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## **Long-term power generation adequacy assessment: the TIMES-ANTARES linking model**

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**Abstract:** Long term energy scenarios modelling and dispatch simulations are two key stages in a methodology for a cost-effective transition to a low-carbon power system. Although these stages are equally important, they are often performed independently. This decoupled approach can lead to future investment trajectories decided by long term energy models with no guarantee of the generation adequacy.

In this respect, the aim of this study has been to develop a general methodological framework using a multi-model approach to investigate optimal energy mixes which meet adequacy requirements. The automated-data-linking model is used to

- i. Plan the optimal power generation mix to meet a given level of future expected electricity demand subject to various constraints using the TIMES framework (The Integrated MARKAL–EFOM System);
- ii. Assess the adequacy of the obtained power generation mix under several climatic and operational future states using the probabilistic operational open-source model ANTARES (A New Tool for the generation Adequacy Reporting of Electric Systems);
- iii. Implement iterative feed-back loops based on the estimated ability of different generating technologies to support peak demand in case of loss of load (capacity credit) to ensure a total firm capacity in line with the electricity supply criterion.

This methodology was applied to a case study of power generation planning in France for the time period 2013-2050. The results show that using TIMES alone exposes the power generation mix for 2030 to a risk of insufficient supply. On the other hand, activating the iterative feed-back loops over capacity credit parameters had the potential to ensure both the economic effectiveness of the mix and the security of the electricity supply criterion set by the French public authorities.

**Keywords:** long term energy models, operational power system models, linking, adequacy assessment.

### **Background: Why linking modeling approach matter**

As Variable Renewable Energy (VRE) deployment increases, concerns have been raised over the methodologies and underlying assumptions employed in standard energy system modeling tools (Pfenninger, 2017; Pfenninger et al., 2017). In fact, these tools are not designed to capture the high short-term variability of renewable capacity factors. As a result, insufficient variability representation either in supply or demand could lead to a sub-optimal, or even inadequate, power generation mix (Nweke et al., 2012). This may create misunderstanding concerns among policymakers and system operators, who may begin to view power generation portfolios derived from long-term energy modeling tools as at odds with the secure provision of electricity requirements (IRENA, 2017). Therefore, two contrasting methodologies have been developed, in order to overcome this drawback: a direct integration approach and a model-coupling approach (Collins et al., 2017). The direct integration approach involves increasing temporal and spatial granularity that permits improving the representation of VRE variability (Ludig et al., 2015; Merrick, 2016), or by integrating new constraints into the optimization model to mimic the effects of some short-term dynamic features of the power system (Drouineau et al., 2015, 2014; Spiecker and

Weber, 2014). In contrast, coupling model methodologies acknowledge the limitation of using a single model to capture all of the power system's relevant operations. (Kannan and Turton, 2013) recognize that even with a high temporal resolution TIMES framework we cannot substitute a dispatch model because some features cannot be represented. Also, the importance of bridging long-term energy system models with operational power system models has been discussed in detail when describing a soft-linking exercise between the two types of models (Deane et al., 2012). In this regard, closing the gap between long-term energy system models and short-term operational models is of growing importance in the energy modelling community (IRENA, 2017).

In this context, the main purpose of this study is to contribute to the development of a multi-model framework based on two models with proven track records in techno-economic power system assessment. The energy system model is MARKAL/TIMES, and ANTARES tool is selected as the probabilistic unit-commitment and dispatch model. The first objective of this work consists of coupling TIMES with ANTARES as part of a one-directional chain models in order to transfer the power generation mix decided by TIMES for a given year of interest to ANTARES inputs database. For that target year the second objective is to focus on the ANTARES dispatch results and adequacy metrics to provide consistent feed-back to TIMES to ensure sufficient supply. This work represents an initial step in planning both a cost-effective and adequate power system, thereby respecting generation adequacy requirements.

### Proposed methodology: an automated-data-linking tool

The framework, as shown in Figure 1, illustrates the linkage of TIMES and ANTARES using a platform we call the automated-data-linking tool. It can be split into two independent main components: coupling part and feed-back part. The first part aim to link TIMES and ANTARES as two modeling tools and the second part aim to address generation adequacy requirements. In such a way TIMES is used to optimize the investment in new generation capacity over a 2013-2050 time horizon. The resulting power generation mix for 2030 is then transferred to ANTARES in which the detailed hydro/thermal dispatch will be decided at an hourly resolution for a large number of stochastic scenarios representing weather-dependent and operational uncertainty. Then, based on ANTARES results the main function of the feed-back loop is to ensure an adequate generation mix. However, the feed-back with the long-term energy system model is not straightforward and requires an iterative process. To this end, the feed-back loop stopping criterion is chosen to be the loss of load expectation limit of 3 hours.

