Online course

Power System Planning with Co-Benefits

Berlin, 2019-08-06

Contents

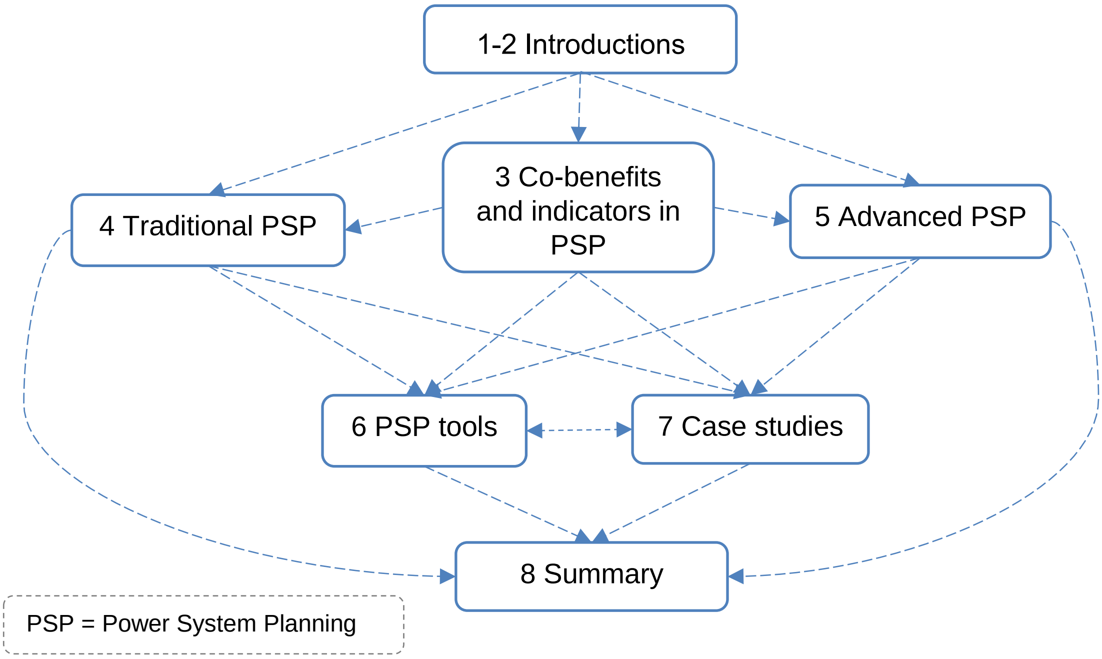
1. Introduction to the course

1.1 Learning objectives and approach to the course

Learning objectives: Upon completion of this course, you should be able to

- distinguish between traditional and advanced power system planning (PSP) approaches,
- compare tools used for power system planning and how co-benefits can be used during the planning process,
- explain how selected co-benefits of renewable energy, e.g. tackling climate change and the human health effects of ambient air quality, affect the outcome of power system planning.

The course is divided into seven chapters, which are shown graphically with their interactions in the following diagram, and further introduced below.



Course chapters and their interaction (Source: Mirakyan, 2019)

The **Introduction** (Chapter 1) presents an overview of the power system and its different planning categories. This will help to explain the complexity of the power system and its planning.

In Chapter 2 and 3, **Co-benefits and indicators in PSP**, the indicators and their roles in traditional advanced planning are discussed in detail.

Traditional PSP is presented in Chapter 4, which explains the main aspects of traditional PSP, including transmission planning. The chapter specifies the main planning stages and interrelations between different stages. The principles of the different load curve approaches are presented as a key planning element.

Chapter 5 focuses on **Advanced PSP**. It highlights the main effects on the power system of an increased share of variable electricity generation, for example from wind or solar photovoltaic (PV) systems.

Approaches to dealing with these effects are discussed. One of the potential solutions – flexibility – is selected and presented in more detail.

As a comparison and assessment of **PSP tools**, Chapter 6 provides a deeper overview of the existing commercial tools, using various aspects to characterise them.

In Chapter 7 several **case studies** are provided to demonstrate the practical implementation of PSP methodologies, tools and assessment of co-benefits.

In the last chapter, the key learning aspects are **summarised**.

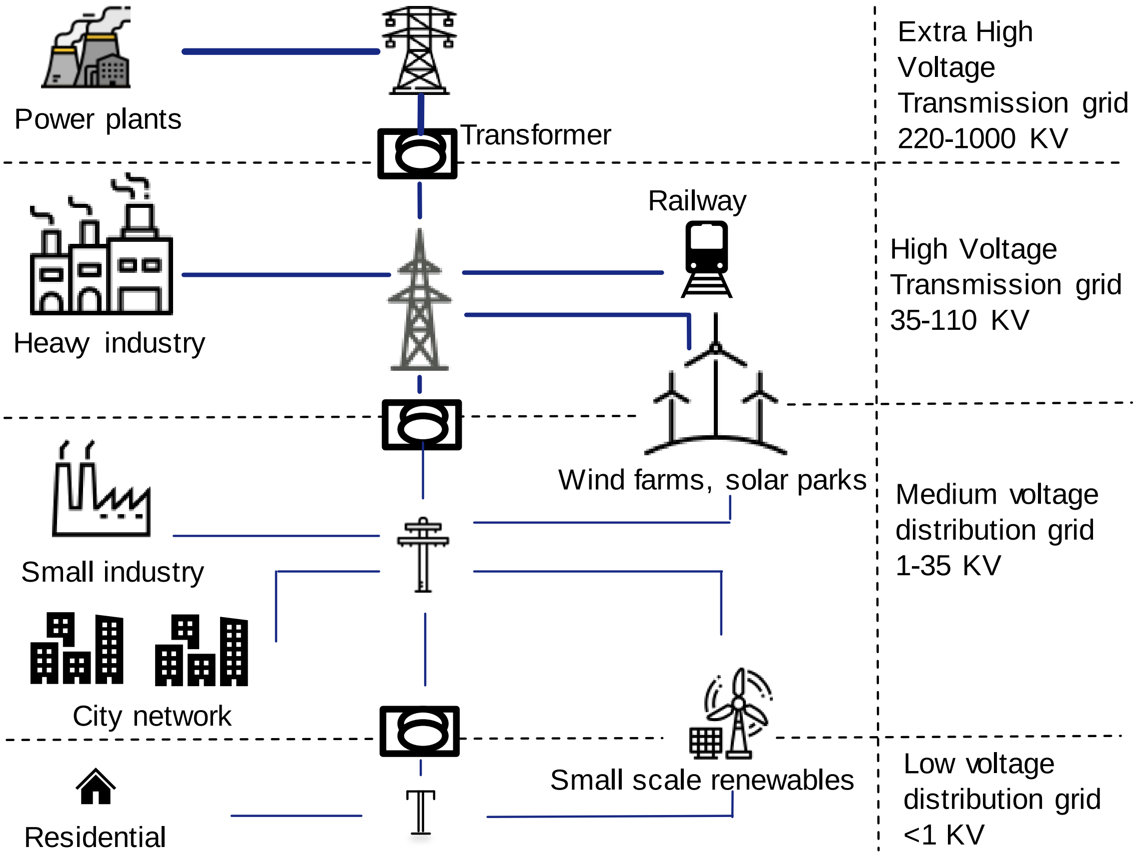
2. Introduction to the power system, its transition and planning

2.1 Integrated power system

Learning objectives: Upon completion of this page, you should be able to

- name and distinguish power system components in overall national or regional energy systems,
- localise the voltage levels of the grid for feed-in of electricity generated by wind or solar PV parks vs other types of large power generating stations,
- explain the main trends in the energy transition and expected changes to the power system.

The power system today consists of multiple elements for energy extraction and power generation, transmission, distribution and final use. The system transforms primary energy to useful energy in the form of power. The electricity grid is divided into transmission and distribution grids with different voltage levels (see the figure below of the European network). The **transmission grid** aims to transport electricity across long distances, thereby increasing overall system stability. The **distribution grid** aims to deliver power to the regional or local end user as final energy. [1]



Simplified view of the power system and the grid in Europe (Adapted from Perras, 2014)

The power system is in transition in many countries. This transition manifests itself in diverse ways, at the technological, economic and institutional or policy level [2], [3]:

- The number and diversity of power generation technologies are increasing constantly in many countries, in particular decentralised systems using renewable energy sources.

- Power is no longer flowing only in one direction, from centralised power plants to the consumer. It now also flows from one to another consumer changing the consumer to become a “prosumer”, besides consuming also producing electrical power.
- The amount of data from these numerous technologies is increasing, as is the intensity of data management.
- Interest is growing in the development of cross-sectoral solutions, such as power-to-gas or power-to-electrical vehicles.
- An increasing number of decision makers, with different interests and preferences, are participating in the planning process.
- Interest in and demands for sustainability are growing (in particular for reducing greenhouse gas [GHG] emissions, local atmospheric pollutants and the depletion of natural resources), whilst meeting the power needs of a growing and increasingly electrified population at lowest cost.

Due to these trends, PSP are facing increasing challenges, which in turn make the implementation of new planning approaches unavoidable.

