High Penetration PV in Power Systems Outcome of the IEA-PVPS Task 14's Subtask 3

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ABSTRACT: During the past four years, national experts from 11 institutions around the world have worked together within Subtask 3 – High penetration solutions for central PV generation scenarios – in order to identify best practice scenarios for a technically and economically improved grid integration of PV focusing on aspects at a power system level.
The study, in order to envision the future PV penetration into a power system in the scope of transmission system level, reviewed the impacts of PV Penetration, the countermeasures for system operation and augmentation planning, and market design including the impact of other variable renewable generation. The study also reviewed the state-of-art methodology of power system operation planning and augmentation planning.

Keywords: photovoltaic, grid integration, transmission grid, flexibility, diversity, market, planning

1 INTRODUCTION

PV generation, one of the RE generation with variability and limited-predictability, different from the traditional thermal and reservoir-type hydro power generation whose output is fully controllable (dispatchable), varies periodically in a year and in a day, and irregularly due to weather condition. The large penetration of PV generation will cause the issues not only of voltage and power flow fluctuation in a local distribution system ,but also of the demand-supply balance of a whole power system, which will result in the problems including frequency fluctuation and difficulty of demand-supply management.

Accordingly, in order to realize high PV penetration to a power system, it is crucial to evaluate the impact on its operation planning and augmentation planning, to envision the future power system. In the planning of operation and augmentation, it is necessary to identify gaps in current PV system technology and electric power systems, to analyze, how large numbers of PV installations can be successfully integrated to a total power system including the technology of smart grids.

This subtask deals with the PV integration to power systems from the total power system view point, based on the PV generation forecasting, power system operation and power system augmentation

The current study has mainly focused on the system level aspects of demand and supply balancing of a power system assuming a strong transmission system, although limited amount of description about the aspect of issues of transmission congestion and the requirement of reinforcement and expansion of transmission network is found in this report.

Section 2, 3 and 4 discuss the impacts of PV penetration and countermeasures including demand activation. Section 5 covers the impacts of other renewable generation. Section 6 discusses the state-of-the-art technology for system operation planning and system augmentation planning.

2 IMPACTS OF PV PENETRATION

2.1 Power System

Electric power systems have a various scale ranging from a system of several hundred Giga-Watt class of developed country on a continent, a system of tens Mega-Watt class on an island, to a system of several tens Kilo-Watt class in a rural area in a developing country. The mission of a power system is to deliver power to a demand in a cost effective, reliable manner to support quality of life, industrial production and social activities.

A commercial power system, being alternating current system, transmit and distribute power to a demand utilizing various voltage levels dependent on distance and capacity, using a transformer to connect subsystems of different AC voltages with power plants and demands. The impacts PV penetration on a power system comes with the variation and limited predictability of PV generation, and the reduction of the operational amount of dispatchable generators.

In the system level, integration of PV into a power system arises various challenges in a system operation and, accordingly, in a system augmentation. Among the challenges, the matching between demand and supply is the most typical impact when PV, or a variable renewable generation, penetrates into a power system to have a substantial share in the market.

2.2 Balancing Operation and generation dispatch

The total power demand, which reflects all the changes of all the individual demands, changes during a day, a week, and a year. In the current power system, where dispatchable thermal and hydro generation have a substantial share, the balance of demand and supply is made by controlling the generation of the dispatchable generators in a demand-and-supply balancing area. When the balance is lost or insufficient, the power system frequency (nominally 50Hz or 60Hz) or the system voltage of a power system will fluctuate and the supply quality is reduced or, in a worst case, a blackout occurs because many of the devices in a power system including power plants, which are designed to operate within a specified range of frequency deviation, are disconnected from the power system.