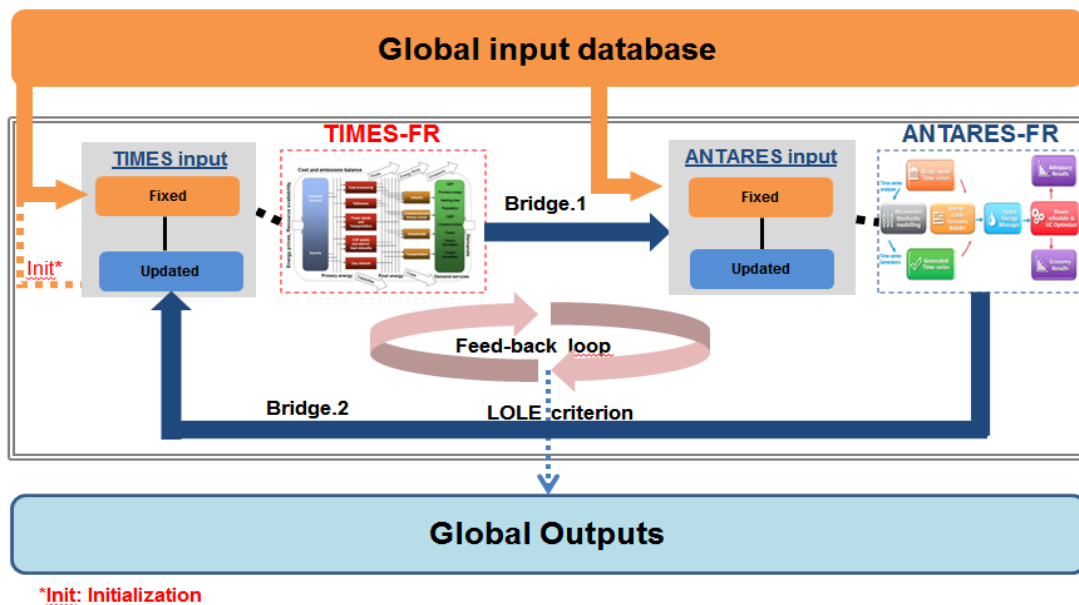


Figure 1 The automated-data-linking model flow-chart

**Coupling part:** the two following steps are built to align ANTARES inputs on TIMES outputs:

- **Global Input database and TIMES initialization:** For consistency before carrying out the linking exercise between TIMES and ANTARES, a necessary first step is to identify the overlapping area between the two models. This means that, as they describe the same power system, it must be possible to obtain a clear mapping of the common input (electricity demand, PV and wind capacity factors, technology data base, and economic parameter). ANTARES being probabilistic, the electricity demand and VRE capacity factors in input are described by numerous time-series to simulate multiple years. As TIMES is deterministic, only one year is represented. It was then decided to use the median scenario of ANTARES as the TIMES input. In such a way, the orange block labeled “global input data” contains the key input data needed in TIMES and ANTARES, and also provides the starting point for our linking exercise. TIMES initialization step consists of selecting a specific long-term scenario and running the TIMES model.
- **Bridge.1:** This step is the core of the linking model. The generation mix as decided by TIMES for a specific year of interest is used as input for ANTARES, which simulates the supply/demand balance of this power system under several operational and climatic conditions. It is important to note that within ANTARES, the stochastic nature of VRE, electricity demand, hydro generation and thermal power plant availability is taken into account by using a large number of annual scenarios conditions (Monte Carlo simulations). Each possible future state corresponds to an alternative realization, created using forecasted meteorological data, and is composed by annual time-series, with hourly resolution using RTE data (Réseau de Transport d'Electricité, 2018).

**Feed-back part:** This part aim to use the linking model to address power system generation adequacy issue.

- **Bridge.2 and feed-back loops:** For a controllable linking, the common power system representation needs to provide common, unambiguous measuring points where the two models should yield identical results (Wene, 1996), e.g. power operation and dispatch. In this regard, after running ANTARES, the outputs are analyzed in terms of the difference between expected power generation, dispatch decisions, and finally the reliability of the power system. Two things may happen:
  - if the outputs show that the legal adequacy criterion is not met ( $LOLE^1 > 3h$ ), then some parameters will need to be updated in the long-term optimization model for that year;
  - if the outputs show that the legal adequacy criterion is met, then the process ends.

