be well summarized by only two components (Figure 23-a). Along the first component (horizontal axis) the scenarios using a lot of controllable ressources are opposed to those using a lot of storage. Along the second component (vertical axis), scenarios using more solar energy are opposed to those using more wind energy. In a second step, the K Means clustering method is performed to group scenarios with relatively similar characteristics. The graph in Figure 23-b presents the different scenarios using the two PCA components and showing the distribution of the 7 clusters that are distinguished by different colors. The clusters on the left of the graph contain scenarios that use a lot of controllable sources, while those on the right use a lot of storage. Clusters at the top of the graph use more solar energy while those at the bottom use more wind energy.

Within each of the resulting clusters, a representative scenario of the cluster is selected (mean scenario), and the ones with extreme values in the group (i.e. the scenario with the minimum storage and controllable capacity, maximum solar and maximum wind capacity, and the mean scenario), as well as the scenario “zero” which corresponds to the scenario with zero capacity of solar and wind energy, and therefore zero storage capacity. This set of scenarios within each cluster is called “representative scenarios”.

a)



b)

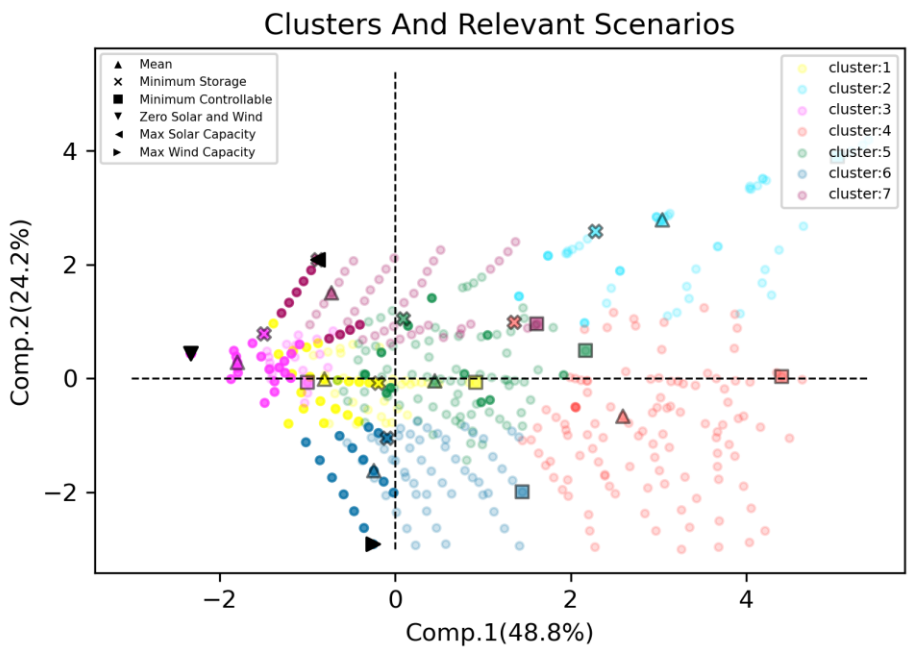


Figure 23 Analysis of scenarios: a) projection of the characteristics of the RES-TMO energy system according to the PCA results over the plane with the components 1 and 2 as axes, and b) clusters and representative scenarios of the resulting scenarios from REPM. γ = 20% & ηStoToDem = 20%.

4.4. Cost evaluation

Evaluation and comparison of different energy transition strategies may consider economical aspects. For energy systems, the economic indicators must consider not only investment and

fixed costs but also the value of money over time, fuel costs, variable costs, and replacement linked to the use-life of the energy production infrastructure. In this research all the costs are expressed as US dollars, assuming the currency value in 2020.
The cost of a scenario "s" is estimated from the calculation of the total cost ($TAC_t^{(s)}$) of each technology "t" used. It is computed as follows :

$$TAC_t^{(s)} = IC_t^{(s)} * (AC_t + FC_t) + EP_t^{(s)} * \left(VC_t + \frac{FUC_t}{\eta_t}\right) \quad (1)$$