In order to keep the balancing in a power system, it is necessary to schedule generation of each dispatchable generation unit. In a power system, the balancing between demand and supply is realized through sophisticated generation schedule to make the best use of the features of each generation unit and system: the balancing hourly through generation unit start and stop scheduling, the balancing in minutes through centralized automatic generation control to specify generation each unit, the balancing in seconds through independent governor control of each unit, and the remaining mismatch is transformed into a fluctuation of system frequency. Because the balancing requirements change by time, by day, by season, as the demand structure, supply structure including the share of variable renewable generation such as PV changes, the key concept to accommodate large amount of variable PV generation is the flexibility of a power system to cope with the balancing. (The flexibility will be discussed in Section 2.2 and 2.3.)

2.3 Power System Operation Planning)

Under a set of operational conditions such as composition of generators, generator characteristics, automatic generation control and economic load dispatch, an operator plans a generation schedule typically for the next day. In the schedule, start and stop timing and generation level of each generator are decided to fit the predicted demand of various levels during the day. The operation plan of a power system, called as unit commitment, is a result of large-scale optimization planning considering economy, stability and security of the power system operation. The economy is mainly dependent on the operational cost of each power plant including fuel cost and generation efficiency of a thermal unit. The operational stability is mainly with the total capability of all generators to change its output. The security is kept through the reserved generation units which may work in a sudden increase of demand or in a sudden loss of generation due to a generation failure. If there is enough balancing capability in a power system, it may be necessary to curtail the variable PV generation to secure the stability of the system operation, even reducing the economy of the system.

In the context of operation planning, the natural variation of PV generation increases the requirement demand-and-supply balancing capability of a power system which results in partial operation of power plants. The uncertainty of PV generation requires additional operation of generation units with lower economy in preparation for the event of reduced PV generation. These changes bring about the reduced economy of the existing generators and the increase of stresses of the generators.

There are many countries where electricity is traded in a power market. The trades are made for various, short or long time frames. In the competitive circumstances, the plan of unit commitment is decided partially in the market. In the unit commitment including the power market operation, PV forecast plays a crucial role to decide the performance of a power system operation.

In the power system operation planning, in order to keep the viability of the analysis, we need to include the parameters such as maintenance schedule of power system elements.

2.4 Power System Augmentation Planning)

In years, demand and generation mix changes in a power system. In order to reduce CO_2 emission in the energy sector, it is widely recognized that energy demand will increase as economy grows in general, the existing power demand will reduce through energy efficiency, much of energy demand will be electrified, and more energy is supplied by variable renewable generation, which leads to a larger power demand and supply structure with more variable renewable generation share including PV.

In the current practices of power system augmentation planning, a planner, following criteria such as economy, reliability, environmental, stability and security, optimize the future power system. When a power system augmentation is planned including RE such as PV, it is usually aimed to find the optimum path to integrate RE into a power system.

In order to support such a future power system, the power system augmentation planning must have the new functionalities so as to accommodate substantial variable renewable generation, satisfying the existing planning criteria and constraints. The impacts PV penetration on the power system comes with the variation and limited predictability of PV generation, and the reduction of the operational amount of dispatchable generators. Possible countermeasures include improvement of load following capability and reduction of minimum operation of existing and new thermal and hydro generators, improvement of PV forecast, demand activation (see Section 2.3) and utilization of energy storage including a pumped storage power plant and batteries.

In the augmentation planning, there should be a set of indicators to evaluate a status of a power system in a specific time slice (for example, a year) and in a series of a period (for example from now to 2030). The indicator can be decided and based on the objectives of the augmentation planning such as energy security economic efficiency and environmental compatibility which supports the ultimate objective, sustainability. The indicator will be further discussed in Section 3.

In the power system augmentation planning, the parameters which are used in the operation planning are necessary to estimate the operational performance of each augmentation scenarios.

In the augmentation planning, the time horizon is the most important parameter. A major thermal generation needs several years of legal procedures and construction period. The distributed generators also need long time for the dissemination. The augmentation planning usually has 10 to 20 years of study period.