2.2 Power System Planning (PSP) – the time horizon perspective

Learning objectives: Upon completion of this page, you should be able to

- distinguish between various categories of PSP according to the time horizon, context or system components considered,
- name typical questions addressed by different PSP approaches,
- appraise the time horizon for different PSP cases.

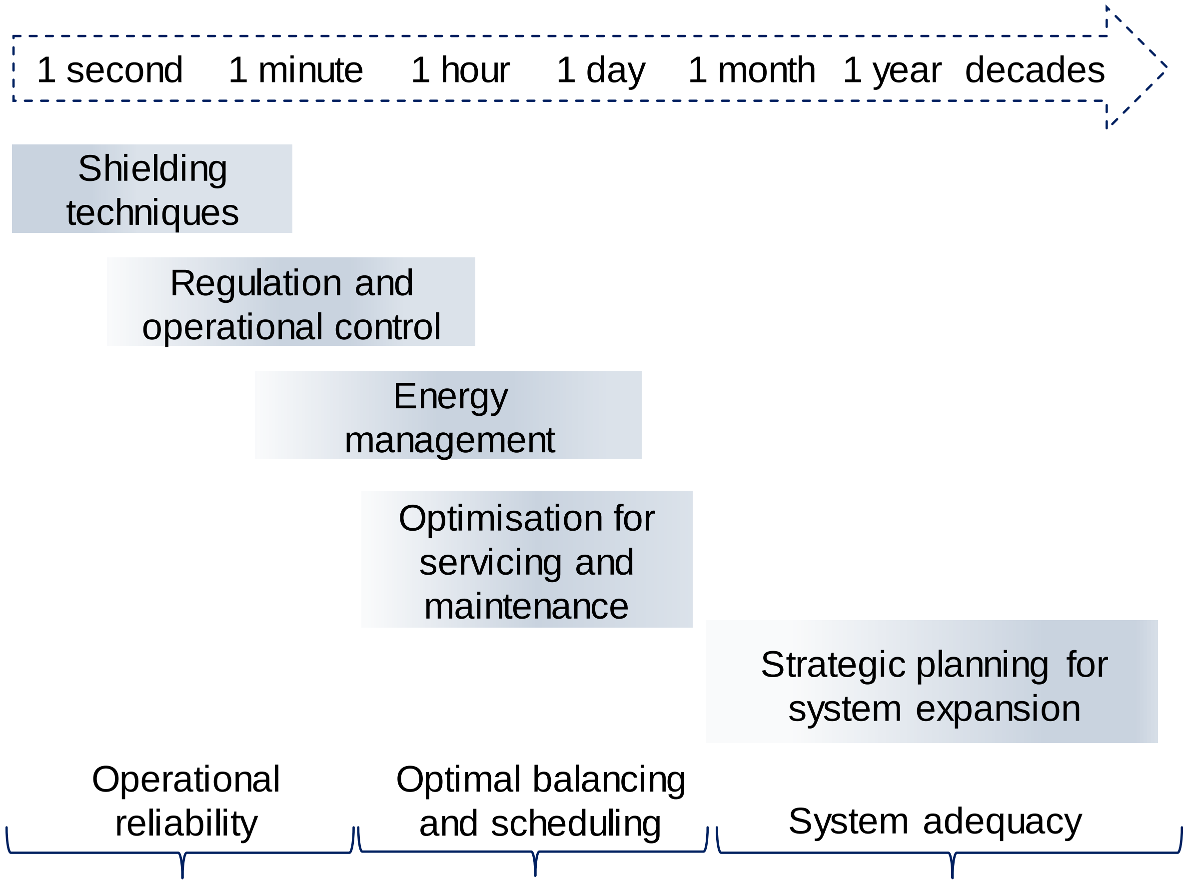
Different PSP activities are performed in the power industry depending on the system needs and associated time span.

Planning and control of **operational reliability** refers to a timescale of minutes and less. Techniques for **automatic shielding** of the system or planning for **optimisation of operational control** are implemented in this timescale. These are protection schemes to minimise damage to equipment and service interruptions resulting, for example, from equipment failures.

Optimal balancing and scheduling of the system operation covers minutes to days or months. Several activities for example the **optimisation of unit commitment and economic dispatch** are implemented to achieve the lowest possible power generation costs. Management of the power portfolio may include increased utilisation of renewables in view of constraints such as emissions limits, planning for the unavailability of power stations because of maintenance, and preparing for the intermittence of renewable energy resources. **Energy management** measures, such as demand response or adapting power consuming organisational / logistical activities of the final electricity user. The measures like shifting the starting time of school operation are implemented to reduce energy demand or to adapt it according to the availability of power generated by renewables.

System adequacy planning or strategic investment planning for system expansion or power generation capacity extension planning are performed to meet peak demand in the long term, from years up to decades, considering a range of constraints, for instance GHG emissions restrictions or the availability of critical power system components.

The figure below illustrates the timescales of the different planning tasks, extending from operational activities for the functional reliability of the system to strategic planning for system expansion. The planning activities and their timescales are not prescriptive and might vary according to circumstances.



Planning levels of the power system and their timescales from seconds to decades (Source. Mirakyan, 2019)

2.3 Chapter endnotes

[1]: Perras (2014)

[2]: Mirakyan (2013)

[3]: Howell et al. (2017)

3. Indicators and co-benefits in power system planning (PSP)

3.1 The role and meaning of indicators and co-benefits in PSP

Learning objectives: Upon completion of this page, you should be able to

- define the term “indicator” in the context of PSP,
- explain the different roles of indicators in PSP,
- understand the term “co-benefits” in the context of PSP,
- categorise diverse types of indicators in context of PSP.

An indicator is a measure that indicated the states of the system or its relation to environment. The indicators used in PSP play a key role in describing the power system, assessing and highlighting important relations between the power system and its environment, communicating information to policy makers and promoting institutional dialogue. Each set of indicators communicates the status of the power system and the consequences of choices that have been made and allows decisions to be made between different system development options.

Indicators have different dimensions depending on their purpose:

One dimension describes the **context**: for example, one set of indicators can be dedicated to *techno-economic* assessment, another can be for assessing the *social* context, and a third may assess *environmental* or *policy-institutional* aspects.

The second dimension is the **role** of indicators used in a given study. Some indicators may have a single role to play, being a *key objective* for PSP, such as minimisation of costs. Others may have co-roles as *co-objectives*, describing more than one aspect of the system or its interrelation with the environment, such as carbon dioxide (CO_2) emissions.

The third dimension is the **impact direction**. Some indicators might measure *positive* impacts, others *negative* impacts, or they might measure *no impac*t. **Co-benefits** are the positive effects assessed by co-objectives.

The fourth dimension is the **evaluation**. An indicator can be defined as an attribute, criterion or a target:

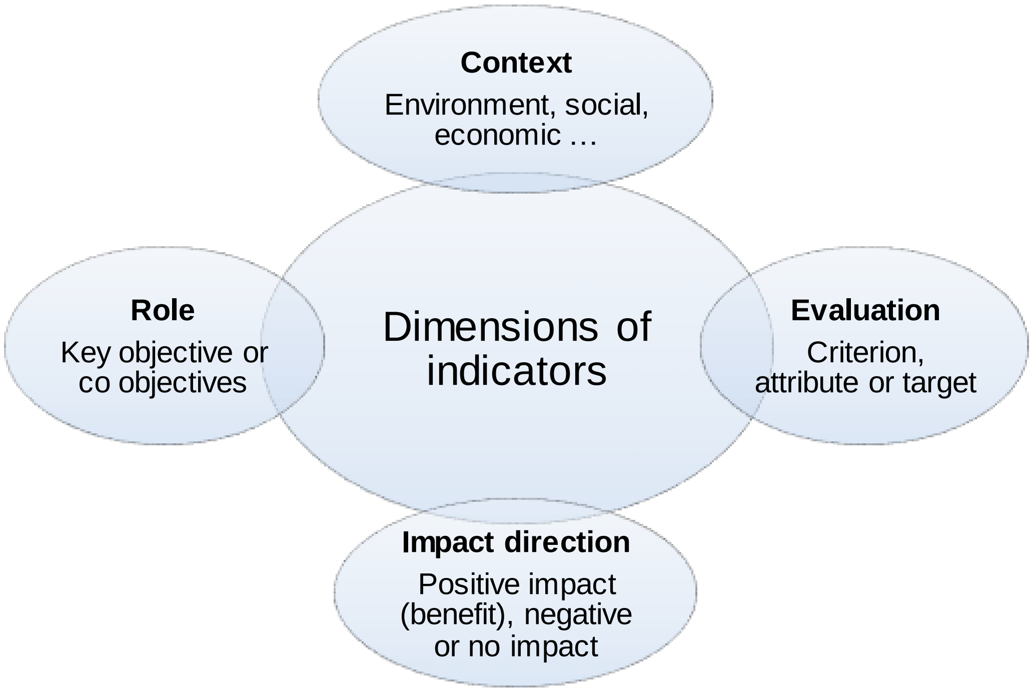
- *Attributes* are indicators or measures that have no limit on the range of their desirability. An example of an attribute can be the minimisation of the cost of the system operation.
- By contrast, *criteria* set limits to the range of acceptable values of a measure, such as a desirable voltage level. Criteria limits are usually set in regulations.
- *Targets*, like criteria, imply a limit to the certain value or range. However, targets have been used more for political or business purposes, and less for technical or regulatory reasons. An example of a political target can be “to achieve an 80% reduction in GHG emissions”.

