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Gilles Notton, Marie Laure Nivet, Cyril Voyant, Christophe Paoli, Christophe Darras, et al.. Intermittent and stochastic character of renewable energy sources: consequences, cost of intermittence and benefit of forecasting. Renewable and Sustainable Energy Reviews, 2018, 87, pp.96-105. hal-01759732

HAL Id: hal-01759732
https://univ-corse.hal.science/hal-01759732

Submitted on 5 May 2020

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Intermittent and stochastic character of renewable energy sources: consequences, cost of intermittence and benefit of forecasting

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Abstract: Solar and wind energy are inherently time-varying sources of energy on scales from minutes to seasons. Thus, the incorporation of such intermittent and stochastic renewable energy systems (ISRES) into an electricity grid provides some new challenges in managing a stable and safe energy supply, in using energy storage and/or 'back-up' energy from other sources. In such cases, the ability to accurately forecast the output of "unpredictable" energy facilities is essential for ensuring an optimal management of the energy production means. This review syntheses the reasons to predict solar or wind fluctuations, it shows that variability and stochastic variation of renewable sources have a cost, sometimes high. It provides useful information on the intermittence cost and on the decreasing of this cost due to an efficient forecasting of the source fluctuation; this paper is for engineers and researchers who are not necessarily familiar with the issue of the notions of cost and economy and justify future investments in the ISRES production forecasting.

Keywords: photovoltaic systems; wind energy systems; production prediction; cost effectiveness.

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1. Introduction

The growth of the market of photovoltaic and wind energy systems over these last years is always continuing with 50 GWp of PV plants and 62.7 GW of wind turbines installed in 2015 (+25% for PV and +22% for wind energy compared with 2014). Thus, the total capacity respectively in Europe and in the World reached 94.6 GW and 227 GW for PV [1] and 141.7 GW and 432.56 GW for wind energy plants at the end of 2015 [2].

As the part of electricity produced by PV and wind energy systems increases, the need for these two intermittent and stochastic renewable energies systems (ISRES) to be fully integrated into electricity grids arises. Thus, one of the main challenges for the near future global energy supply is the high integration of renewable energy sources [3]. The stochastic and intermittent behavior of solar and wind resources pose numerous problems to the electricity grid operator which will be discussed in the first paragraph, these problems have then a negative impact on the production cost.

As defined by the business dictionary in 2015 [4], "cost is usually a monetary valuation of (1) effort, (2) material, (3) resources, (4) time and utilities consumed, (5) risks incurred, and (6) opportunity forgone in production and delivery of a good or service". This definition may be adapted to our problematic: cost is relative to an under or overproduction cost due to the random and fluctuating variation of solar and wind resources what make less secure the electricity production and distribution because not always available or non guaranteed.

Decreasing or smoothing these "unpredictable" variations need to use energy storages and back-up energy production means able to compensate immediately the power variations; then, backup generators must often stay switched-on for being able to maintain promptly the production/consumption balance; moreover, PV and wind energy systems must sometimes be switched off when their electrical production exceeds a certain percentage of the global production.

It is obvious that such difficulties induced by the intermittence of wind speed and solar radiation will lead to an additional production cost compared with conventional production. Presenting costs is a very difficult task because it depends, on various parameters such as the country and on legal incentives, on the situation of the electrical network (connected, partially connected or remote grid), on meteorological conditions of the implementation site, etc.

The objective of this paper is to present an overview, affordable by non-economic specialists, on intermittence extra-costs and on the positive influence of a reliable production forecasting on the production cost for wind and solar production. This would allow to help to justify future investments in the ISRES production forecasting in showing the benefits of forecasting for utilities. Predicting with a good accuracy the electrical power produced by wind or PV farms (and consumed by the load) allows to anticipate the actions of the electrical grid operator, to improve the electricity balance management and especially to ensure better safety of the electrical grid.

Predicting accurately the intermittence of renewable sources creates a cost-effective access to these energy resources. The reasoning is as follows: the intermittence of solar and wind resources is costly [5-6], sometimes very costly; a good forecasting of these intermittences allows to manage more efficiently the overall electrical system; then, the negative cost impact of these ISRES on the electrical network is decreased and at last, the cost effectiveness of PV and wind energy systems is increased.

Evaluation and forecasting of ISRES power help developers of renewable energy power plants to decide more easily where to install and how to operate them most efficiently by reducing the use of conventional electricity production means as much as possible.

In this paper, we will answer to the following questions:

- Why does the integration of ISRES into an electrical grid pose technical problems to the energy manager?

- Why is the price of the electricity not constant?
- Why do the variability and the behaviour of the solar and wind sources induce a cost and what is the order of magnitude of this cost?
- Why does forecasting PV and wind production improve the management of the electrical system and decrease the integration cost of ISRES?

This review paper syntheses the physical reasons to predict solar or wind fluctuations, it shows that the variability and stochastic variation of ISRES have a cost, sometimes and often high. It provides useful information on the intermittence cost and on the decreasing of this cost due to an efficient forecasting of the renewable source fluctuation, for engineers and researchers who are not necessarily familiar with the issue of the notions of cost and economy.

2. ISRES integration into an electrical grid

The uncertainty and variability of wind and solar resources pose problems for grid operators. This variability requires additional and complex actions to balance the system. A greater flexibility in the system is necessary to accommodate supply-side variability and the relationship to generation levels and loads.

The electrical operator has often some difficulties to maintain the production/consumption balance with conventional and manageable energy production means, mainly in small and/or no interconnected electrical grid (as island ones). The reliability of the electrical system then becomes dependent on its ability to accommodate expected and unexpected changes (in production and consumption) and disturbances while maintaining quality and continuity of service to the customers [7].

Even if no ISRES are integrated in the electrical network, energy and power reserves are needed, they can be divided in two categories: contingency reserve, used in case of specific event (such as power plant switch-on) and no-event reserves used continuously (due, for instance, to unreliable load prediction) [8]. These reserves (contingency and no-event ones) are started at various time scales: within 1 minute (primary reserve) using spinning generators, from 1 min to 1 hour (secondary/tertiary reserves) and more than 1 hour [9]. ISRES introduction in an electrical network only affects the non-event reserve particularly due to the imperfect forecast of their production [8].