The feed-back loop between ANTARES and TIMES is based on the capacity credit value, which is used to measure the contribution to demand peak. In TIMES model, capacity credit is incorporated as an exogenous parameter within the peaking reserve constraint. In our work we propose a methodology based on the IEA approach to estimate the capacity credit value and taking advantage of ANTARES outputs to estimate accurately all of the capacity credits of system generators. For example, the VRE capacity credit is calculated as the difference between peak demand and peak residual demand, expressed as a percentage of the variable renewables installed (IEA, 2015). Hence, in our work capacity credit is evaluated with respect to ANATRES outputs following equation 1.

$$cc_i = median_{s \in Scenario} \left( \frac{LDC^s(t' = 1) - RLDC_i^s(t' = 1)}{Capacity_i} \right) \quad (1)$$

Where

- $LDC$  is the load duration curve,  $RLDC$  is the residual load duration curve, and  $Capacity_i$  is the installed capacity of a technology  $i$ .
- $Scenario$  is the set of ANTARES scenarios.

To summarize, the bi-directional data exchange between the two models is set up as follows:

- TIMES mainly provides the generation portfolio to ANTARES

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<sup>1</sup> Loss of load expectation

- For a specific year, ANTARES assesses the adequacy criterion and provides capacity credit iteratively over available technologies.

The proposed and developed framework was applied to France on a “copper plate” (i.e. neglecting grid congestions on the French grid) and stand-alone basis (i.e. without taking into account interconnections with other countries). The long-term scenario assumes a mix where 60% of the French electricity consumption would be sourced from renewables technologies by 2050 and 2030 was chosen to be the target year for the linking model. Within ANTARES, the probabilistic simulations incorporate a reference framework including 200 climatic scenarios (VRE capacity factors and load) representing different future states for 2030. All those climatic realizations will be simulated in combination with the availability of the thermal facilities and hydro conditions (wet, normal or dry), thus simulating 1000 scenarios

## Primary Results

This section comprises two parts. In a first part, the dispatch schedule results from both models are compared and analyzed. It is important to highlight at this level that as TIMES is deterministic and ANTARES is probabilistic, this comparison is based on ANTARES median scenario which served as an input in TIMES model(consistency). A second part focuses on the assessment of the generation adequacy and the impact of the iterative feed-back loop on the power generation mix.

### 1. Dispatch schedule comparison

A first observation is that, despite an identical power generation mix in both models, differences on terms of dispatch schedule can be observed. This graphical representation shows three patterns. First, aggregating the high variability of a renewable (especially wind) capacity factors into 84 times slices tends to underestimate the short-term variations. Second, TIMES overestimates the Residual Load Duration Curve (RLDC) compared to the hourly ANTARES RLDC. Third, the VRE representation in TIMES is totally different from ANTARES. Indeed, curtailment is allowed in TIMES because availability factors are given as an upper bound. In other words, renewables generation is a decision variable in TIMES. However, in ANTARES, wind and solar generation time series are considered as known inputs. More precisely, they are subtracted from the load to obtain a net load, then, ANTARES decides which dispatchable units (thermal and hydraulic) can supply this net load at a minimal cost.