3 COUNTERMEASURES FOR VARIABLE RENEWALE INTEGRATION

The variability and uncertainty introduced by wind and solar generation technologies calls for a higher level of grid flexibility. The amount of flexibility needed to accommodate the introduction of new wind and solar facilities depends on the amount of variable renewable energy capacity and the existing flexibility in the system's infrastructure and operation. The most appropriate mitigation methods depend on economics and the characteristics of the specific grid, including the generation sources, infrastructure, and operational practices. This section describes a few of the methods that are generally recognized as efficient integration mechanisms, grouped in four categories: 1) System Operations, 2) Forecasting, 3) Market Design and 4) Planning.

3.1 Flexible resources

Increasing the flexibility of generation sources is one mechanism for addressing generation variability and ensuring the balance of demand and supply. It can be important to consider the flexibility of new generating capacity additions. It is also possible to enhance the flexibility of existing conventional generators to allow for quicker responses to changes in variable output. The flexible operation of conventional generators often results in increased fuel, maintenance and capital costs that will have to be balanced against the benefits of increased levels of renewable energy in the system.

Aside from flexible conventional generation sources, resources that enhance the flexibility of the system, such as storage systems and demand response, can help operators balance steep ramps. Fly-wheels, pumped-hydro storage and compressed air energy storage are examples of storage systems that are able to respond to dispatch requests at quicker rates. Demand response can reduce the costs of maintaining additional spinning reserves, particularly during extreme events of over- or under-supply of variable renewable energy power.

3.2 Geographical diversity

Geographical dispersion of supply can be helpful in smoothing the variability of renewable energy sources. Figure 1 shown below was produced by simulating the output of over 25 solar PV power plants located throughout a large geographical area (roughly half the size of Italy). The variability caused by cloud cover was reduced as the outputs of a higher number of solar plants were combined. The resulting output profile (shown in a solid, blue line), is not only more predictable and steady through the day, it also matches day-ahead forecasts more closely.

Similarly, larger balancing areas, with a larger pool of available generation and demand, will generally be more capable of integrating larger amounts of variable renewable energy sources. Variability in load and in generation can be smoothed out when balancing occurs over a larger area. Furthermore, large balancing areas can provide access to additional flexible generators than may be available in smaller areas. Combining adjacent balancing areas within the same synchronous area can be employed as a mitigation strategy to increase resilience and promote the integration of variable renewable energy sources in existing grids. Alternatively, cooperation across existing balancing authorities can achieve the same purpose through the optimized share of balancing activities between areas.

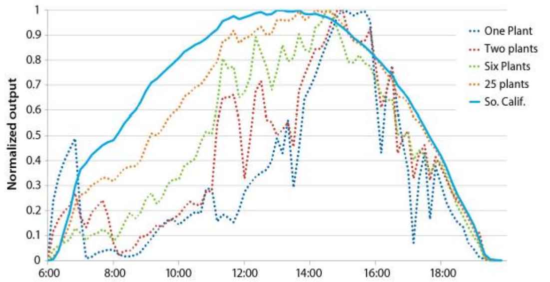


Figure: 1 The smoothing effects of aggregating PV plant outputs over various geographic areas.

3.3 Forecasting

Forecasting can reduce the uncertainty associated with variable renewable energy generation technologies. This allows generators or grid operators to plan ahead for generation service or balancing service variations in the output of solar and wind generators and reduce the level of operating reserves needed, thus lowering the cost of balancing the system. Short-term forecasts assist in the determination to dispatch quick-start generators, demand response mechanisms, or other methods to quickly balance demand and supply.

Forecasts are more widely used to predict wind power generation variability, but solar forecasting is emerging. Cloud movements are the primary cause for solar variability, besides diurnal cycles. Sky imagers can be used to produce short-term forecasts, whereas satellite images can be used to predict changes in solar power production over a span of a few hours.3.4 Market design

As the emerging challenges in several power markets where variable renewable generation has a substantial share, there are on-going many studies and discussions about the improvement of the power market design.

In our report, we discussed about sub-hourly scheduling and capacity markets. However, there are many discussions about the relationship between optimum power system operation and the market design.