Criteria or targets need to be met, while attributes need to be optimised.

The indicators that are selected will relate to what is being studied. Depending on the context, the same indicator can play diverse roles, with different dimensions in different studies. For example, for a certain study the **role** of an indicator “minimisation of the total delivered power costs” is a key objective, it is in an *economic* **context**, it is **evaluated** as an *attribute*, and it is expected to have a *positive* **impact**. In the same study “CO_2 emission reduction by 10%” as an indicator has the **role** of a *co-objective*, it is in the *environmental/climate* **context**, it is **evaluated** as a *target* or *constraint* in the minimisation algorithm and it is expected to have a *positive* **impact**, a *co-benefit* in that study.

There are several other co-benefits in climate policy, such as improved health, enhanced energy access, or protected biodiversity. [1]

The figure below presents the discussed dimensions of indicators.



Dimensions of indicators (Source: Mayrhofer and Gupta, 2016)

3.2 Key objectives and co-benefits in Traditional Integrated PSP (TIPSP)

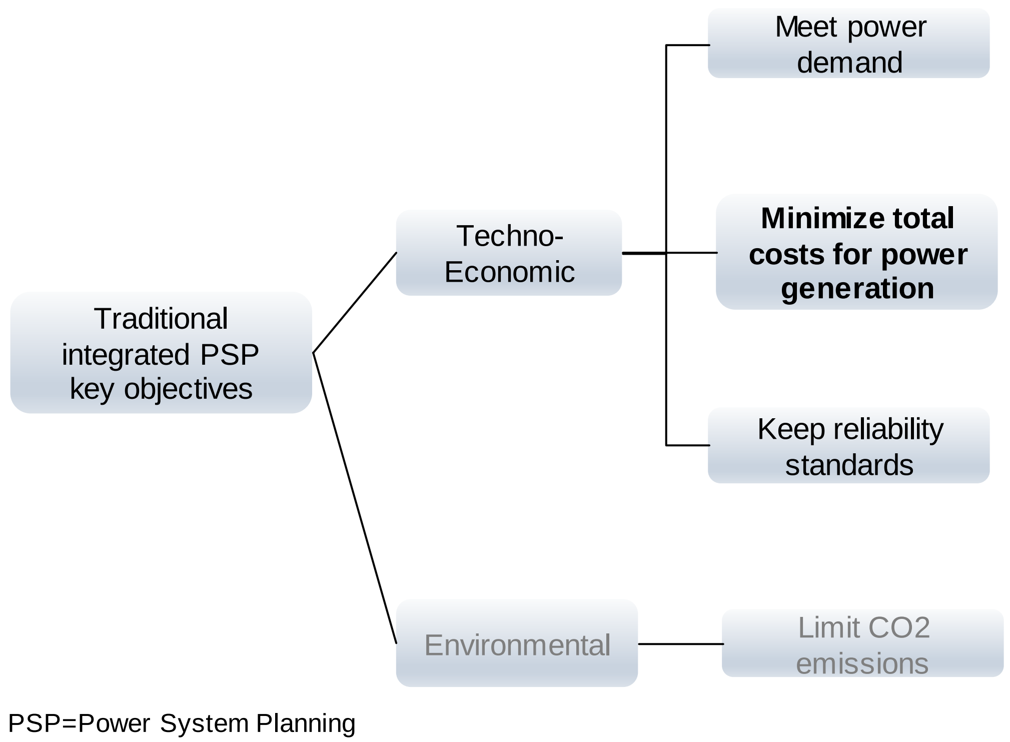
Learning objectives: Upon completion of this page, you should be able to

- define the term "Traditional Integrated PSP" (TIPSP),
- categorise several types of objectives in the context of TIPSP,
- summarise the commonly used objectives and co-benefits.

TIPSP can be defined as follows: **TIPSP** is an approach used to plan the expansion of the power system and the associated resources to meet anticipated demand growth with high reliability, and to minimise the total costs of system expansion. [2] Both the supply system and the demand side are considered in the planning process. However, the demand side is considered to be passive, without simultaneous demand response optimisation with the supply side.

More recently, CO_2 emissions have been incorporated as co-objective, or a constraint to optimising energy supply options in the planning process. The planning objectives can therefore be categorised into three groups: technical, economic and environmental. [3]

The figure below presents commonly used planning objectives in a value tree, organising the objectives into distinct groups and subcategories. TIPSP is mostly formulated as a single-objective optimisation problem, having a key objective – the minimisation of costs. Other indicators are co-objectives, which are mathematically formulated as constraints in optimisation studies. Such a co-objective is GHG emissions.



Main traditional PSP objectives (Source: Mirakyan, 2019)

The total costs of running the power system include capital expenditure (CAPEX) for new investments and operational expenditure (OPEX, for instance for fuels).

Not all GHGs – for example methane or nitrous oxide – are considered in TIPSP, but only emissions of CO_2, and in some studies only those emitted by conventional thermal power generation stations. (In the figure above, emissions are shaded in grey because they are not frequently considered in such planning studies. Other environmental objectives, such as reducing air pollutants, are hardly ever found in TIPSP studies.

Several reliability standards are considered in TIPSP, for example loss-of-load probability (LOLP). LOLP is the probability that power generators are not able to supply the given load level, for a given time frame. Another commonly used technical criterion is the (n-1) or (n-2) criterion. The principle of (n-1) or (n-2) means that systems are still reliable when one or two components fail. For example, in network planning the network remains (n-1) reliable even if one component, such as a transformer or a circuit, fails or is shut down at the same time. Additional transformers have to be considered. For power generation planning additional reserve power generation unit(s) equal to the biggest unit size of operated or planned power plants are included in the planning to achieve the (n-1) reliability.

3.3 Key objectives and co-benefits in Advanced Integrated PSP (AIPSP)

Learning objectives: Upon completion of this page, you should be able to

- define the term “Advanced Integrated PSP” (AIPSP),
- categorise several types of objectives in the context of AIPSP,
- summarise the commonly used objectives and co-benefits.

AIPSP considers the whole power system from resource, through power generation, transmission and distribution, up to final use. The special focus of AIPSP is the planning of a power system with a higher share of distributed generation from intermittent renewable energy sources, such as wind and solar PV. Compared to TIPSP, AIPSP incorporates a comparable number of indicators as objectives and co-benefits.

AIPSP can be defined as follows: **AIPSP** is an approach to find environmentally friendly, institutionally sound, socially acceptable and techno-economically effective solutions (best mix of power generation, demand-side measures, transmission and distribution options) to satisfy long-term anticipated power demand. It is a transparent and participatory planning process, an opportunity for planners to present complex, uncertain issues in structured, holistic and transparent way, for interested parties to review, understand and support the planning process and make decisions. (Adapted from [4])

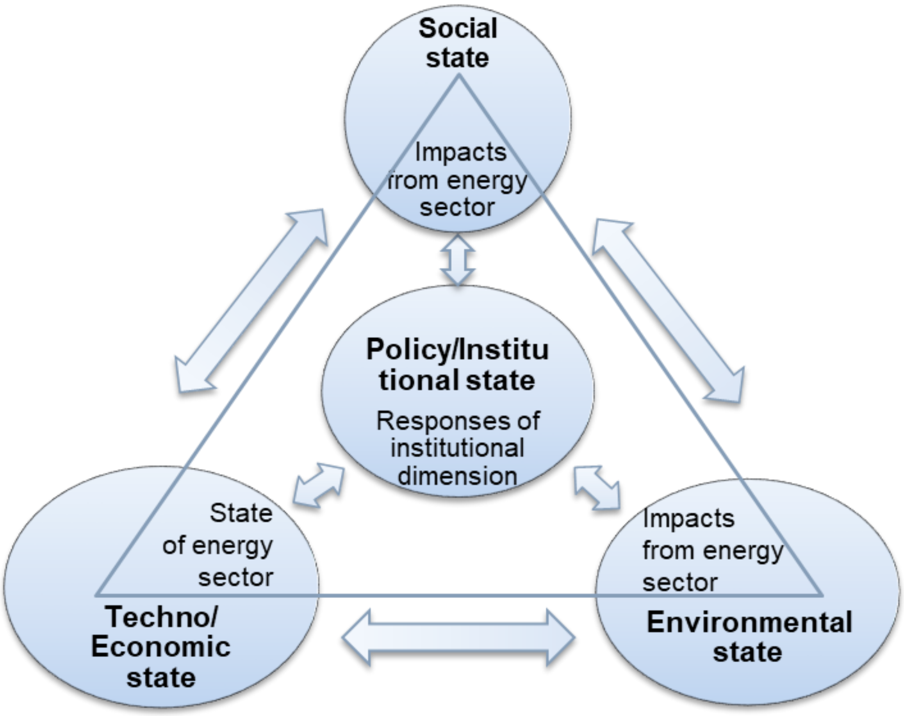
Thus, AIPSP has multiple objectives, and some AIPSP studies formulate the problem not as a single but as a multi-objective optimisation problem. The most commonly used indicators for quantifying the (co-) benefits can be derived from the work of the International Energy Agency [5], [6] and the experiences of RENAC. The list of indicators is presented in the table below.