Already, it appears that a predicted and anticipated event is easier to manage. The electrical energy operator needs to know the future of the electrical production and consumption with various temporal horizons (Fig. 1) [10-11].

Figure 1. Prediction scale for energy management in an electrical network [10-11].

The integration of ISRES into an electrical network intensifies the complexity of the grid management [10,12-13]. The intermittence and the uncontrollability of ISRES production bring also problems such as: voltages fluctuations, local power quality and stability issues [14-16].

Sufficient energy resources in reserve are required to accommodate significant up or down ramps in ISRES power generation to balance energy generated and energy consumed. When ISRES power generation is available during low load levels, conventional generators need to turn down to their minimum generation levels, with a bad efficiency and a high production cost. Balancing the energy generated and the energy consumed at all times creates costs and even more, if ISRES are integrated in the electrical network at a high level.

In case of a rapid decrease (or increase) of ISRES production, an instantaneous increase (or decrease) of the delivered electrical power by a connected production mean has to occur and/or a starting of a new production mean is needed; but the rise speed in power (ramp rate) of an energy plant and its starting time is not instantaneous [17-18]. Then, an activation of a new production system or a modification of the operating regime must be anticipated [7,17].

Bird *et al* [16] highlighted this need for flexibility for a high penetration of wind energy: with an utilization of wind energy, conventional generators must meet the net load (net load = demand minus wind energy) and, sometimes, this net load change or ramp is quicker than the load alone; then, the remaining generators are operating at a low output level (called "turndown") with a low efficiency [13,19], increasing the cost of electricity production, this is another effect of intermittence on the extra cost. PV production is often more in line with load [20] but during an evening load peak, the loss of a PV production after sunset increases the ramping needs to balance the evening demand [16]. ISRES power on electric grids requires all thermal fossil plants to turn on and off more often and to change their output levels more frequently to adapt it to the load with two major consequences: an increase in wear-and-tear on the units and a decrease in efficiency of about 4% (in the range of 0-9% [8]), with a thermal stresses on equipment. A limit in the percentage of ISRES production in the overall electrical production had to be introduced and induced several curtailments for wind and PV production. Variability and uncertainty of ISRES power generation increase the cost of maintaining the short-term energy balance in power systems [21].

A complete impact analysis of ISRES on the electrical grid was performed, based on observed and modelled data and on a bibliographical study, it concluded that [8]:

- the primary reserve must be increased by 0.6% (0.3-0.8%) of the wind capacity;
- all the reserves must be increased by 7% (6-10%) of the installed wind capacity;
- wind curtailments occur for a penetration rate up to 30% with a loss of production between 0.4 and 3.5% of the wind energy production.

All these negative impacts have inevitably a consequence on the production cost.

3. Predicting ISRES production: a necessity for a better integration

Forecasting the output ISRES power systems is required for a good operating of the power grid and for an optimal management of the energy fluxes occurring into the ISRES [22]. It is necessary for estimating the reserves, for scheduling the power system, for congestion management, for optimally managing the storage and for trading in the electricity market [3,12,14,23-27].

Due to the strong increase of ISRES power generation seen in the beginning of paragraph 1, the prediction of solar and wind productions becomes more and more important [11,24,28-30]. A small forecast error induces two negative effects: the network operator can receive high penalties because the inaccurate forecast did not allow to reach the predicted production profile and the use of back-up generators is more important for compensating the gap between predicted and real production [18,31]. A solution consists in using local storage in combination with ISRES in order to compensate deviations between forecasted and produced electricity [18-19,22,31] or in combining several ISRES spread over a large area in such a way that individual prediction errors of each ISRES are independent and the overall forecast error is reduced (aggregate effect) [32].

Various storage systems were being developed and are a viable solution for absorbing the excess of power and energy produced by ISRES (and releasing it in peak consumption periods), for bringing very short fluctuations and for maintaining a continuity of the power quality. These storage means are usually classified into 3 categories [33-34] (Table 1):

- Bulk energy storage or energy management storage used to decouple the timing of generation and consumption.
- Distributed generation or bridging power, for peak shaving; the storage is used for seconds to minutes and assures the continuity of service when switching from one energy source to another.
- Power quality or end-use reliability. The stored energy is only applied for seconds or less to assure continuity of quality power.

Table 1. Application category specifications [34]

Category	Discharge power	Discharge Time	Stored Energy	Representative Application
Bulk energy	10-1000 MW	1-8 h	10-8000 MWh	Load levelling, spinning reserve
Distributed generation	0.1-2 MW	0.5–4 h	50–8000 kWh	Peak shaving, transmission deferral

Power quality	0.1-2 MW	1–30 s	0.03–16.7 kWh	End-use power quality/reliability

Table 1 shows that the energy storage means act at various time levels and their management requires to know the power or energy produced by the ISRES at various temporal horizons: from very short or short for power quality category to hourly or daily for bulk energy storages [23].

A good forecasting is then useful for storage management: it allows to decrease the amount of flexibility reserves [18-19,30-31] and to optimize the management of the energy storage in anticipating the charge and discharge phases.

Similarly, the electrical operator needs to know the future production (Fig. 1) at various time horizons from one to three days for preparing the production means (and to schedule preventive maintenances), from some minutes to hours for planning the start-up of power plants in reserve (between 5 minutes to 40 hours according to the energy production means [17]).

Consequently, the relevant horizons of forecast can and must range from 5 minutes to several days as it was confirmed by Diagne *et al*. [11]. Elliston and MacGill [35] reviewed all the reasons to predict solar radiation for various solar systems (PV, thermal, concentrating solar thermal plant …) insisting on the forecasting horizon. It therefore seems apparent that the time-step of the predicted data (daily or hourly energy, 10-min or 20-min energy …) varies depending on the objectives and on the forecasting horizon. Fig 2 [11,24] summarizes the existing methods versus the forecasting horizon, the objective and the time step.