Sub-hourly scheduling: Markets operating at an hourly schedule or using a fixed hourly energy delivery scheme are not as efficient at integrating larger levels of variable renewable energy sources, because they don't have enough flexibility to accommodate for wind and solar generation variability.

Markets operating at 5- or 15-minutes intervals are more efficient at handling both load and generation variability, and minimize reserve requirements. Additionally, some markets have adopted new ancillary ramping products to encourage generators to perform in a flexible manner and ensure sufficient system-wide ramping capability.

Capacity markets: Because solar and wind have very low marginal costs, they can bid at a very low price in wholesale markets and exert a downward pressure on electricity prices. In some markets, this can raise longer term concerns about the integration of large amounts of renewable energy because owners of other types of generators may not earn enough revenues and lose their ability to operate. Additionally, lower wholesale prices may reduce the incentives to build additional generation plants and consequently increase the risk of capacity shortfalls. Ideally, energy-only wholesale electricity markets should provide enough incentives (in the form of higher wholesale prices) for generators when demand outpaces supply. However, in markets where this is not the case or where regulators have capped wholesale prices to contain volatility, capacity and availability can be rewarded through a separate mechanism designed to incentivize the necessary level of installed capacity for the future. Capacity markets have emerged as a complement to energy-only electricity markets to compensate owners of dispatchable resources for guaranteed deliverability. Critics argue that capacity markets increase electricity costs over energy-only markets and commit future incentives to existing technologies, thereby limiting investments in alternative and innovative generation technologies.

3.5 Planning: Comprehensive Approaches

Comprehensive planning approaches that integrate transmission, distribution, generation and system performance goals, from distribution to bulk power system across an entire network, greatly facilitate and reduce the implementation costs of variable renewable energy integration. The coordination and integration of planning processes helps regulators prepare for the potential impacts that variable generation may have on the system and evaluate the available options to optimize generation and transmission costs.

Planning processes that integrate multiple jurisdictions facilitate transmission expansions and the geographic distribution of renewable energy sources. Integrating local and regional planning efforts helps promote the cooperation or enlargement of balancing authorities, diversifies demand and supply and eases the integration of higher levels of variable renewable energy generation.
Resource planning takes many different forms around the world. However, the experience in different countries shows that there are a few practices that can be applied in many different regulatory contexts. Three key principles that have been identified include:

1. Integrating the planning of generation, transmission, and system performance
2. Ensuring institutions and markets are designed to enable access to physical capacity
3. Building from local and regional planning to better integrate and coordinate information across jurisdictions (Cochran, et al. 2012).

Planning processes that optimize generation, transmission and other resources across an entire network greatly reduce the need and cost of variability mitigation mechanisms.

4 DEMAND ACTIVATION AND DISTRIBUTED ENERGY MANAGEMENT

As discussed in Section 2.2, we need to secure flexible resources to cope with the variability of renewable generation, and the traditional generation is the first and largest flexibility resource. However, when the share of variable renewable, the share of thermal and hydro power plants which currently provide flexibility to a power system, necessarily decreases. For the future, we are identifying new flexibility resources.

Demand has been used for demand and supply balancing since 1990's, being called as demand side management (DSM). The DSM has two areas of energy efficiency, reduction of energy, and load levelling, reduction of peak load. The load levelling is often called demand response, which means that a demand responses to a signal of cost, incentive or control. However, as far as it is a human who make a response to the signal, its acceptability and reproducibility are low and the effectiveness of DSM is limited. US DOE states about the Demand Response as "Demand response is a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized. ".