Theme	Sub-theme	Indicators
Social	Accessibility	Share of households (or population) without electricity or commercial energy
	Affordability	Share of household income spent on fuel and electricity
	Disparities	Household energy use for each income group and corresponding fuel mix
	Health and safety	Accident fatalities per unit of energy produced by fuel chain
Environmental/ climate	Climate change	GHG emissions from energy production and use per capita and per unit of GDP
	Air quality	Air pollutant emissions from energy systems
	Water quality	Contaminant discharges in liquid effluents from energy systems, including oil discharges
	Soil quality	Soil area where acidification exceeds critical load
	Forest	Rate of deforestation attributed to energy use
	Solid waste generation and management	• Ratio of solid waste generation to units of energy produced • Ratio of solid waste properly disposed to total generated waste • Ratio of solid radioactive waste to units of energy produced • Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste
Techno-economic	Overall use	Energy use per capita
	Overall productivity	Energy use per unit of GDP
	Supply efficiency	Efficiency of energy conversion, transmission and distribution
	Production	Reserves to production ratio
	End use	Industrial/agricultural/commercial/residential/transport energy intensities
	Diversification (fuel mix)	• Fuel shares in energy and electricity • Renewable energy share in energy and electricity, or • Non-carbon energy share in energy and electricity
	Prices	End-use energy prices by fuel and by sector
	Employment	Induced jobs created due to economic stimulation
	Import security	Net energy import dependency
	Strategic fuel stocks security	Stocks of critical fuels per corresponding fuel consumption
Institutional/ policy	Political impact	Policy impact indicator expressed in the International Energy Agency World Energy Outlook
	Historical record of achieving targets	Number of achieving targets
	Existence/creation of institutions	Number of institutions created in a given year

Most commonly used energy indicators (Adapted from IAEA, 2005; Vera and Langlois, 2007)

Notes: Grey coloured indicators are the only indicators which have been frequently used in the traditional power system planning; GDP = gross domestic product; WEO = World Energy Outlook.

The dynamics among different indicators are presented in the figure below.



Interrelationship between energy indicators (Adapted from IAEA, 2005)

3.4 Objectives and co-benefits used in electrical network planning

Upon completion of this page, you will be able to

- list and distinguish between the main network planning objectives,
- explain different network planning objectives.

Electricity network planning objectives can be divided into several groups with many subcategories. For example, the table below provides the six main network planning objectives and explains their importance. [7] There are other criteria, such as local construction standards and choice of conductor, that are not presented in the table below.

Dimension	Network planning objectives	Explanation and comments
Criterion	Contingency	The contingency criterion establishes the minimum capability of the network to be reconfigured after a fault, so that the unfaulted portions of the network are restored.
	Steady state	The steady-state criterion sets the adequacy of the network to supply the energy requirements of users within the component ratings of frequency and voltage limits.
	Stability	The stability criterion defines the necessary probability of the network remaining in stable equilibrium operating condition following all credible network disturbances.
	Quality of supply	The quality of supply criterion relates to the voltage and current waveforms in the network, and criteria are established for the following aspects: voltage fluctuation, system frequency, harmonic distortion, voltage unbalance and network reliability.
Attributes	Environment	The environmental aspects require the minimisation of environmental impacts and compliance with environmental regulations. Several subcategories are referred to in this group, such as electromagnetic fields, land-use issues, noise and visual amenity. Depending on the study context these indicators can be defined as criterion.
	Economics	The economic indicator sets the economic viability of a plan, i.e. the selection of an option with the most favourable net present value with lowest network losses.

Traditional network planning objectives and explanation (Source: Utilities Commission, 2013)

3.5 Chapter endnotes

[1]: Mayrhofer and Gupta (2016)

[2]: Swisher et al. (1997)

[3]: ACEEE (2014)

[4]: Mirakyan (2013)

[5] IAEA (2005)

[6] Vera I. and L. Langlois (2007)

[7]: Utilities Commission (2013)

4. TIPSP methodology

4.1 Characterisation of different electricity load curve approaches

Learning objectives: Upon completion of this page, you should be able to

- name and explain different electricity load curve approaches,
- identify the advantages and limitations of using different load curve approaches.

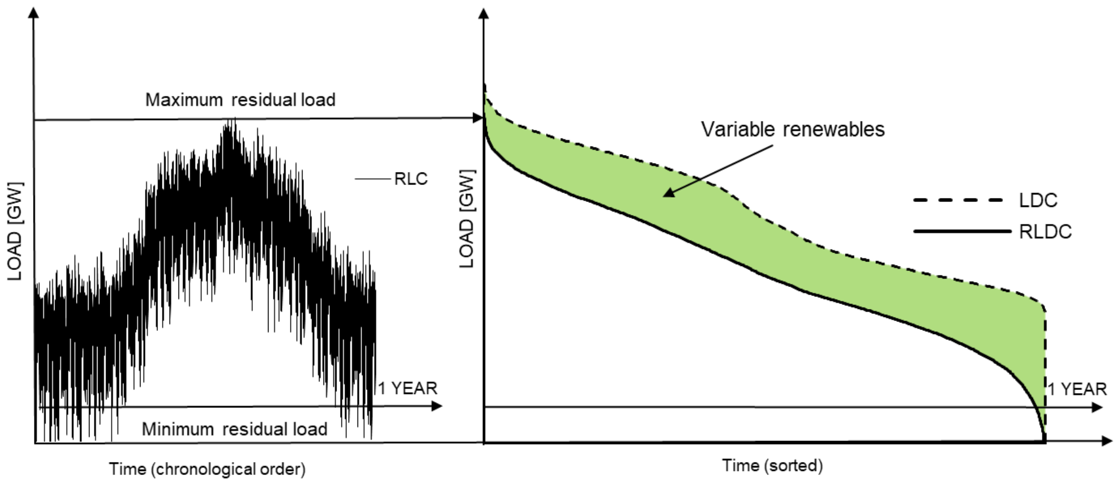
Load curves are used to characterise power demand, i.e. the load, for power system planning (PSP). Different load curve approaches are used for this purpose.

The common presentation of the load is its **chronological** representation. This represents seasonal, daily, hourly and sometimes even finer time disaggregation of the distribution of power consumption during a representative year. However, the **chronological load curve (CLC)** approach is demanding for detailed data and IT intensity for long-term planning models.

The **load duration curve (LDC)** is derived by sorting the load curve, i.e. the CLC, for one year from highest to lowest values, means the hour with the highest electricity demand comes first (peak load on the very left), and then the second largest, and so on until all data are ordered in descending order (minimum load with value on the right) The maximum value of an LDC indicates the capacity required to cover the highest annual power demand. The total annual energy demand equals the area below the LDC curve (see figure below right). LDC simplifies the computation and reduces the data intensity of large models in case where no detailed power demand or generated VRE (variable renewable energy) data are available. However, it does not capture the chronological interdependency between power demand and VRE, that CLC does.

To overcome the above-mentioned limitation, the residual load duration curve approach has been implemented in recent planning studies. The **residual load curve (RLC)** is a time series that is derived by subtracting the time series of VRE from the time series of power demand. [1], [2]

The **residual load duration curve (RLDC)** is derived by sorting the RLC into descending order (see figure below right). The area between the RLDC and the LDC (coloured green in the figure) equals the contribution of VRE. Note that there are limitations for the modelling of interregional power exchange. [1], [2]



Driving the LDCs: RLC (left); LDC and RLDC (right) (Source: Mirakyan, 2019)