Figure 2. Relation between forecasting horizons, forecasting models and related activities [11, 24]

4. Variation of the electricity price due to technical constraints.

Hirth [36] wrote: "If electricity was an economic good as any other, the variability of variable renewable energy would have virtually no implications. But electricity has peculiar characteristics, most of which stem from the fact that it can be stored only at high cost. As a consequence, simple microeconomic analyses such as maximizing welfare with respect to the mix of different generation technologies require care and specific tools". The temporal variation in the electricity production, more important for ISRES, and the electrical grid operator's work to balance this variation affects the energy cost [20].

As previously underlined, using electricity imposes strong costly constraints [36]: the storage and the transmission of electricity must be realized with a minimum of losses, a permanent balance between supply and demand must be maintained to guarantee frequency stability. These aspects require an appropriate treatment of the electricity in economic analyses [37] and particularly for intermittent electricity production [38].

The electricity price varies over time, space, and lead-time between contract and delivery:

- as the production and the consumption vary significantly, the electricity price varies largely over time, sometimes by two orders of magnitudes and [38] even by a factor 10 [39] within one day; this daily price variation is rarely observed for other goods.
- the electrical grid capacity limits the amount of electricity able to be transported and leads to sometimes high price spreads between quite close locations.
- the rapid adjustment of power plant output for ensuring the production/consumption balance is costly and the price of electricity supplied can be very different from the contracted price.

Across all three dimensions (time, space and lead-time), price spreads occur both randomly and seasonally (and with predictable patterns) [36].

Thus, even in a conventional energy market, using only controllable energy means, the kWh price varies greatly. It is already clear that knowing perfectly what will be the electrical consumption (load) and production at various horizons will improve the management of the various energy sources and will reduce the corresponding energy price.

5. Cost of intermittency

The solar radiation variability occurs at various time scales: seasonal due to the Earth position in relation to the sun, diurnal due to the variation of the angle between solar radiation and the Earth ground, minute or second variations due to local meteorological conditions such as clouds and dust storms [40-42]. The fast variations are very troublesome for utility operations [13,43-46], because the purchase electricity contracts are decided in advance, because back-up generators must be stopped or switched depending on the ISRES production variations, because some of them must stay operating even if they don't produce for compensating rapidly (instantaneously) the short production variations. All these intermittences induce extra-costs [36-37,47-48]: ISRES production does not follow load and as the electricity storage is not unlimited and costly, this variability is costly; ISRES production is uncertain until the last moment, and as electricity trading takes place the day before delivery, the deviations between forecasted and actual production have to be balanced on short notice, which is costly [49]; The ISRES production depends on the location and as electricity cannot be transported easily, costs occur because electricity transmission is costly and good renewable energy sites are often located far from demand centres. Thus, the average economic value of electricity produced by ISRES is higher than if the same amount of electricity was produced at all hours of the day [39].

Electrical systems need additional flexibility (new operational practices, storage, demand-side flexibility, flexible generators …) to be able to adapt them to the constraints induced by the variability of renewables, this adaptation has a cost.

A large review on the impacts of intermittency on the electrical grid management and extra-costs, based on more than 200 international papers was realized by the UK Energy Research Centre (UKERC). A cost tag is lied to each of these characteristics, to compare them economically [36] (Fig. 3).

Figure 3. The characteristics of variable renewable energy and corresponding cost components [36, 50].

The ISRES integration into power systems causes "integration costs" for grids, balancing services, more flexible operation of thermal plants, and reduced utilization of the capital stock embodied in infrastructure.

Variability, uncertainty, and location specificities involve specific costs and technical phenomena summarized in Table 2.

Previous studies defined integration costs as "an increase in power system operating costs" [51], as "the additional cost of accommodating wind and solar" [47], as "the extra investment and operational cost of the non-ISRES part of the power system when ISRES power is integrated" [49], as "the cost of managing the delivery of IRSES energy" [52], as "comprising variability costs and uncertainty costs" [53], or as "additional costs that are required in the power system to keep customer requirement (voltage, frequency) at an acceptable reliability level" [54].

Hirth *et al* [50], on the basis of a literature review on more than 100 papers, estimated the ISRES integration costs and suggested to divide it into three sub-costs, according to the ISRES power particularities as seen in Table 2 [55]: temporal variability, uncertainty, and location-constraints; these three "negative" effects can be reduced by a reliable forecasting.

Table 2. ISRES properties and corresponding integration costs in a market-based and an engineering-type framework [55].

ISRES Characteristic		Variability			Uncertainty	Location specificity
Definition		Wind and solar production vary over time			Real production differs from day-ahead forecast	Wind and solar production vary across space
Power System Perspective	**Impact on power system***	(1) Non-sequential: Shift of residual load** duration curve (RLDC)	(2) Sequential: RL varies more from one hour to another	(3) Intra-hourly: RL varies more within each hour	RL forecast error increases	Grid constraints become more binding; transmission losses increase
	Response	Shift generation mix towards mid/peak load ("economically flexible" plants)	Provide scheduled flexibility ("technically flexible" plants)		Provide contingency flexibility (short-term response)	Grid investments; re-dispatch incl. curtailment
	Impact on thermal plant operation*	Utilization of plants decreases ("utilization effect")	More flexible plant operation ("flexibility effect")	More spinning and stand-by-reserves ("uncertainty effect"		Re-dispatch Market splitting → regional utilization/flexibility effects
Market Perspective	**Economic importance**	Electricity is not a homogeneous good over-time (storage constraints)		Short-term response is costly		Electricity is not a homogeneous good across space (grid constraints)
	Corresponding market	Day-ahead spot market		Intraday and balancing power markets		Nodal spot markets (or grid fees)
	Price impact	Hourly price structure changes (e.g. lower prices during times of high NPRE in-feed)		Regulating power/ balancing price increases		Locational price structure changes (e.g. lower prices at nodes with much ISRES in-feed)
	Impact on ISRES value	Profiles costs		Balancing cost		Grid-related costs

* Impacts on the power system and thermal plant operation for large-scale ISRES deployment. At small scale, the effect could be the opposite, e.g. a reduction of hour-to-hour variation of residual load due to positive correlation of ISRES generation and demand. The terms "utilization effect" and "flexibility effect" are from Nicolosi [56]

** Residual load = net load = load - ISRES production (see paragraph 2)

The largest integration cost component is the reduction of utilization of the capital embodied in the power system. The ISRES requires flexible thermal plants (easy to start, with a rapid starting, a high ramp rate and a large work range) [7], but even more so they require plants that are low in capital costs.