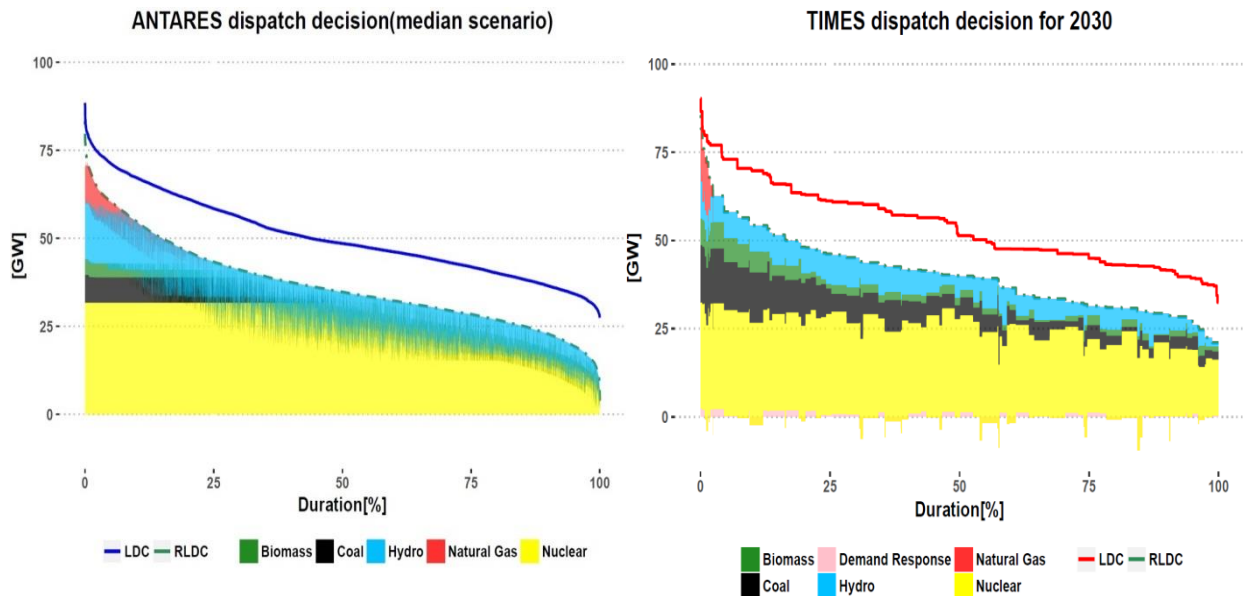


Figure 2 Production stack comparison between TIMES (right) and ANTARES median scenario (left)

Consequently differences in terms of annual energy generation can be observed for a set of technologies. Figure 3 presents for each installed technology (at 2030), the annual electric energy generation computed from the dispatch in the TIMES model (red) and the corresponding ANTARES model (blue). For both non-dispatchable generation technologies (especially wind and solar) and nuclear, we observe negligible differences. These depend on a range of factors, such as the economic merit order behind this aggregated indicator, which ranks renewables and nuclear first. On the contrary, we observe a significant gap for mid-merit power plants (i.e. coal) and peak technologies (natural gas). The principal cause for the differences of the annual dispatchable power generation can be found in the way TIMES and ANTARES models approximate the residual load (Figure 2).

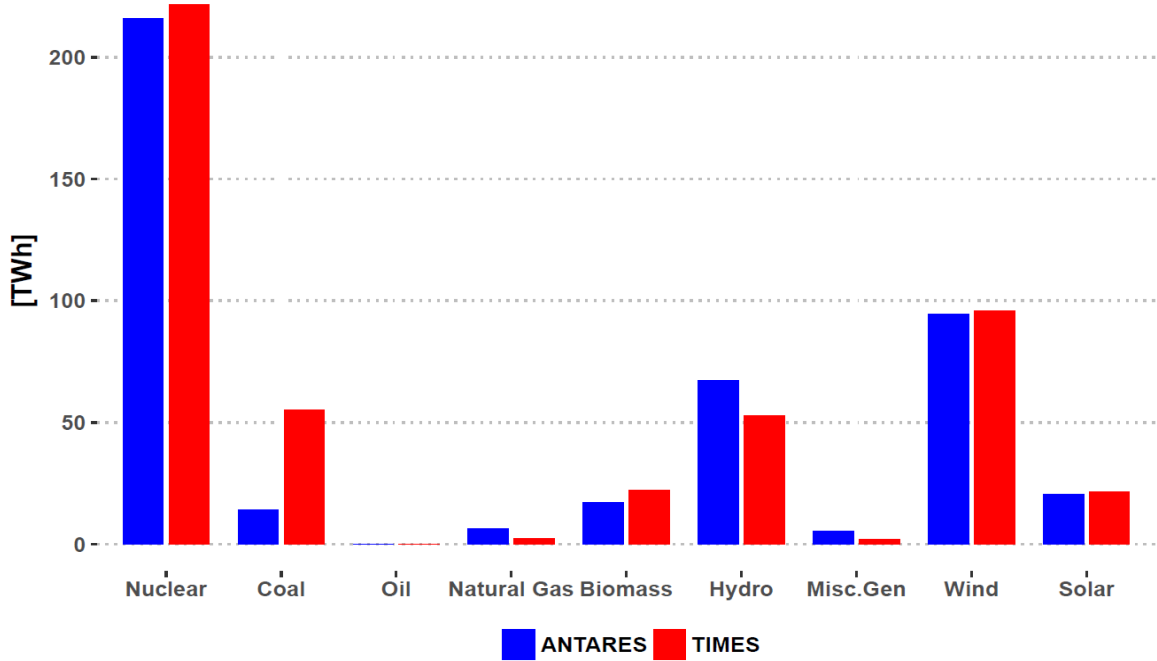


Figure 3 Annual power generation comparison between TIMES (red) and ANTARES median scenario (blue)