The demand response has been introduced in the field of an industry with resources of large DRs and also in the field of households and small businesses where is with the dissemination of smart meters. Recently, in line with the development of information and telecommunication technology, new devices are becoming available including, innovative distributed energy management systems such as HEMS (Home Energy Management System) and BEMS (Building Energy Management System). With these devices which can control appliances and equipment, it is expected that demands in houses, commercial buildings and factories can be "activated" automatically, for example, in response to a price signal. (See Figure 1)
Figure 2 depicts the concept to activate demand. Centralized energy management, which prepares unit commitment schedule for the next day, decides the hourly or time-dependent power prices for the next day using PV and wind generation forecast. The centralized energy management sends the power prices to a decentralized energy management such as HEMS at a house. The distributed energy management system optimizes the power use of the house for the next day by minimizing cost without reducing service level by scheduling the period of EV charging and water heating. In an urgent situation, air conditioner might be controlled to reduce the peak load. A battery in a building will be a good resource to provide additional flexibility at the demand side.

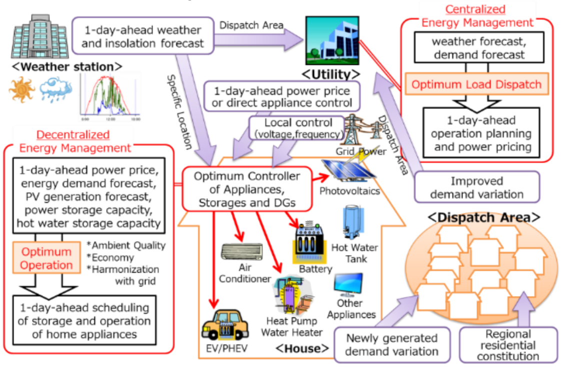
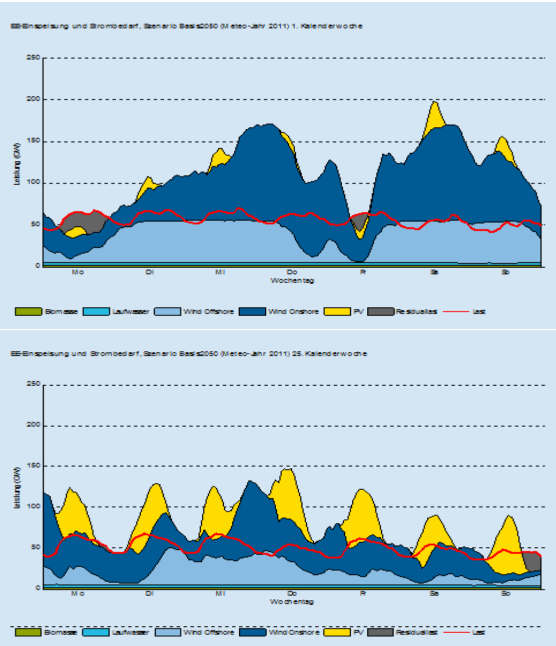


Figure. 2 The concept of Demand Activation

Electric vehicles, which are becoming popular these days, are emerging large power demands. The charging of EV which will tend to occur after each trip of individual cars will be one of the focuses of demand activation, because there is a certain allowance for charging period with each EV without reducing the service level.

There will be many other demands which have a potential to be activated. Demand activation will be an innovative and dominate countermeasure for the flexibility of a future power system. Its wide deployment will require large investment and various changes of technology, infrastructure, institution, economy, people's acceptance, security. For the substantial deployment of variable renewable generation such as PV, the activated demand is expected increase the flexibility which is necessary to balance the additional variation with limited predictability of PV generation. In order to follow the change of PV generation due to time and weather, one-day-ahead and real time pricing and responsive distributed energy management systems will be applicable.



Figures 3 a) and b): Exemplary weeks in a) winter and b) summer, based on a scenario for the year 2050, calculated with the meteorological year 2011. With the load (red curve) fluctuating around 50GW the need of conventional power production can be reduced to only a few hours per week by increasing the installed capacities of mainly wind offshore (light blue), wind onshore (dark blue) and PV(yellow).

5. IMPACTS OF OTHER VARIABLE RENEWABLE ENERGY

Wind energy is similarly to PV a temporally and spatially fluctuating electricity resource. Unlike PV wind power is also available during the night and is – in the Northern hemisphere – usually more abundant in winter than in summer.