These over-costs can also be divided into costs due to “system balancing impacts” and “reliability impacts”, the first one relative to rapid short term adjustments for managing fluctuations from minute to hour and the second one to the uncertainties of production [13,53].

The effect of the merit order on the ISRES kWh price vas analysed by Hirth [57] who shows that the kWh price is all the more decreased than the installed ISRES capacity is high.

In view to compare the costs, all the moneys were converted in euro with the conversion rate of the 1st January of the year of publication of the corresponding paper.

Numerous papers gave a cost for the ISRES integration or intermittence costs, in a large range of values because depending on the country, on the year of publication, on the renewable energy potential of the site, on the electrical network characteristics… some of these papers are a review of previous studies :

- in 2011, based on several studies and feedbacks from various countries [49], the balancing costs due to wind turbine integration for wind penetration of up to 20% was about 1-4 €/MWh corresponding on 10% or less of the wind energy kWh price. This range of prices was confirmed by a feedback in West Denmark, with the same cost for existing wind farms and from the Nordic day-ahead market between 1.4 and 2.6 €/MWh for a 24% wind penetration.
- in 2014, a large review showed that between all the impacts due to the introduction of ISRES into an electrical grid, only the increase of reserve has a consequence on the system cost of 1-6 €/kWh of ISRES [8], similar order of magnitude than previously.
- a more recent review confirmed the previous results [58] that the range of intermittence or balancing costs is large: from 0 to 6 €/kWh for costs estimated from models with a moderate increase with the ISRES penetration rate and from 0 to 13 €/MWh for observed costs with no influence of the penetration rate. These gaps seems to be lied to

the peculiarities of the national markets; the need of an improvement of forecasting is underlined for reducing these costs.

The ranges of integration costs are quasi similar for the three reviews: 0-6 €/kWh.

Higher costs were found: at high penetration rates, 30-40%, ISRES integration costs are found to be between 25 and 35 €/MWh, i.e. up to 50% of generation costs [50].

The cost of variability of solar thermal, solar photovoltaic, and wind by summing the costs of ancillary services and the energy required for compensating variability and intermittency were computed [59]; it depends on the technology and is estimated to 8-11 $/MWh (6.16-8.47 €/MWh) for solar PV, 5 $/MWh (3.85 €/MWh) for solar thermal and around 4 $/MWh (3.08 €/MWh) for wind systems. Variability adds about 15 $/tonne CO_2 (11.55 €/tonne) to the cost of abatement for solar thermal power, 25 $ (19.25 €) for wind, and 33-40 $ (25.4-30.8 €) for PV.

For wind energy systems, integrations costs between 1.85 $ and 4.97 $ per MWh (1.57-4.22 €/MWh) [60-61].

The "costs of intermittence" in Great Britain, are between 5 and 8 £/MWh (7.3-11.7 €/MWh) divided in 2-3 £/MWh (2.92-4.38 €/MWh) for short balancing costs and 3-5 £/MWh (4.38-7.30 €/MWh) for maintaining a higher system margin, the direct cost of wind production being around 30-50 £/MWh (44-73 €/MWh) [13]; thus, the intermittence cost represents about 16% of the kWh cost.

Based on independent systems operators, the integration cost for wind generators were found in the range of 0.5-9.5 $/MWh (0.34-6.46 €/MWh) [62]. The sub-hourly variability costs for 20 wind plants was 8.73 $±1.26 $ (5.93 €±0.86 €) per MWh in 2008 and 3.90 $±0.52 $ (2.81 €±0.37 €) per MWh in 2009 [53].

The Bonneville Power Administration [63] established a wind integration charge of 2.85 \$/MWh (1.94 €/MWh) [61,63] and added a tariff of 5.7 \$/MWh (4.8 €/MWh) for wind plant in view to recovering the integration costs [64].

For photovoltaic plants integration, the literature is poorer and the calculated integration costs equally different:

- the solar variability increases the PV power cost by about 12 \$/MWh (about 10 €/MWh) [65].
- for a large-scale PV solar plant on the Tucson, Arizona, and for a 20% solar generation, the social cost was estimated at 138.4 \$/MWh (113.53 €/MWh) with the unforeseeable intermittency representing only 6.1 \$/MWh (5 €/MWh) [66] i.e. half of the previous value.

The impacts on the production of fuel generators from high penetrations of ISRES power (33% of generation) in the Western Interconnection of the United States were estimated in the WWSIS-2 study. More than one hundred cases and conditions were taken into account concerning the fuel generators (coal or natural gas) regarding hot, warm, and cold starts, running at minimum generation levels, and ramping. All the estimated costs were used to optimize commitment and dispatch decisions. High penetrations of ISRES leaded to cycling costs of 0.47 \$/MWh to 1.28 \$/MWh (0.36-0.97 €/MWh) per fossil-fueled generator, on average, i.e. 35 M\$/year to 157 M\$/year (26.6-119 M€) across the West, while displacing fuel costs saved approximately 7 G\$ (5.3 G€) [6]

6. Predicting for increasing the benefit of ISRES systems production.

As said in paragraph 2, the random production of ISRES systems causes stresses on the fossil fuel generators, increasing the fuel generator cycling, decreasing their efficiency at low operating regime and increasing the electricity production cost. Coal-fired thermal plants have the highest cycling costs and many combustion turbines can have significant costs as well. Hydropower turbines, internal combustion engines, and specially designed combustion turbines have the lowest cycling costs [16]. Combustion turbine are well adapted for peak production and can be started rapidly [7].

Wind and solar power forecasting allows to reduce the uncertainty of variable renewable generation. The use of forecasts helps grid operators more efficiently to commit or de-commit generators to accommodate changes in ISRES generation and react to extreme events (ISRES production or load consumption unusually high or low). Forecasts reduce too the amount of operating reserves needed for the system, reducing costs of balancing the system.