where,

- $IC_t^{(s)}$ is the installed capacity in MW,
- AC_t is the annualized capital cost in $/MW/yr, i.e. the initial investment of the infrastructure amortized over its estimated lifetime,
- FC_t is the annual fixed costs in $/MW/yr, which corresponds to the costs of operating the system over a year and includes staff costs, insurance, taxes, repair, or spare parts,
- $EP_t^{(s)}$ is the annual energy production in MWh/yr,
- VC_t is the annual variable costs in $/MWh/yr, which includes expenses related to the variation of the mean capacity factor of the system, e.g. contracted personnel, consumed materials, and costs for disposal of operational waste per year, excluding fuel costs,
- FUC_t is the cost of fuels consumed for electricity production in $/MWh/yr, used with the fuel usage efficiency η_t.

AC_t is calculated based on the overnight capital costs of the technology "t" (CC_t) in the energy mix in $/MW, the lifetime "l" in years, and the discount rate "r" :

$$AC_t = CC_t * \frac{r * (1 + r)^l}{(1 + r)^l - 1} \quad (2)$$

As a consequence, the AC_t has a value different from just dividing the capital investment costs by the lifetime in years due to the value of the money change in time according to r. A r value of 5.77% is used for the analysis of energy strategies based on the values reported in published studies.
The total annualized costs of scenario "s" ($TAC^{(s)}$) is obtained as the sum of the $TAC^{(s)}$ for all technologies in the energy matrix and a term, NEF, corresponding to the cost of the energy resources used for combustion rather than for electricity production (i.e. imported subproducts, domestic subproducts obtained by refining domestic oil, and domestic subproducts obtained by refining imported oil) :

$$TAC^{(s)} = \sum_t TAC_t^{(s)} + NEF \quad (3)$$

The costs of storage, are computed with a zero value of FUC_t/η_t (since no fuel costs are associated with storage) and $ES_t^{(s)}$, the annual energy stored in MWh/yr :

$$TAC_t^{(s)} = IC_t^{(s)} * (AC_t + FC_t) + ES_t^{(s)} * (VC_t) \quad (4)$$

The AC_t of storage is calculated based on the number of utilization periods (np, in years of using the storage infrastructure) :

$$AC_t = CC_t * \frac{r * (1 + r)^{np}}{(1 + r)^{np} - 1} \quad (5)$$

"np" is taken as the minimum between the lifetime of the storage technology "l" and the ratio between the yearly cycles of storage and the use-life cycles :

$$np = \min\left(l, \frac{simulated\ cycles}{use\ life\ cycles}\right) \quad (6)$$

Figure 24 shows the cost evaluation of the less costly scenarios of each cluster (including the scenario zero which uses no intermittent sources). In Figure 24-a and 24-b, the energy of the controllable is provided entirely by combined cycle gas turbines (CCGT) and the storage by large concrete towers. The intermittent energy is produced by wind turbines and photovoltaic solar panels.

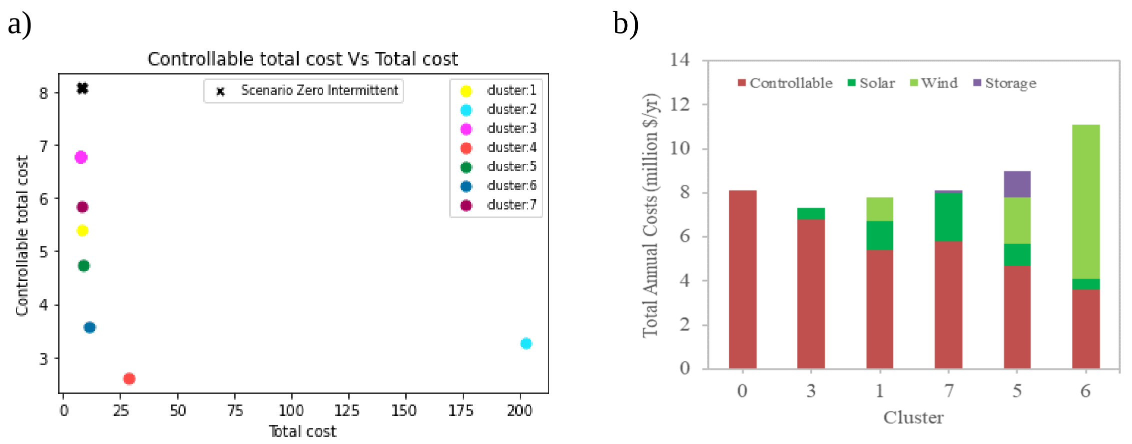


Figure 24 Costs of controllable and total costs for the scenarios with the less TAC within each cluster, and the scenario of zero intermittent in the system, using as technologies of reference horizontal axes wind turbines and photovoltaic solar panels for the intermittent energy sources, and for the controllable and storage, combined cycle gas turbines (CCGT) and large concrete towers. The costs are expressed in billion US Dollar per year.