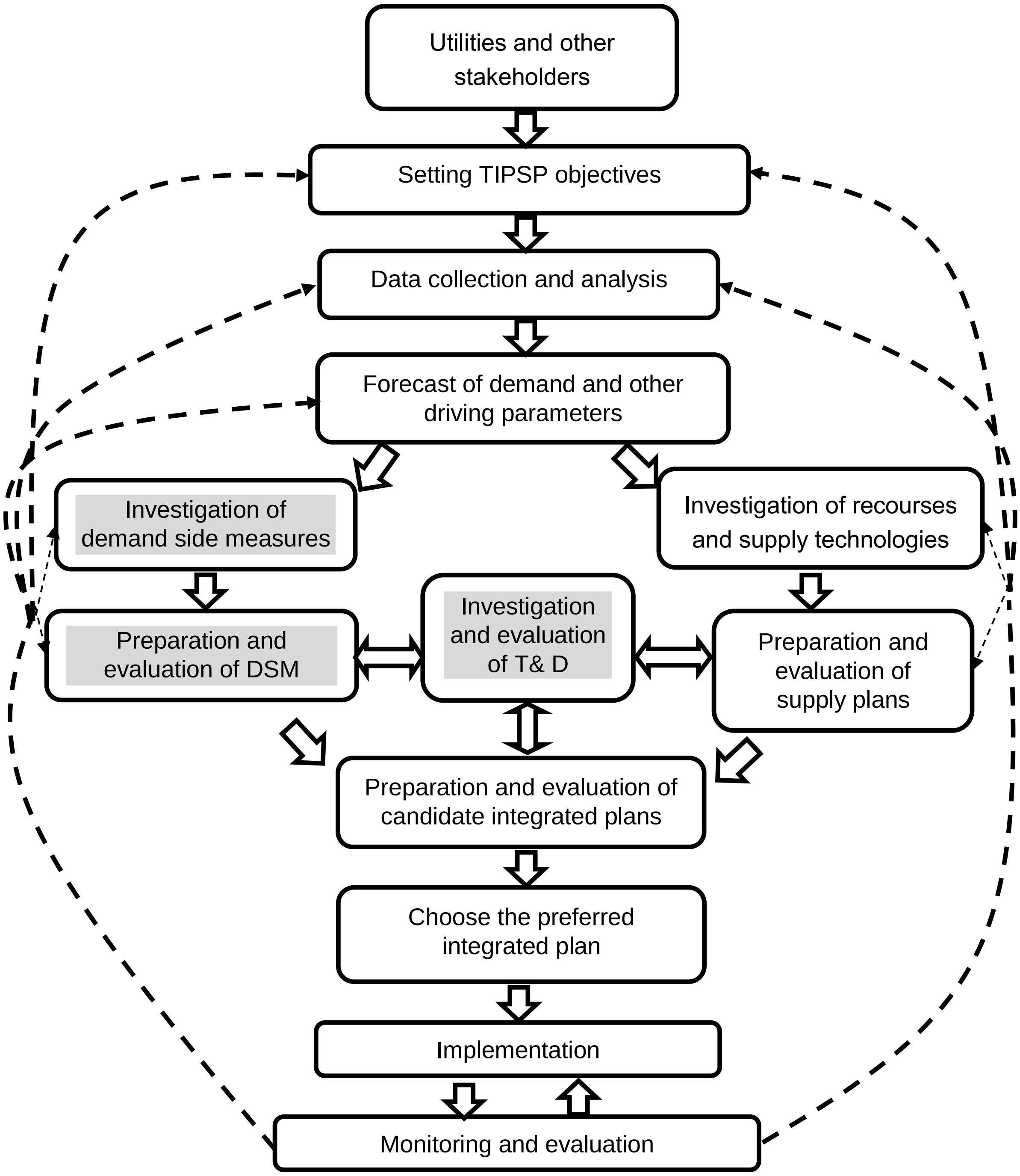
4.2 The traditional integrated power system planning methodology (TIPSP)

Learning objectives: Upon completion of this page, you should be able to

- explain the TIPSP process,
- understand the evolution of traditional power system planning,
- name the main planning stages and interaction between various planning stages.

The discussion in this screenpage is focused on techno-economic, model-based TIPSP. This kind of planning study requires analytical software tools. In some studies, it is referred to as integrated resources planning (IRP). While institutional and regulatory factors also are important in power planning, they are not discussed here.

Until the early years of this millennium most TIPSP studies used the load duration curve (LDC) approach in the planning. Recently an increasing number of studies use chorological load and residual load duration curve approaches. TIPSP has different planning steps. The diagram below presents the overall TIPSP planning process with the key planning steps.



Notes: DSM = demand-side management; T&D = transmission and distribution. Grey planning steps are considered in very few studies.

TIPSP process (Adapted from Greacen et al., 2013)

In general, TIPSP focuses on minimising the total costs. This is achieved through an optimal combination of supply options (resources and power generation technologies) to meet anticipated growth in demand with high reliability, generally with little consideration for other aspects such as air pollution or employment effects. [3] Some studies go beyond supply-side expansion planning and include the investigation of demand-side measures for the reduction or management of power demand, implementation of efficient technologies, or investigation of transmission and distribution planning possibilities in conjunction with different supply- and demand-side options. However, only very few studies conduct these planning steps, and therefore they are written in grey in the figure.

TIPSP inputs include fuel prices (coal, oil and natural gas), load growth, variability in hydro and other renewable resources like wind and solar, power system structure and technological data (efficiency or capacities), and more recently any regulations on carbon dioxide (CO_2). Common risks and uncertainties are addressed by scenario or sensitivity analyses. Often, public review and approval is also part of the planning process. However, for the sake of simplicity it is not included in the figure above. It is important to note that there is no specific chronological order or duration to the planning stages, but repeated iterations of the planning stages are possible. Additionally, some planning stages might be performed with extensive time delay. [3]

4.3 Traditional transmission system planning (TTSP) methodology

Learning objectives: Upon completion of this page, you should be able to

- define traditional transmission system planning (TTSP),
- explain the basics of the transmission power system planning process,
- name the main planning stages and interaction between various planning stages.

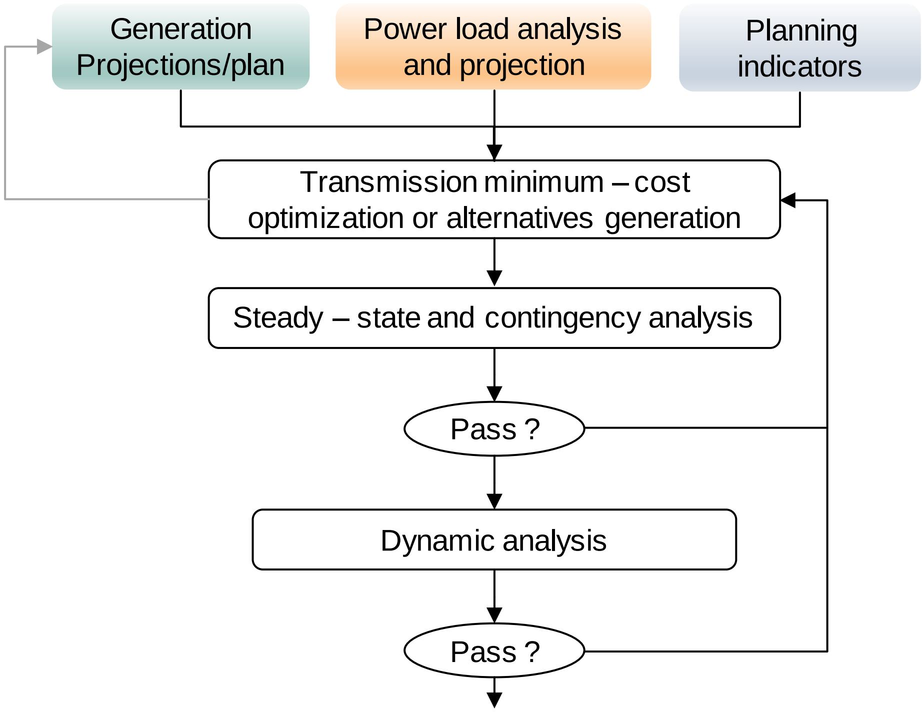
TTSP involves determining and scheduling the least-cost expansion or modernisation plan for long-distance transport of electricity from generation to demand, maintaining and enhancing the system's performance according to the planning criteria and being consistent with regulations or policies.

There are trade-offs between the planning objectives discussed in an earlier chapter, predominantly between the economics and the quality of supply as well as specific technical objectives like the stability, the steady state and the contingency criterion for reliability.

While planning methodologies can be highly complex, the basic building blocks of the TTSP process can be summarised as follows:

- gathering generation and demand projections,
- selecting planning indicators, such as reliability criterion n-1 considerations,
- analysing expansion or modernisation of transmission lines and substations versus power generation; selection of minimum-cost alternative,
- Analysing steady-state contingency, followed by dynamic analysis.

Practical implementation of the building blocks will depend on the key characteristics of the system that can impact transmission planning, including the composition of generation sources, interconnection with other regions or countries, and network losses. [4].



Building blocks of a basic TTSP process (Adapted from Madrigal and Stoft, 2012)

Similar to TIPSP, transmission planning can address different time spans. Short-term planning focuses on determining immediate needs, while mid-term planning focuses on determining needs for the next two to five years. Usually short- or mid-term planning is carried out in connection with regulatory requirements for cost recovery of the transmission assets. Short-term planning could focus on immediate reliability and interconnection needs in specific areas of the system or in the system as a whole. Long-term planning refers to identifying transmission needs for usually a 5- to 20-year timeframe. This type of planning is usually carried out in combination with generation expansion planning in the context of TIPSP, to identify a long-term development plan for the network. [4]

4.4 Traditional distribution system planning methodology

Learning objectives: Upon completion of this page, you should be able to

- define distribution system planning,
- explain the distribution system planning process,
- name the main planning stages and interaction between various planning stages.