Thus, using variable generation forecasts, grid operators can schedule and operate other generating capacity efficiently, reducing fuel consumption, operation and maintenance costs, and emissions as compared to simply letting variable generation "show up" [67].

A COST Action (European Cooperation in Science and Technology) [68] on Weather Intelligence for Renewable Energies (WIRE, ES1002) realized a bibliographical study; concerning wind forecasting, the final document underlined "even though the necessity and advantages of wind power forecasting are generally accepted, there are not many analyses that have looked in detail into the benefits of forecasting for a utility". However, some positive and important impacts were found in literature.

The uncertainty and/or forecasting error is a significant parameter in the integration costs [69]. The lack of a good forecasting implies to use larger energy reserves which cannot be used for other utilizations [70].

Today, forecast errors generally range from 3% to 6% of rated capacity for a prediction one hour ahead and 6% to 8% for a day ahead on a regional basis (higher errors for a single plant due to the aggregate effect). In comparison, errors for forecasting load typically range from 1% to 3% day-ahead [71], some progress stay to do. Day-ahead forecasts are used to make day-ahead unit commitment decisions and thus drive operational efficiency and cost savings. Short-term forecasts are used to take decision concerning a quick-start generator, demand response, or other mitigating option and thus drive reliability.

When forecasting errors are reduced, ISRES production is predicted with more confidence, then fewer reserves will be needed, reducing integration costs [67,72].

The importance of a good forecasts was stated by the operations manager, Carl Hilger, from Eltra [73]: "If only we improved the quality of wind forecasts with one percentage point, we would have a profit of two million Danish crowns." Also, for the Xcel Energy forecasting project, Parks [74] reported savings of 6 million US$ (4.5 million €) for one year alone for three different regions, an amount which significantly exceeds their investment. These two sentences, alone, illustrate, in some words, all the interest to predict.

CAlifornia Independent System Operator (CAISO) [75] is using a wind forecasting service since 2004, and all the other major ISOs/RTOs (Regional Transmission Organizations) currently utilizes wind forecasting services for reliability planning and market operations. He also began to experiment a solar forecasting, provided by AWS Truepower, a leading renewable energy project development and operations, for planning and market operations.

In the Western United States (WGA), a dozen of balancing authority areas, encompassing 80% of wind capacity, use forecasting [76]. Xcel Energy reduced its mean average errors from 15.7% to 12.2% between 2009 and 2010, resulting in a savings of 2.5 M$ (1.9M€) [76].

For GE Energy [77], the utilization of production forecasts reduced operating costs by up to 14%, or 5 billion $/year (3.45 billion €/year) corresponding to a reduction of operating cost of 12-20 $/MWh (8.28-13.6 €/MWh) of ISRES generation.

In Scotland, in 2008 [78], a survey of wind farm operators shows that only half of them forecasts their production on a day-to-day basis and they perceive the benefits around 4.50 £/MWh (6.93 €/MWh). The minimum size to justify the forecasting expense was 100 MW but will be able to reach 10 MW rapidly.

For a 35% ISRES penetration, using a day-ahead generation forecasting reduces annual operating costs by up to 5 G$ annually (3.6 G€), or 12 to 17 $ (8.64-12.2 €) per MWh of renewable energy [79].

The influence of an improvement of the forecasting reliability in the integration cost have been studied in numerous papers:

- a 1% MAE (Mean Absolute Error) improvement in a 6 h-ahead forecast had relatively modest influence with an reduction of 972 k$ (748 k€) on 6 months (0.05% of the total system cost) and a decrease of wind curtailments of about 35 GWh [80].
- a similar study realized on the basis of the Irish electricity system with a wind penetration of 33% [81], concluded that an improvement from 8% to 4% in MAE saved 0.5% to 1.64% the total system costs and induces a curtailment reduction of 9%.
- a wind forecasting improvements of 20% doubled the savings compared with a 10% improvement [71] (Fig 4). Moreover, at low penetration levels (up to 15%), savings are modest and for higher penetration levels (e.g., 24%); the savings is not linear versus the forecasting improvement as noted also in [79]. In Fig 5, the 100% perfect forecast is not possible but shows the maximum possible benefit of a good forecasting on the operating cost [71].

Figure 4. Average annual operating cost savings versus wind penetration, for 10 and 20% wind forecast improvements [71] (1$ = 0.75€).

Figure 5. Average annual operating cost savings versus wind forecast improvements, shown for 3, 10, 14, and 24% WECC wind energy penetrations(1$ = 0.75€) [71].

The effects of a 100% perfect forecasting was sometimes studied and can be used as a reference:

- operating costs were reduced by 5 billion $/year by using a forecasting method and an additional reduction of 500 million $/year (345 million €/year) [77] could occur if the ISRES forecasts were perfect (10% improvement).
- a perfect forecast would reduce operating costs in WECC by an additional 1 to 2 $ (0.72-1.44 €) per MWh of renewable energy compared with the forecasting method used [79] (8.3-11.8% improvement).
- based on several wind integration studies, Table 3 [76,79] summarizes the reduction cost due to a day-ahead wind forecasting (between 20 million $ and 510 million $ per year (14.4-367 million €)). A perfectly forecasted output, should save again 10 million $ (compared to 510 million $) to 60 million $ (compared to 180 million $).

Table 3. Projected Impact of Wind Forecasts on Grid Operating Costs [76, 79].