Putting this together, we can conclude that, since TIMES captures less residual demand variation, the model overestimates the use of mid-merit order and peak load technologies compared to an hourly dispatch. These conclusions are broadly consistent with the findings of the (Poncelet et al., 2014) work on the importance of integrating the variability of renewables into long-term energy-planning models.

## 2 Adequacy assessment and feed-back loop

ANTARES outputs result in LOLE equal to 117 h, which is not conform to the three-hour limit. A statistical analysis of loss of load duration shows that close to 10% (i.e. 1 in10) of the 1000 climatic future states last more than 300 hours with a maximum value of 950 h. Figure 4,5 show the impact of iteratively updating the capacity credit values on the loss of load distribution calculated by ANTARES (left) as well as the least-cost power generation mix proposed by TIMES (right). Seven iterations were necessary to build a power generation mix with sufficient supplies to meet the adequacy criterion. Two important observations are that, the first iteration (renewables capacity credit) has a significant impact on reducing the LOLE indicator, while the last iteration affecting the thermal power fleet has a limited impact (1-4 hours). On the other hand, while feed-back loops mainly affect the peak time-slice constraint, mid-merit power plants (biomass) increase their share over iteration. Feed-back loops are not simply adding peak generation to the existing mix; iterations are substantially changing the mix structure by adjusting mid-merit power plants capacities.