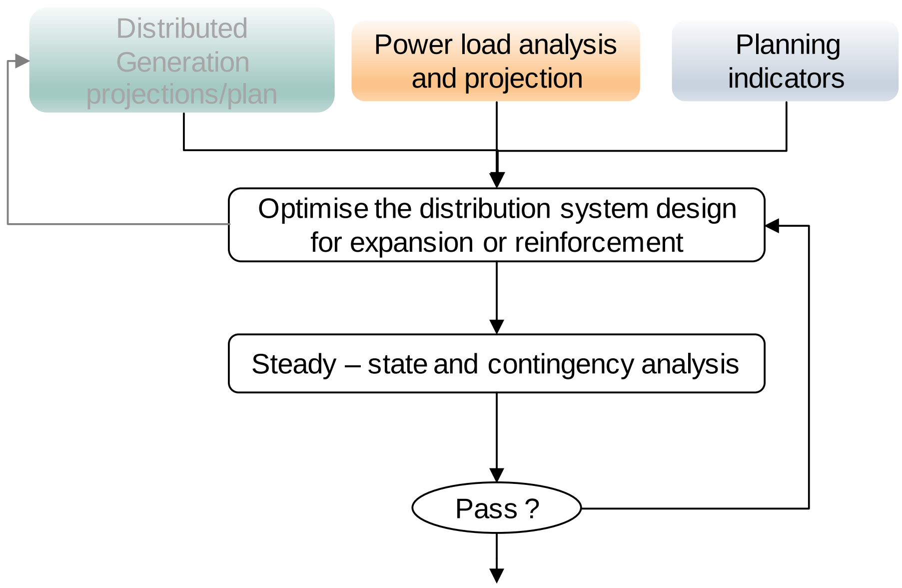
The purpose of distribution system planning (DSP) is to provide for an orderly and economic expansion or reinforcement of distribution system equipment and facilities (location, sizing) to meet future electrical demand, maintaining and enhancing the system’s performance according to the planning criteria and being consistent with regulations or policies. In order to cope with future uncertainties, some studies perform stability-based (probabilistic) planning, while others perform only economic-based (deterministic) planning.

Distribution planning has a short- or long-term time horizon too. Short-term planning is focused on making sound decisions to meet the lead time for operational or emergency tasks. Long-range planning (5 to 20 years) is motivated by the aim of ensuring short-range planning decisions have lasting value, and the planning of diverse elements of a distribution system (e.g. distribution substations or feeder systems) coordinates with the entirety in a least-cost system. [5]

The objectives of distribution system planning are discussed in an earlier chapter: they are predominantly economics and quality of supply as well as specific technical objectives like stability, steady state and the contingency criterion for reliability. In the past, distribution planning was typically done outside the context of integrated resource or transmission planning.

In practice, distribution planning is a challenging task due to the multi-faceted nature of the distribution system – its size, interconnection, and the many uncertainties tied to many of the elements that must be considered. However, the basic build blocks of the planning methodology are quite similar to transmission planning.

Nevertheless, in the traditional distribution system planning methodology the inclusion of distributed power generation like wind power and photovoltaic was not a common planning task, until the past two decades (see the figure below; the writing in grey signifies not active).



Building blocks of a basic traditional distribution system planning process (Adapted from Madrigal and Stoft, 2012)

4.5 Chapter endnotes

[1]: Ueckerdt et al. (2015)

[2]: Markus Pöller (2012)

[3]: Wilson and Biewald (2013)

[4]: Madrigal and Stoft (2012)

[5]: Willis (2004)

5. Advanced power system planning methodology

5.1 Properties and the implications of power generated by VRE plants and the required power system properties

Learning objectives: Upon completion of this page, you should be able to

- explain the main properties of power generated by VRE generators,
- name the main power system requirements for integration of power generated by VRE,
- construct the links between VRE properties and system requirements.

High levels of VRE penetration will have environmental, technical, social and economic implications. Several co-benefits are expected, for example a reduction in air pollutants, GHG emissions, water or land use. [1]

With a focus on technical implications, four properties of VRE generators that contrast with conventional generators are particularly interesting for assessing the implications of VRE for the power system and power system planning. [2]

Variability: VRE production is weather dependent (i.e. it is unable to maintain constant output in terms of energy and power in line with installed capacity) and has variable seasonal and diurnal (i.e. within-day) patterns of generation.

Uncertainty: Short-term VRE generation forecast quality has improved significantly, but it is still a challenging issue and there continue to be forecast errors linked with future intermittency of VRE.

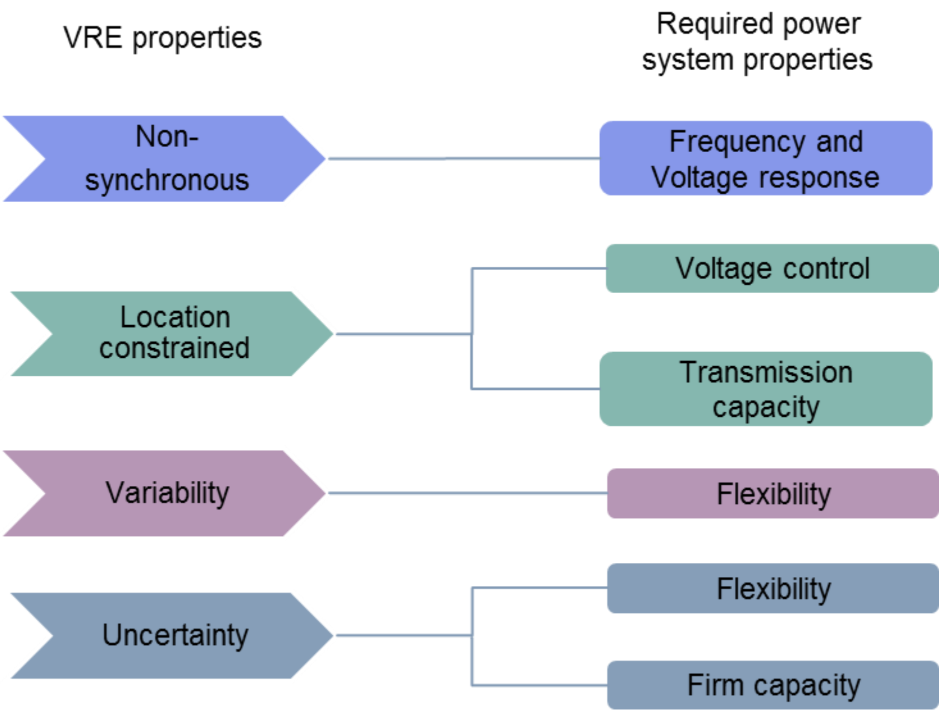
Location-constrained: VRE generators are normally built where the availability of the primary energy source is good, e.g. according to wind maps. These sites may be far from centres of demand and require additional power transmission.

Non-synchronous: This characteristic of power generated by VRE means that, under certain circumstances, it may be challenging to maintain system stability, which traditionally relies on the "inertia"[1] provided by synchronous generators used in conventional power generators.

These characteristics influence either the nature of, or requirements for, certain functional properties of the power system, the most important being: firm capacity, system flexibility, transmission and distribution capacity, voltage and frequency control, and voltage response.

The figure below schematically summarises which properties of VRE influence or impact the system-level functional properties.

[1] Inertia is defined as the "stored rotating energy in a power system provided by synchronous and induction generation".

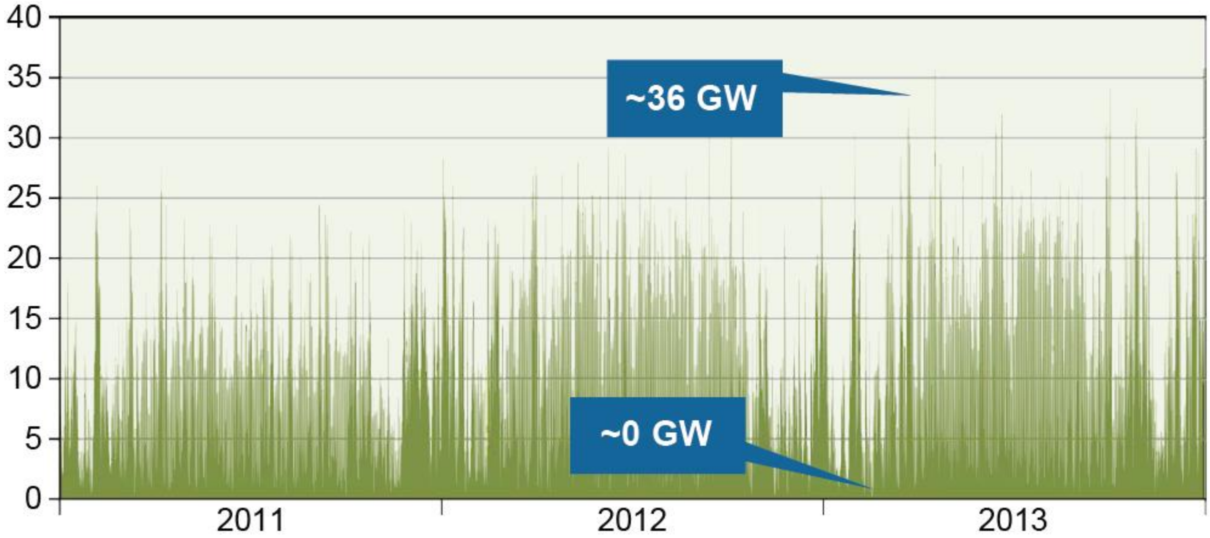


Key links between VRE and power system properties (Source: IRENA, 2017)

The requirement for power system flexibility is dealt with in detail on the next screenpage. Firm capacity is the amount of power available for production and transmission that can be guaranteed to be available at a given time and a certain reliability level. The firm capacity of a specific power station is also known as its reliable capacity. It describes how much this power station contributes to the systemwide reliability of supply. The reliable capacity of one specific power station is the fraction of its installed capacity that contributes to reliable generation given a certain reliability level. To calculate the reliable capacity, studies take into account the reliability of all power plants in the system, as well as power generation with wind power and PV power plants during times with the highest load (recursive convolution).