			Projected Annual Operating Cost Savings		
	Peak Load (GW)	Wind Generation (GW)	State-of-art forecast vs. no forecast in M$ (M€)	Additional savings from in M$ (M€)	Gain perfect forecast vs. State of art forecast (%)
California	64	7.5	68 (49)	19 (13.7)	+27.9%
	64	12.5	160 (115.2)	38 (27.4)	+ 23.7%
New York	33	3.3	95 (68.4)	25 (18)	+26.3%
Texas	65	5.0	20 (14.4)	20 (14.4)	+100%
	65	10.0	180 (130)	60 (43.2)	+33.3%
	65	15.0	510 (367)	10 (7.2)	+1.9%

For PV systems, using National Renewable Energy Laboratory (NREL) Solar Power Data for Integration Studies, a similar study [82] was realized in considering 7 scenarios: (1) No solar power, (2) no solar power forecasting, (3) with solar power forecasting, (4) 25% improvement, (5) 50% improvement, (6) 75% improvement and (7) Perfect solar power forecasting—100% improvement. The main conclusions were (Figure 6):

- with a 25% solar power integration rate in Independent System Operator New England (ISO-NE) and the use of forecasting methods, the net generation costs is reduced by 22.9%; Net Generation Costs = Fuel Costs + Variable Operations and Maintenance Costs + Start-Up and Shutdown Costs + Import Costs – Export Revenues;

- without forecasting, this reduction is only 12.3% with an over-commitment of generation and a higher solar power curtailment.
- with an 25% improved forecast, the net generation costs are further reduced by only 1.56% and no significant savings are realized for further improved;
- a better solar power forecasts or sub-hourly timescale could still provide additional savings.

Figure 6. Net generation cost and solar power curtailment (1 $=0.73 €) [82]

The utilization of a forecasting method for a temporal horizon up to 75 min for a 1 MW PV power plant reduced the flexible energy reserves by 21% (5 min) and 16% (15 min) compared to the persistence model and to reduce the probability of imbalance by 19.65% and 15.12% [83]. The forecasting improvement on the operating reserve shortfalls (insufficient generation available to serve the load) and on the wind curtailment (due to overproduction of wind turbine or electrical congestion) was estimated [71] (Fig 7).

Figure 7. Reserve shortfalls (a) and Percentage reduction in curtailment (b) with improved Wind generation forecasts for the 24% WECC wind energy penetration case [71].

Improved wind generation forecasts reduce the amount of curtailment by up to 6% and increase the reliability of power systems by reducing operating reserve shortfalls. A 20% wind forecast improvement could decrease reserve shortfalls by as much as 2/3 with 24% wind energy penetration.

Rarely the case of Concentrating Solar Power (CSP) is studied and direct normal irradiance forecasts are rare; a study [84] was realized for the 50 MW CSP system Andasol 3 in Spain and concluded that the use of a statistical forecast model reduced the amount of penalties (due to day-ahead market) by 47.6% compared with the use of a simple persistence model.

7. Conclusion

Solar and wind forecasting should be the first response to manage the variable nature of solar or wind energy production, before the more costly strategies of energy storage and demand response systems would be put in place. Furthermore, once a forecasting system is in place, it provides additional benefits through the optimized use of these demand-side resources.

Even if the various studies analysed in this paper show a wide disparity about the integration costs, due to definition of costs and calculation methods, due to applications to various situations, various back-up systems, various integration rates, various meteorological conditions, some general conclusions can be drawn:

- the integration costs due to intermittence and variability of the production result from the non guaranteed ISRES production imposes to electrical grid manager to take specific measures for maintaining the production/load equilibrium. Some of these measures have a negative impact on the operation of other energy production means;
- these integration costs includes various sub-costs for which a good prediction of the production has not the same influence;
- these integration costs depend on the ISRES integration rate in the electrical network: more the integration rate is high, more the integration cost is important and more the influence of a good forecasting will benefit.

A reliable forecasting method both for wind and solar production will have very positive influence on:

- the reduction of the integration costs;
- the decrease of the average annual operating costs;
- the decrease of the reserve shortfalls;

- the increase of the percentage reduction in curtailments of PV systems or wind turbines.

The improvements effects of a good forecasting depend of the integration level of the renewable systems in the electrical network.

The improvement of the adequacy of the forecasting methodology was also studied (from 0 to the theoretical value of 100%): beyond a given percentage of improvement of the forecasting model, his influence is reduced.

This review illustrates too that current state-of-the-art forecasts are likely to achieve most of the economic benefits possible and that the interest for forecasting is increasing even for small or medium ISRES. The energy storage development needs specific operating strategies for an optimal management which cannot be developed without a good knowledge of the future input and output energies.

Acknowledgement: This work was carried out in the framework of the Horizon 2020 project (H2020-LCE-2014-3 - LCE-08/2014 - 646529) TILOS "Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage". The authors would like to acknowledge the financial support of the European Union.

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Figure 2. Prediction scale for energy management in an electrical network [10-11].

Figure 2. Relation between forecasting horizons, forecasting models and related activities [11, 24]

Figure 3. The characteristics of variable renewable energy and corresponding cost components [36, 50].

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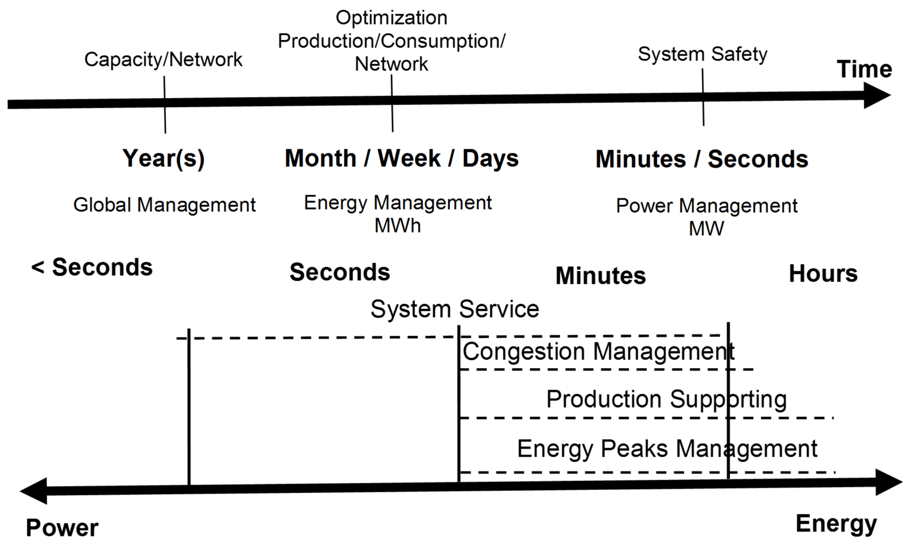