Figure 24-a shows the total annual cost of cluster 4 and 6 is higher than the other clusters while the cost of their controllable sources are the lowest. These two clusters use a large amount of solar energy and require large storage capacities (Figure 23). Due to their prohibitive total cost, they do not appear on the graphics of Figure 24-b. This figure shows the repartition of the costs between the controllable, solar and wind sources and the storage for the cheapest scenario of each cluster. The cost of controllable resources decreases as more and more energy is produced by intermittent resources. The total annual cost becomes more expensive than scenario 0 when a large amount of intermittent resources is introduced into the mix (scenarios 5 and 6). In such a situation the model finds that more wind energy is required than solar energy.

5. REPM - PERSEUS comparison

Since the REPM (Unistra-CNRS, Strasbourg) and the PERSEUS (KIT) model offer two different frameworks to analyze the energy strategies of the Upper Rhine Region, a comparison of the results was organized.

The very first comparison of the 2 models showed very different results for the URR region. The PERSEUS model suggests developing mostly PV energy production whereas REPM encourages more wind energy production to fulfill the 2050 objectives. Actually, PERSEUS considers outside regions and their renewable energy production potentials. For economic reasons, it can suggest producing wind energy in regions offering the best potential, for instance in the north of Germany. The REPM does not consider such a strategy. It focuses on local renewable energy production and characterizes the energy system needs as a function of the local share of renewable energy. The local share may be decided by the stakeholders who want to introduce it in their energy mix to answer to the local energy demand. Thus, these comparisons proposed here did not intend to definitively conclude on the disadvantages/advantages of each system but are proposed to illustrate how these comparisons were used to understand the results of energy modeling systems.
Let us remember first that REPM is developed to answer for one year to the hourly energy demand, covering a large range of scenarios, varying the intermittent energy sources contribution as well as the controllable peak-shaving parameters and the storage losses. The current energy production is not considered to start a simulation: The model is used to characterize the needs in terms of storage or controllable to answer to the demand with a certain percentage of renewable energy in the energy mix. No cost optimization is used to select one scenario or another. All the possible scenarios are classified and are evaluated *a posteriori* in terms of costs, GHG emissions, etc. On the other hand, the PERSEUS model target function demands a minimization of all decision-relevant expenditure within the entire energy supply system considering the actual energy production, and the available technologies, and allows for a simulation of several years (current and future ones). The optimization concludes with an optimized scenario as a function of carbon taxes. Differences lead also in the description of the energy demand and potentials: the REPM model uses real hourly profiles of the energy demand and potentials over a whole year, while the use of PERSEUS is based on only 4 representative weeks (1 week per season of a year) per year that are used to reproduce yearly results.
Because of the two different configurations, the model comparison cannot consist of a direct comparison of the outputs of the two tools. Among all possible REPM scenarios, we selected the closest REPM scenarios to the optimized PERSEUS scenarios for 2050, and discuss them here.
Thus, the KIT team provides the following inputs and outputs of a scenario computed by PERSEUS for the Upper Rhine Region in 2050:

- the input electrical demand profile sampled on 4 representative weeks;
- the input solar and wind potentials, expressed as capacity factors sampled on the 4 representative weeks.
- the output capacities and energy produced by the energy system, including total energy imports and exports from the regions outside the Upper Rhine Region. Tableau 1 presents these outputs per renewable energy source.

Tableau 1 PERSEUS 2050, scenario outputs.