Also, wind energy from offshore-wind farms usually generates more energy per installed capacity due to better wind conditions and thus can be regarded as an additional renewable energy option with unique characteristics.

In the future, the impact of supply characteristics of fluctuating renewables will dominantly determine how the energy sector will look like in respect to storage, load management requirements, back-up capacity and load factors of conventional power plants. Two weeks – illustrating a "normal" situation of supply and demand variations in a very advanced future energy scenario dominated by fluctuating RE is shown in Figure 3 a) and b) (left: week in winter / right: week in summer).

All three fluctuating renewable energy sources are important if impact on the energy system should be optimized. For Germany an analysis has shown that the residual load of the electricity sector is smoothest when different energy fluctuating renewable energy sources are combined. With residual load, the instantaneous electricity demand less the energy production from PV, wind energy on- and offshore is meant.

6. PLANNING METHODOLOTY: State of the art

6.1 Operation Planning

Under the increased variability and uncertainty due to PV and wind generation penetration, in order to preserve reliability in an economic way, it is crucial to improve the predictability and flexibility in the operation of a power system.

To take into account the above uncertainties, a methodology was developed by the research centre RSE on request of the Italian operator for renewables development (GSE).

Given the unit-commitment and dispatching of the conventional generators assessed in the sale/purchase session of the energy market and given the forecast of load and renewables PV and WIND, the steps of the assessment of the balancing reserve are:

- the uncertainty evaluation concerning the load demand, the wind and solar power generation, the forced outage risk of thermal units; and
- the probabilistic combination of the above mentioned uncertainties and the consequential evaluation on the needed balancing reserve to match the demand for a given confidence level.

Figure 4 depicts the basic flow scheme of the adopted methodology aimed to the balancing reserve calculation for one day ahead.

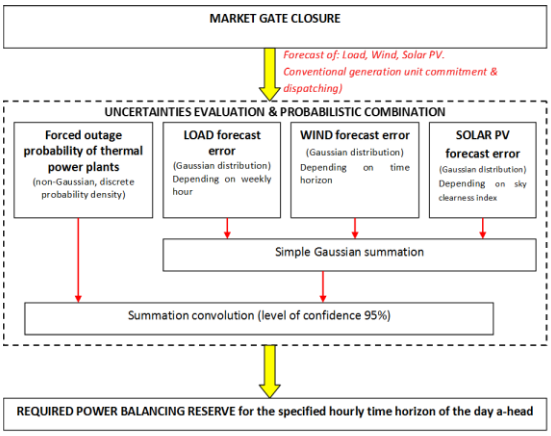


Figure 4: Flow scheme of the methodology for the evaluation of the hourly balancing reserve

Under the high variability and unpredictability, in a power system operation, it is crucial to assure reserve margin at a least cost and maximum reliability including the technical and regulatory measures discussed before.

6.2 Augmentation Planning

In the last few decades, the increasing penetration of variable generation technologies – most notably wind and solar – has required changes in the way the electric grid is operated. The daily and seasonal variability patterns observed in wind and solar technologies present a challenge to their efficient integration into existing electrical grids. Given the complexity of modern grids, it is necessary to employ computational simulation models to fully understand the effects of introducing increasing variable generation levels, devise effective mechanisms that facilitate their integration, and optimize costs.

The design and complexity of the optimal variable generation integration model will depend on the goals of each study, as well as the levels of added solar PV capacity. Some of the study components presented in this section may be omitted for studies looking at shorter time horizons, or relatively low levels of increased solar PV penetration, for example. Before designing a solar PV integration study it's important to consider its main goals. Examples include:

- Evaluating the costs of integrating variable renewable energy source into the system
- Identifying variable renewable energy integration impacts on grid operation
- Measuring the amount of variable renewable energy the existing system can absorb before changes in operation or physical configuration are needed

To address the complexity, the model structure can be divided in elements corresponding to relatively independent tasks as depicted in Figure 5. Modularity also helps scale the model complexity to match actual needs. Most solar PV integration studies will follow an iterative process where a few of the steps are repeated, using outputs from certain modules to modify previous assumptions, or as inputs for other modules.