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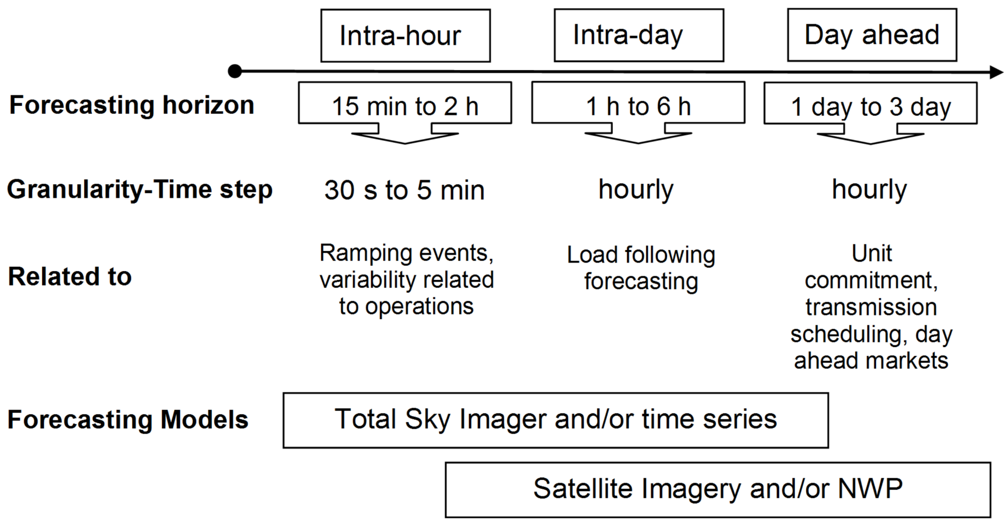
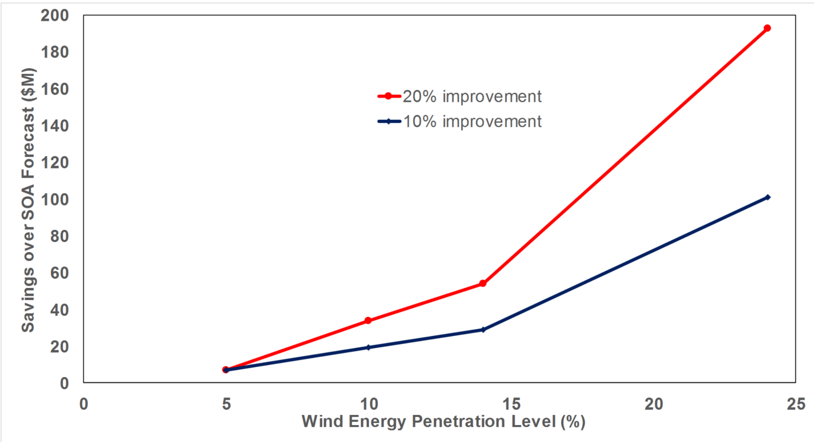


Figure 2. Relation between forecasting horizons, forecasting models and related activities [11, 24]

Output is **fluctuating**	Output is **uncertain**	Bound to **certain location**
• Wind speeds and solar radiation vary over time • Electricity is not a homogeneous good over time (storage constraints) • Thus its value depends on ***when*** it is produced	• Winds and radiation are uncertain day-ahead • Adjusting generation on short notice is costly (ramping constraints) • ***Forecast errors*** are costly	• Resource quality varies geographically • Electricity is not a homogeneous good across space (grid constraints) • Thus its value depends on ***where*** it is generated
“Profile costs” (“shaping costs”)	**“Balancing costs”** (“imbalance costs”)	**“Grid-related costs”** (“Location/infrastructure costs”)

Figure 3. The characteristics of variable renewable energy and corresponding cost components [36, 50].



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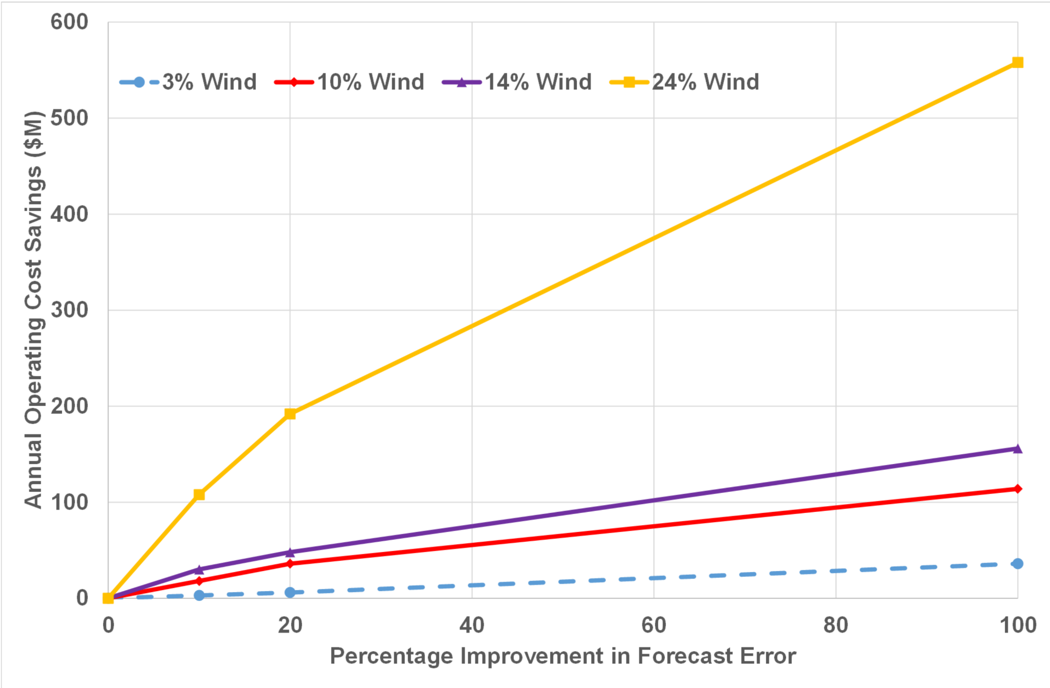