2050	GAS	HYDRO RIVER	BIOMASS	PV	WIND	TO PSP	TO GAS STORAGE	Exports	Imports
CAPACITY (GW)	6,69	2,22	0,02	27,96	1,88	3,23	5,97	31,22	49,81
ENERGY (TWh)	6,35	7,54	0,11	31,63	2,78	5,27	10,32		

In order to be compared with REPM, the PERSEUS data was converted into the REPM format. The controllable, intermittent, and storage information issued from PERSEUS were for instance were used as followed:

- the gas, hydro river, and biomass capacities were added together in order to calculate a global controllable capacity;
- the gas, hydro river, and biomass energy produce were also added together in order to calculate global controllable energy produced;
- the imported energy results were added to the controllable energy produced too because REPM considered the controllable energy as potentially imported energy;
- the PV and Wind capacity and energy produced were summed into an intermittent capacity and energy produced;
- the sum of “To PSP” (Pumped Storage Plant) and “To Gas Storage” results gives the total storage capacity and energy results. Note that the storage energy represents the total energy flux delivered to the storage.

Tableau 2 summarizes the PERSEUS results into data that could be used or compared with REPM results. The storage number of cycles represents the number of times that the storage charges and discharges fully its capacity. It is calculated as the storage energy on the storage capacity.

Tableau 2 Conversion of PERSEUS data into the REPM format.

PERSEUS 2050	GAS	HYDRO RIVER	BIOMASS	PV	WIND	TO PSP	TO GAS STORAGE	Exports	Import
CAPACITY (GW)	6,69	2,22	0,02	27,96	1,88	3,23	5,97	31,22	49,81
ENERGY (TWh)	6,35	7,54	0,11	31,63	2,78	5,27	10,32		

Intermittent Capacity (GW)	Intermittent Energy (TWh)	Controllable Capacity (GW)	Controllable Energy (TWh)	Storage Capacity (GW)	Storage Energy (TWh)	Storage Nb Cycles	Exports (TWh)
29,84	34,41	8,92	63,81	9,21	15,59	1693,09	31,22

The REPM input data were produced based on this scenario:

- the energy demand was hourly reproduced on a full year from the 4 representative weeks of the PERSEUS input data and fixed at 47.75 TWh for 2050 (“Demand Total”);
- the percentage of the demand delivered by the intermittent source (“%INT”)
- the balance between solar and wind energy in this intermittent energy production (“%SolWind”) were computed as follows:

$$INT\% = \frac{PV_{Energy} + Wind_{Energy}}{Demand\ Total} = \frac{31{,}63 + 2{,}78}{47{,}75} = 72{,}06\%$$

$$SolWind\% = \frac{PV_{Energy}}{PV_{Energy} + Wind_{Energy}} = \frac{31{,}63}{31{,}63 + 2{,}78} = 91{,}9\%$$

Defining these percentages in the REPM inputs allowed it to have the same intermittent energy production as PERSEUS. The wind and solar potentials were kept as for REPM in order to have a more accurate intermittent energy hourly profile with the same total energy produced. With such inputs, many possible scenarios were modeled with REPM through the different variables of the algorithm: controllable maximum capacity, controllable minimum power threshold, and storage losses. These scenarios are obtained with γ = 100% and $\eta_{StoToDem}$ = 40%. The demand used corresponds to the same profile used as input for the PERSEUS model in the Upper Rhine region.

The obtained results from REPM account for 1260 scenarios of intermittent energy introduction in the region. The PERSEUS scenario can be compared to all these REPM scenarios, however only a few of them propose the same capacity of controllable and storage. The most representative REPM selected scenario is presented in Tableau 3.

Tableau 3 Results of the closest REPM scenario in terms of controllable and storage capacity, computed from the same energy demand and intermittent energy production as used in the PERSEUS model.