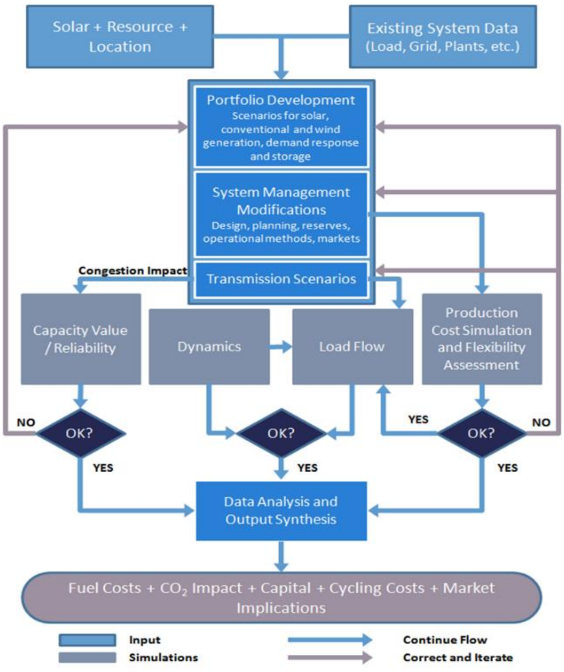


Figure 5: PV integration study recommended practices diagram.

7. CONCLUSION

Through the study, it has been revealed that the major issues of increasing PV penetration at transmission level is the demand supply balancing due to an increased variability of PV and other variable renewable generation and due to decreased flexibility of the traditional generation fleetness. The countermeasures are the additional flexible resources such as flexible generation, demand activation and geographical smoothing of PV generation by stronger transmission system including interconnections.

In order to optimize the utilization of the flexible resources in terms of economy and stable operation, generation forecast technologies have also a crucial role to play. To realize the best use of the power system technologies, power markets have been continuously improved including closer to real time gate closure time for bidding and shorter (sub-hourly) trade intervals. Capacity markets concepts, a market for generating capacities, emerge also as a compliment to the energy-only market in order to address remuneration issues.

The methodologies of power system operation and augmentation have been adapted to accommodate the flexible resources, geographical diversity, generation and demand forecast uncertainty and improved market designs. From the case studies member countries has shown the wide range of efforts for PV penetration including following aspects:

- PV integration studies with various levels of penetration targets under a variety of power system conditions, from a continent-wide system to an island or an area,
- Evaluation and optimization of new flexible resources based on the analysis of detailed operational impacts
- Research and Development of new flexible resources and system operation including generation forecast
- Optimization of a total power system operation and market design improvement
- Participation of many stakeholders such as regulators, TSOs (ISOs), utility, generators, manufacturers, research Institutes, consultancy companies and Renewables associations

For PV to become a major electricity source, power systems has to be transformed stepwise to facilitate the increased need for the flexibility. The required flexibility at each PV penetration level will be mitigated through the geographical and technological smoothing effect of the weather dependent PV variability. And there are a large numbers of existing and potential flexible resources including traditional generation fleetness, control of variable renewable generation, demand activation, innovative storage technologies, transmission lines and interconnection, innovative centralized and decentralized energy management, power markets evolutions, etc…

The case studies have shown that all stakeholders, including regulators, operators, manufacturers, researchers, power customers have been practicing their efforts to realize high penetration of PV through technological but also regulatory innovation. There are enough technological potential to accommodate the transition to a high PV penetration. But increased efforts will be required in the area of regulations including whole sale and retail market and centralized and decentralized operations so as to realize the optimum evolution of a power system.

ACKNOWLEDGEMENT

The study of the IEA Task 14 Subtask 3 have been supported by the specialists of all the participating countries.

REFERENCES

Complete list of the references are found in the coming report of the IEA Task 14 Subtask 3.