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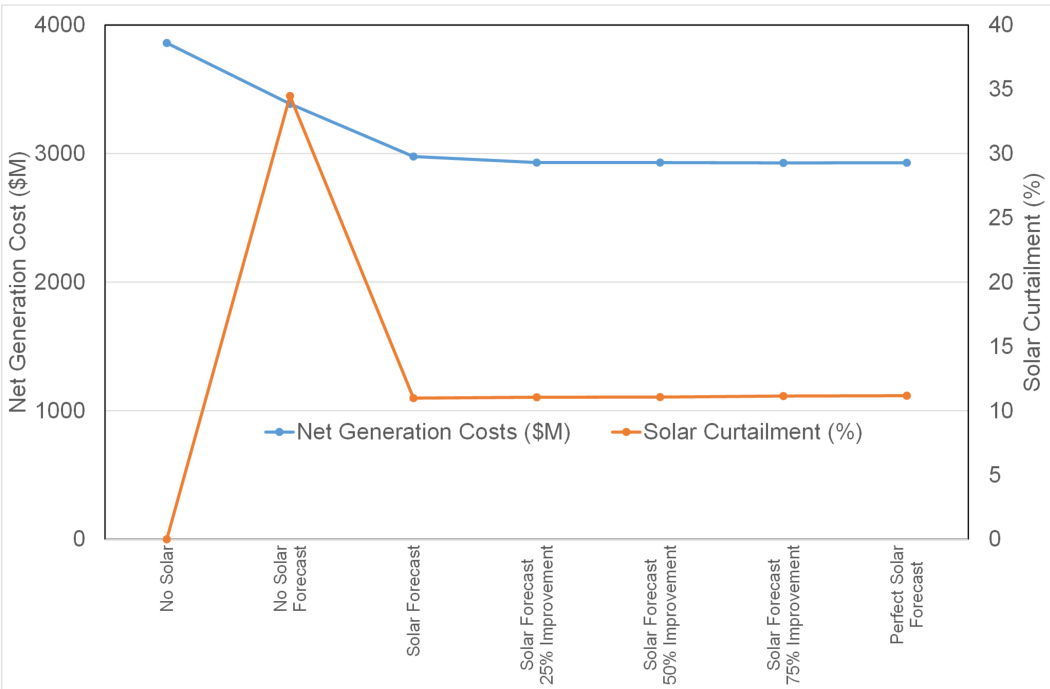

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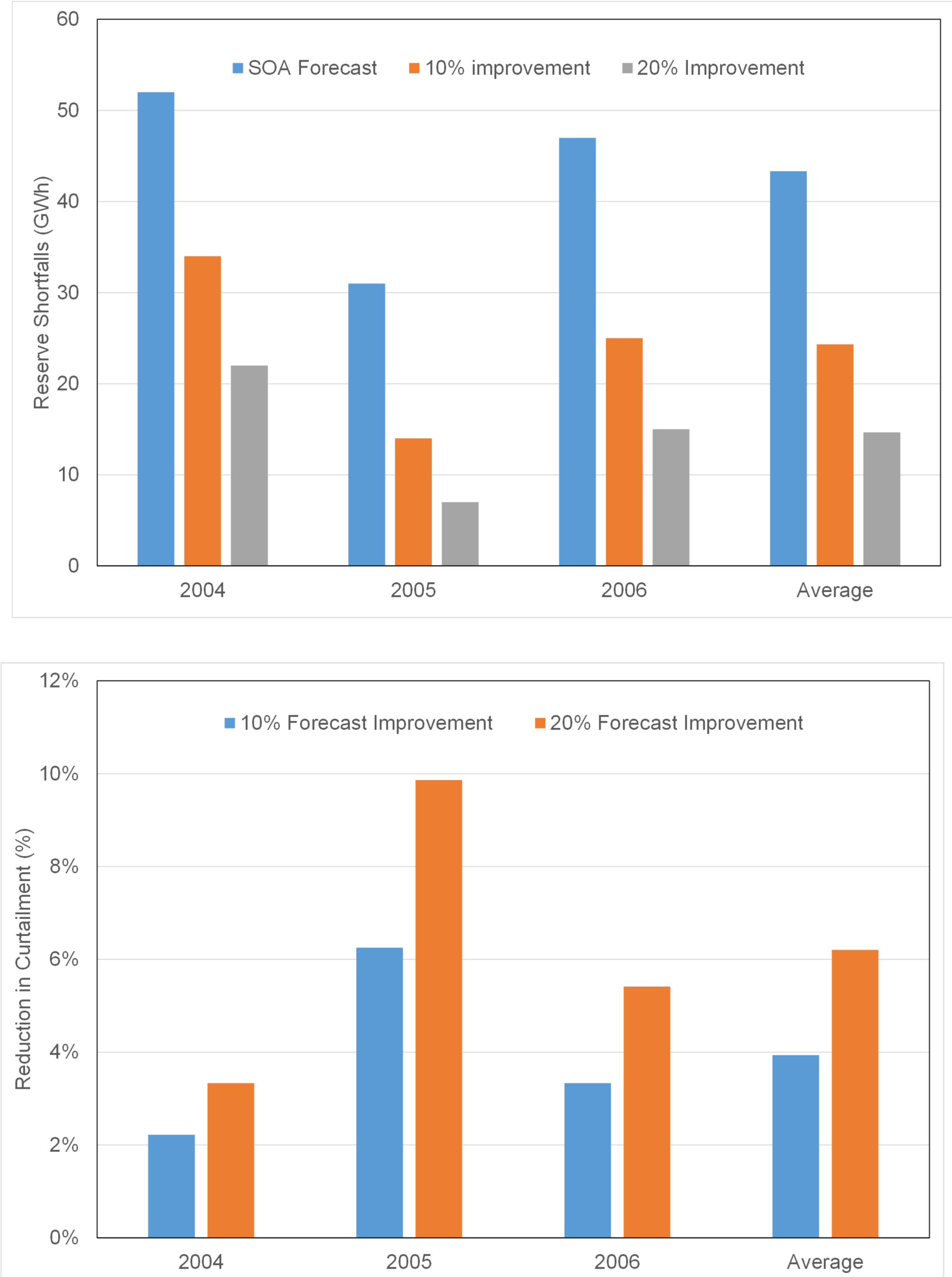

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