	Intermittent Energy (TWh)	Controllable Capacity (GW)	Controllable Energy (TWh)	Storage Capacity (GW)	Storage Energy (TWh)	Storage NbCycles	Exports (TWh)
PERSEUS	34,41	8,92	63,81	9,21	15,59	1693,09	31,22
REPM 1	34,41	7,50	65,70	9,53	0,03	3,52	48,75

While the energy modeling systems simulate quite similar controllable energy productions (65,7 TWh for REPM, 63,81 TWh for PERSEUS), we can note that the REPM model calculates a lower need of controllable capacity (power) than PERSEUS. Actually, the PERSEUS dimension is the controllable capacity to be able to answer the demand in any case to avoid energy supply security problems. We can also note that for a similar storage capacity, REPM operates much less the storage system with a low amount of energy stored (0.03 TWh) compared to PERSEUS (15.59 TWh). This significant difference shows a difference in the storage management between the two models. Indeed, without any restriction due to the costs, the REPM model allows for long time storage with a seasonal accumulation of energy stored. This reduces the number of cycles of the system. For cost efficiency, PERSEUS operates the storage on a short time basis, with a limited storage capacity, and consecutive higher use of storage infrastructure.

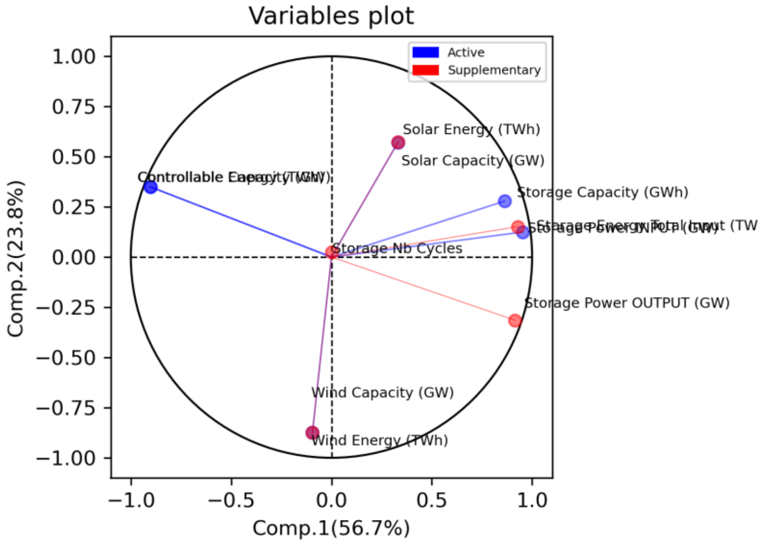
To deal with this difference in the storage management, a REPM simulation was produced with a fixed storage capacity (without this condition, the REPM dimension the storage as needed according to the need of peak shaving, i.e. there are any restrictions on the storage capacity). Such storage capacity limitation leads to excess energy in the system when the intermittent production is high or new needs for energy that cannot be handled by the storage anymore: to meet these new needs, import and export energy are recomputed to simulate a new energy balance. In our study, let us remember that imported energy is considered as a part of the controllable energy production and added to the controllable results.

Tableau 4 Results of the closest REPM scenario in terms of controllable and storage capacity, computed from the same energy demand and intermittent energy production as used in the PERSEUS model, and with the same storage capacity, fixed to 9.21 GW.

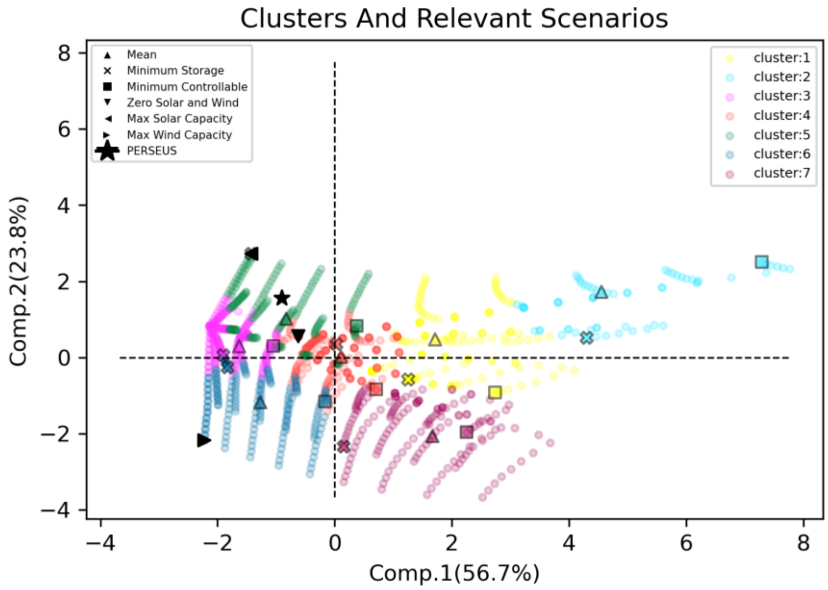
	Intermittent Energy (TWh)	Controllable Capacity (GW)	Controllable Energy (TWh)	Storage Capacity (GW)	Storage Energy (TWh)	Storage NbCycles	Exports (TWh)
PERSEUS	34,41	8,92	63,81	9,21	15,59	1693,09	31,22
REPM 2	34,41	3,50	37,68	9,21	2,76	300,03	20,14