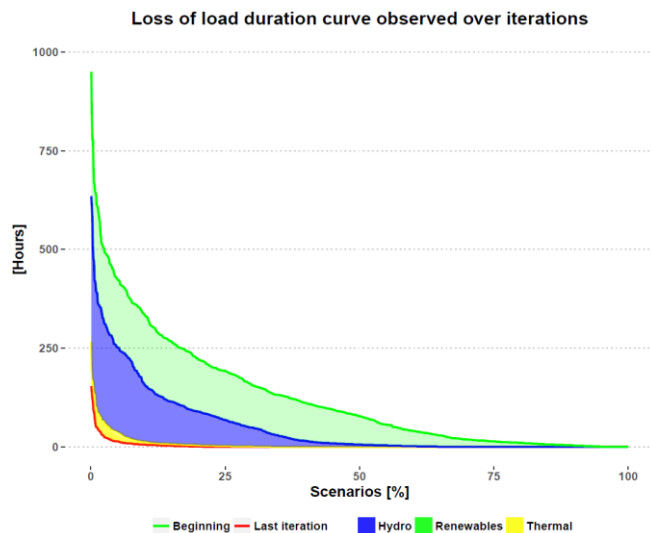


Figure 4 Loss of load duration curve over iterations for 2030

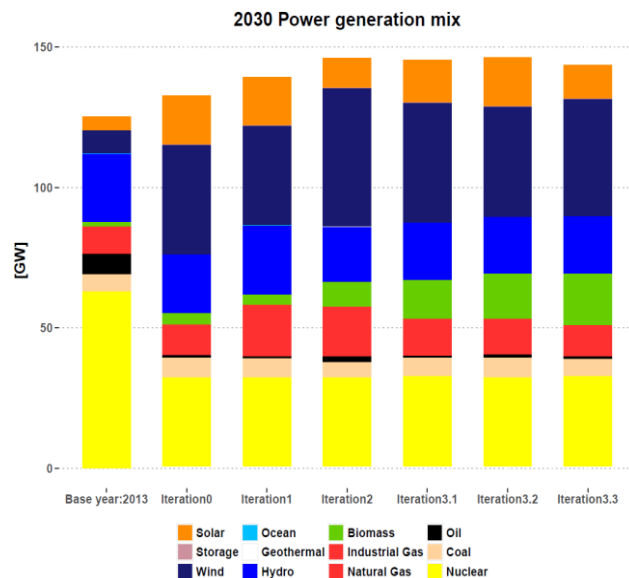


Figure 5 Power generation mix over iterations

From an economic viewpoint, any improvements in the reliability of the system involve additional costs. An important indicator in TIMES is the discounted total cost (including investment costs, variable and fixed costs) derived from TIMES for 2013-2050 periods. On the other side, the overall cost calculated in ANTARES is associated with the operating cost; unsupplied energy cost and spilled energy cost. Figure 6 shows that French energy system costs will be increased over iterations by 28% to satisfy 2030 adequacy criterion, while overall costs drop up by 40%. Notably, overall costs show a significant decrease over the iterations (Figure 7). This result is logical, because as LOLE decreases, the unsupplied energy cost diminishes. In addition, focusing on the last iterations, the results suggest that the incremental cost of few hours (3-4hours) of reliability improvement needs more investment than the first iteration, which presents a significant reduction in the LOLE index (50-75 hours). This is an important point, since the additional cost is mainly driven by investment costs, while variable and fixed costs remain almost constant.

Total system cost discounted over 2013-2050 horizon



Figure 6 Total discounted costs (2013-2050) over iterations

ANTARES overall cost for 2030

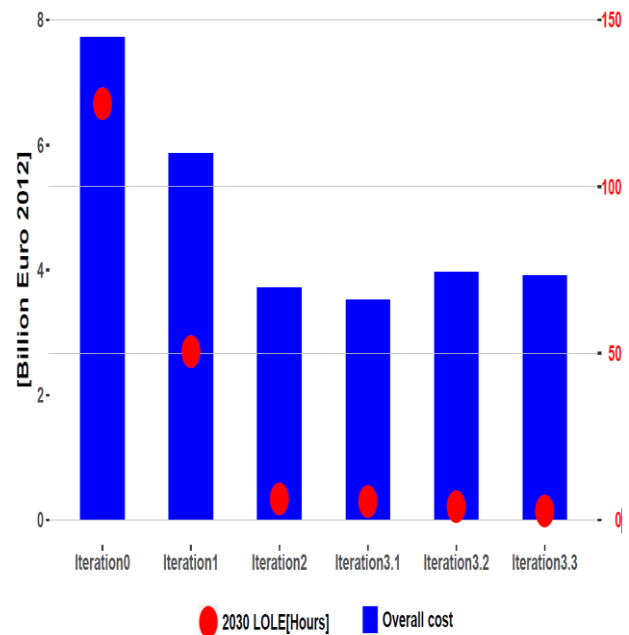


Figure 7 Overall costs (2030) over iterations

## Conclusion

As a case study, the developed methodology is applied to electricity generation planning for France without any cross-border exchanges (stand-alone basis). The study focused on the energy transition for the time period of 2013-2050, under a constraint to increase renewable power generation uptake to 60% by 2050. The adequacy assessment was carried out for 2030, whose behavior was assumed to be representative of the whole optimization horizon. Several conclusions arose from this study:

- Dispatch results from both models show significant differences, mainly due to an overestimation of the residual load duration curve observed by TIMES.
- The capacity mix as derived from TIMES for 2030 does not meet electricity security of supply requirements set by the French public authorities (a LOLE < 3h)
- Feed-back loops between ANTARES and TIMES based on capacity credit estimation have the potential to ensure sufficient firm capacity (supply) to meet demand
- From 3 (first simulations set: ANTARES 200 scenarios) to 7 (second simulations set: ANTARES 1000 scenarios) iterations were needed to converge to the 3h criterion
- From a planning point view, TIMES economic outcomes shows an underestimation of the total discounted cost of 28%, driven mostly by investment share
- From an operational point view, ANTARES economic outcomes shows that the overall cost for 2030 drop up by 40%,

In addition to examining other trends and developments scenarios, the linking model could be improved in several ways. A first set of necessary additions to the model is to assess adequacy over the entire period represented by TIMES (here from 2013 to 2050) and to represent accurately the cross-border exchanges, by taking into account the power mix used by the neighboring countries, which is essential to adequacy studies. Furthermore Drouineau et al., 2015 have developed an approach to stability by introducing in TIMES additional constraints based on estimates of instantaneous kinetic and magnetic energies (). In a similar way, Daly P. and al performed an external linking with an off-the-shelf optimal dispatch, while in Cardoso C., 2016, an internal linking introducing nonlinear transient stability dynamic effects has been described. The data-linking model could be interestingly extended to add an interaction with transient stability analysis tools used on a regular basis by power system dynamics experts.



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