As expected, a limitation of the storage capacity leads to a higher number of storage cycles (Tableau 4) : around 300 cycles against 3.5 for the previous scenario. This number of storage cycles keeps below the PERSEUS results. An assumption is that the PERSEUS algorithm manages the storage based on other criteria, such as the energy prices and needs to design a less costly scenario. It can be noted that the REPM controllable capacity is even reduced compared to the previous scenario, without fixed storage capacity (from 7.5 to 3.5 GW). This is due to a more intense peak-shaving. Indeed, the original scenario (without storage capacity limitation) requires a high storage capacity in order to reduce the controllable capacity to 3.5 GW.

Finally, in order to better illustrate this comparison, the PERSEUS scenario has been included in the projection of the REPM scenarios (see Figure 25). Despite the differences which have been underlined between the two models, we can see that the results found by the KIT belong to one of REPM cluster of scenarios.



a)



b)

Figure 25 Comparison between PERSEUS and REPM results: a) projection of the characteristics of the RES-TMO energy system according to the PCA results over the plane with the components 1 and 2 as axes, b) Representation of the clusters for the scenarios obtained with REPM. Representative scenarios of each cluster are included. The projection of the scenario corresponding to the results of the PERSEUS model is represented (it is located in cluster 5). The plane used to represent the scenarios is composed of the components 1 and 2 obtained from the implemented PCA method over the scenarios. γ = 100% & ηStoToDem = 40%. The demand used as input for REPM corresponds to the same profile used for PERSEUS.

To conclude, REPM allows to model scenarios close to PERSEUS results in very specific conditions of storage restriction. The important differences found in the storage characteristics underline a difference in the storage management method. REPM may actually use the storage for a controllable peak-shaving purpose. Applied to an energy system based on nuclear energy, it can help to reduce nuclear capacity needs. This would lead to a direct reduction of the risks that nuclear implies. We noted that in the PERSEUS model if there is no need for peak-shaving, the storage system can be operated whenever it is needed and within the limits of the capacity allowing a higher frequency of utilization (high number of cycles). In this way, additional scenarios using storage and economically more optimized could be modeled.
With fewer storage restrictions, the lowest costly REPM scenarios use fewer controllable resources and tend to reduce storage by increasing wind production at the expense of solar production.

6. Conclusions

The energy balance of the Upper Rhine region is heavily dependent on imports of fossil resources. A new methodology has been tested in the framework of the RES-TMO project to evaluate how local renewable energy production strategies could meet 100% of the electrical demand of the Upper Rhine region. The calculation of the wind and solar energy production potentials in the Upper Rhine Region shows that these potentials are sufficient to meet 100% of the electrical demand, or even more. A large set of scenarios have been designed varying the amount of intermittent energy sources (solar and wind) introduced into the electricity mix and computing the storage and controllable energy needed to fulfill the energy demand.
The scenarios were sorted into clusters. Then, a set of technologies have been associated with each scenario to compute the total annual cost of each scenario (one technology used to produce the controllable resources and another one for ensuring the storage). The cheapest scenario has been chosen as the "representative scenario" of each cluster. The results have shown that the cost of controllable resources decreases as more and more energy is produced by intermittent resources. The total annual cost of the scenarios becomes more expensive than the scenario using only controllable sources when a large amount of intermittent ressources is introduced into the mix. In such a situation the REPM model finds that more wind energy is required than solar energy. It is however important to note that the results obtained are preliminary. The analysis of the different possible scenarios still needs to be improved by introducing the possibility to consider a set of technologies for the production of controllable energy as well as for the storage.

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