Reliable generation capacity is an important contribution to the expansion planning of generation. It means that electricity is generated at agreed times or during peak loads. The methodology for calculating reliable generation capacity takes into account a certain probability. This is never 100%, but close to it. E.g. the German grid study assumed non-availability of 15 min / year. In Germany, only 6% of the wind power capacity is reliable and 0% of the PV capacity, because the peak load in Germany is after sunset in November and Germany is often confronted with calming during this time.

The figure below illustrates the significant variability of hourly PV and wind generation in Germany—from producing nearly zero output to about 36 gigawatts (GW).



Hourly PV and wind generation over a three-year period in Germany (Source: EPRI 2016)

5.2 Impacts of VRE-generated power at various timescales and the relevant flexibility solutions

Learning objectives: Upon completion of this page, you should be able to

- explain the key role of flexibility for successful power system transition,
- describe different flexibility solutions and name important examples,
- identify flexibility solutions for different impacts of VRE power generation according to different timescales.

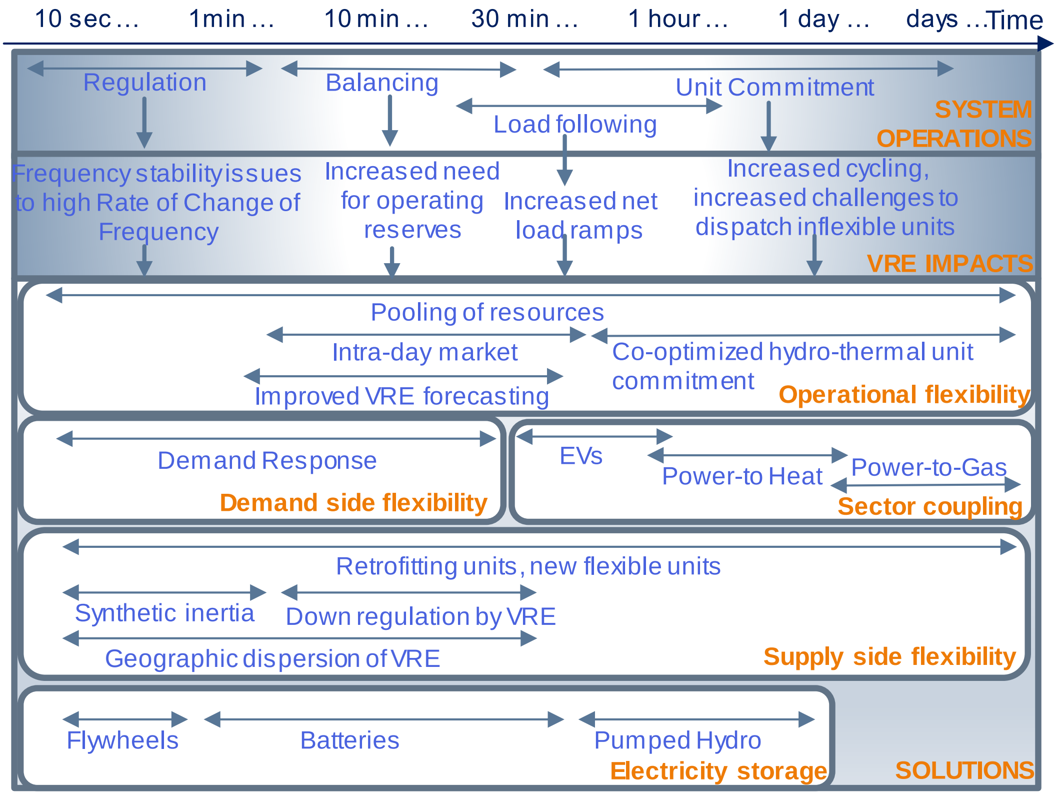
Flexibility is one of the properties of a power system to deal with the multiple implications of VRE-generated power in the system. An overall definition for flexibility is provided by [3]:

> "Power system flexibility is defined as the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales."

Accordingly, flexibility has multiple dimensions, not only technical but also institutional or economic, such as market flexibility. The technical and operational flexibility solutions can be grouped into:

- operational flexibility,
- demand- or supply-side flexibility,
- sector coupling,
- operational flexibility, and
- flexibility from electricity storage.

The figure below shows the impacts of VRE at different time scales and the relevant technical and operational flexibility solutions to deal with them.



Impacts of VRE at various timescales and relevant flexibility solutions (Source: IRENA, 2018)

Supply-side flexibility refers to power generators that can ramp up or down rapidly, have a low minimum operating level and have fast start-up and shutdown times, e.g. gas turbines. [2]

Storage technologies can be implemented successfully to deal with several VRE impacts at a range of timescales that extend from seconds to days. However, for the effective application of storage technologies certain characteristics, such as response time, roundtrip efficiency and cost, are important for defining the appropriated storage technology type. [4]

Demand response can be used along with energy storage for the further reduction of VRE curtailment. Demand response refers to specific types of demand-side management programmes where the demand pattern is shifted to better match electricity supply. [5]

Operational flexibility refers to how the assets in the power system are operated. In addition to the constraints of each technology's capabilities, it is dependent on the regulatory and market environment. [5]

Sector coupling increases system flexibility over a long-time scale – over days even for seasonal storage. It interconnects the power sector with the broader energy sector (e.g. heat, gas, mobility). It includes charging of battery of electric vehicles (EVs), and production of heat and hydrogen from electricity. [5]

5.3 Chapter endnotes

[1]: NREL (2012)

[2]: IRENA (2017)

[3]: IEA (2018)

[4]: Luo et al. (2015)

[5]: IRENA (2018)

6. Advanced integrated power system planning methodology (AIPSP)

6.1 Overall process of AIPSP methodology and comparison with TIPSP

Learning objectives: Upon completion of this page, you will be able to

- explain the advanced power system planning (AIPSP) methodology,
- name the main planning stages and interaction between different tasks,
- compare AIPSP with TIPSP.

Compared with TIPSP and according to its definition, AIPSP

- considers the energy system as a whole for more comprehensive planning, i.e. energy demand, generation, transmission and distribution systems,
- includes more objectives for the analysis and assessment of co-benefits,
- performs modelling and analysis with deeper temporal and spatial resolution for better utilisation of VRE potentials,
- considers cost-effective system operation with unit commitment (whether and which power station units will be committed to produce power at a certain time) and economic dispatch (optimal operational allocation of the committed power stations to meet the load at minimum costs)
- considers reliability issues reflected in long-term planning,
- is a multi-stakeholder participatory planning process.

Compared with TIPSP, AIPSP requires several changes to planning tasks and additional methods. The main AIPSP process is presented in the figure below. The new planning activities are in green. These were either missing from TIPSP or had less importance in TIPSP and now have more relevance. Additionally, AIPSP involves more geospatial planning, intersectoral coupling and better integrated analysis of distribution and transmission networks.

The investigation of flexibility is one of the important new planning tasks in AIPSP.

Flexibility assessment of a system is conducted to:

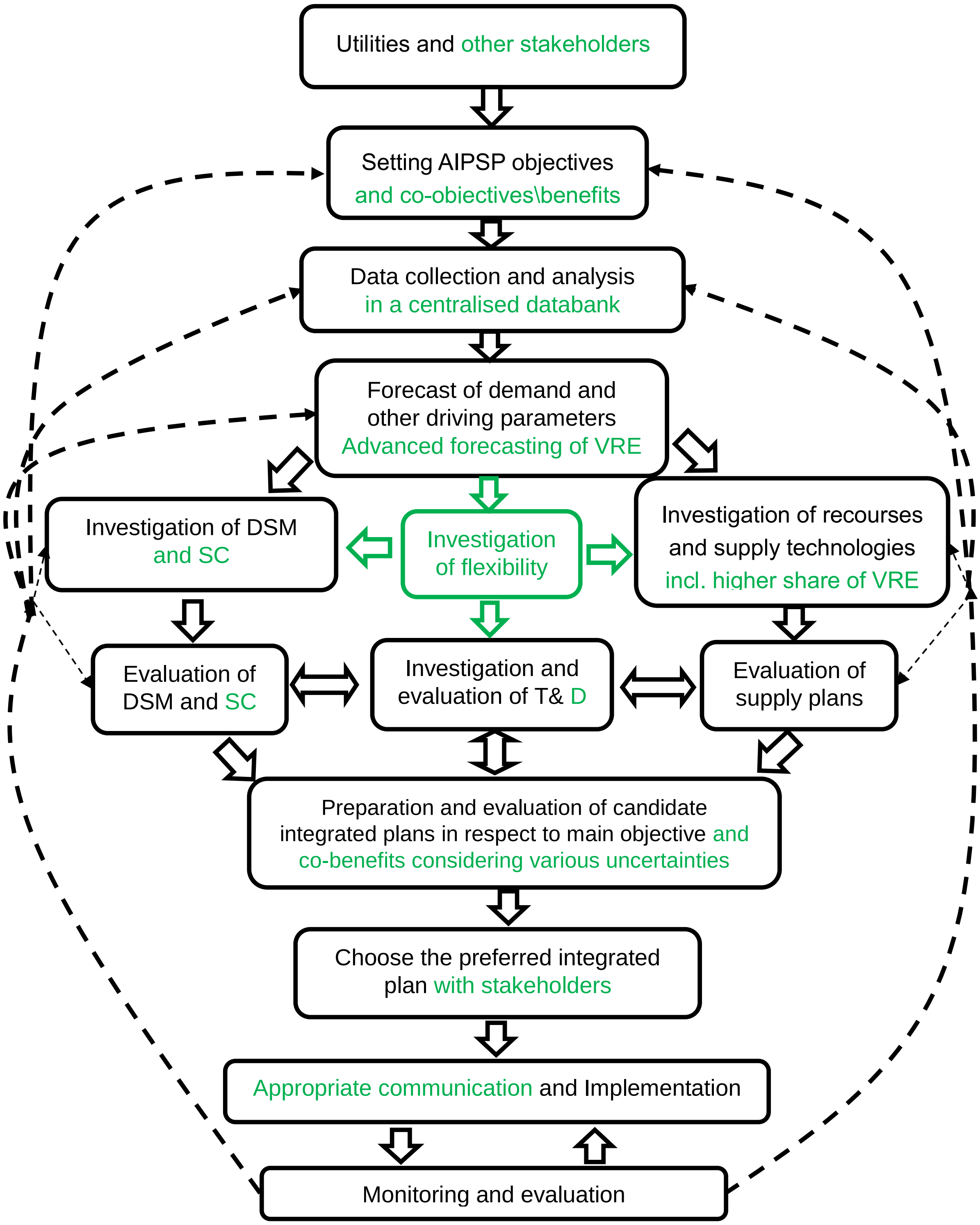
1) identify current flexibility gaps,

2) assess how much more VRE can be integrated without significantly changing the non-VRE component in power system,

3) assess the time left until the existing flexibility is exhausted (relevant to the lead time for new investments, based on capacity expansion plans),

4) identify a least-cost set of solutions to unlock existing flexibility and, at a later stage procure additional flexibility for the integration of a high share of VRE, which might require significant changes to non-VRE components. [1]

5) assess proactively how the non-VRE component in power system, means especially the must-run-power generation capacity and the transmission / distribution grids have to change to integrate very high percentages of power generation with wind and solar.



Notes: DSM = demand-side management; T&D = transmission and distribution; SC = sector coupling.

AIPSP process (Adapted from Greacen et al., 2013)

6.2 Methods supporting the additional tasks in AIPSP

Learning objectives: Upon completion of this page, you will be able to

- explain the additional methodological needs of AIPSP,
- name methods to support the additional AIPSP tasks,
- explain the added value of using these methods.

In addition to the incorporation of flexibility assessment in power system planning, other new tasks are included in AIPSP methodology (see previous graphic of the AIPSP process). The main new tasks and required methods are discussed in this section and depicted in the figure below.

- As more and more *stakeholders with different preferences* are involved in the planning process, there is a need to support this process methodologically. Bagheri and Hjorth [2] state that "…to be within the process of learning, it is required that both policy makers and all stakeholders as well as experts be involved in the process of planning and model building". There are different approaches to support the participatory planning processes, for example the method for establishing shared objectives using value trees. A detailed review of such methods is provided by Mirakyan and De Guio. [3]
- *Advanced short-term VRE forecasting* approaches can forecast VRE by presenting the variability and uncertainty of the forecasts more detailed. This will improve system operation and can be helpful for better utilisation of VRE potential [4]. A review of short-term advanced forecasting methods, such as neural networks or hybrid methods combining approaches from different domains (e.g. physical and statistical models) are provided by Zheng et al. [5] and Chaturvedi and Isha [6].
- With increasing amounts of data, which themselves have higher temporal and spatial resolution, the need for the storage and management of data in a *centralised databank* increases. [7], [8] and [9]
- In most planning cases TIPSP is deterministic without sufficient *consideration of uncertainties* [10]. With increasing proportions of VRE this aspect becomes more important. There are different methods for supporting these processes, for instance probabilistic sampling methods or methods based on scenarios analysis. [11]
- For the investigation of the system flexibility, the modelling approaches need to assess the system with higher disaggregated spatial and temporal resolutions that can reflect complex interactions such as feedback effects.
- Levelised cost of flexibility (LCOF): LCOF is a simplified metric based on LCOE (Levellised Cost of Energy). It provides an estimate of the additional cost associated with generating or consuming 1 megawatt hour (MWh) of electricity more flexibly. LCOF provides a single, simplified metric that can be used to compare different types of systems and flexibility services in terms of their cost. [11a, page 197]

Methods for supporting participatory planning process and for definition of objectives and co-benefits	Value tree, network of problems, soft system methodology
Centralised data storage and management	Centralised data management system or data warehouse
Forecast of demand and other driving parameters with advanced forecasting of VRE	Approaches from statistics and artificial intelligence, or hybrid approaches combining them with physical models
Investigation of system flexibility	Modelling approaches with more disaggregated spatial and temporal resolution to assess complex interactions
Assessment of uncertainties	Probabilistic-based approaches such as Monte Carlo simulation or scenario analysis with possibilities for long-term system development

Examples of methods for supporting additional AIPSP tasks (Source: Mirakyan, 2019)

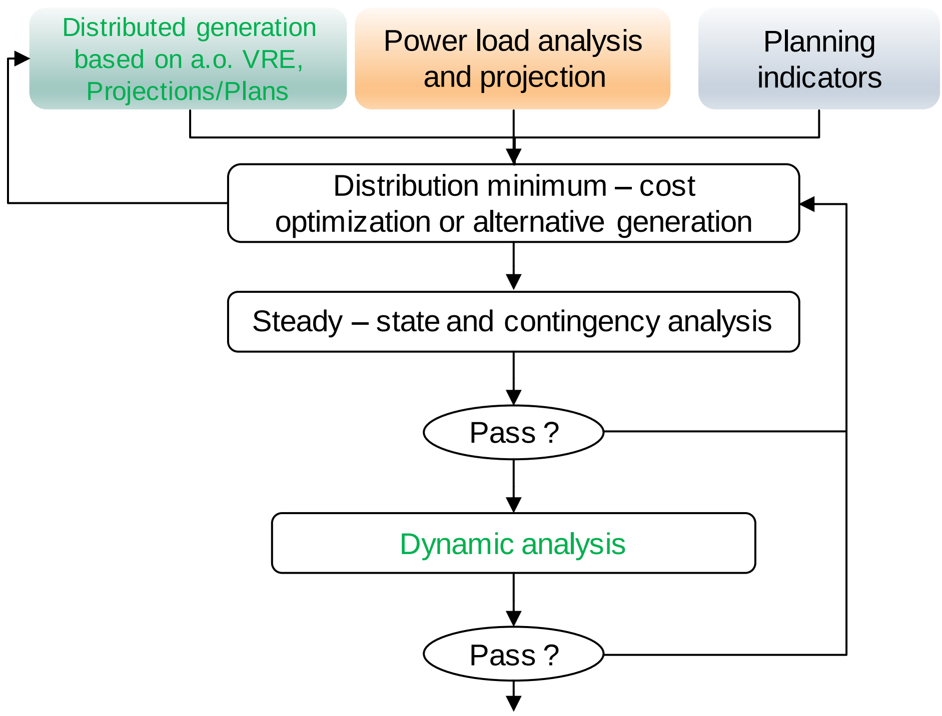
6.3 Impacts of high-penetration VRE on network planning

Learning objectives: Upon completion of this page, you will be able to

- explain the implications of high-penetration VRE on T&D planning methodologies,
- name the main advanced distribution system planning (ADSP) stages and interaction between different tasks,
- compare ADSP with traditional distribution system planning (TDSP).

New system equipment is integrated into T&D networks to support the higher penetration of VRE, for instance advanced digital substations or fault current limiters (i.e. resistive, inductive, superconducting or flux-lock [12]). However, while the traditional transmission planning process remains relevant [13], distribution system planning must become more proactive and integrative, interacting closely with transmission and generation planning.

ADSP is presented in the figure below. The new planning activities (in green), which were missing from TDSP or had less importance, now have more relevance. For example, distributed generation planning specifically focusing on VRE will be an important part of the planning process. Moreover, depending on the system size and configuration, dynamic analysis might be required.



Main building blocks of ADSP with a high share of VRE (Source: Mirakyan, 2019)

Additional themes also arise from smart grid concepts and planning for a future active distribution network (ADN). Also, the optimal integration between electricity distribution and information and communication technology (ICT) systems must be considered, as must the participation of different stakeholders in the planning process [14].

In general, the traditional network planning process will be extended to include flexibility analysis (also embraced for AIPSP) and the characterisation and estimation of net load (or residual load) with higher temporal resolution, more nodes and by better geospatial representation. Additionally, stability-based (probabilistic) planning becomes increasingly useful [15]. The iterative integration of network and generation planning options might increase in the analysis, with the optimisation of different network configurations affecting energy flows, generator dispatch and costs.

6.4 Chapter endnotes

[1]: IRENA (2018)

[2] Bagheri and Hjorth (2007)

[3] Mirakyan and De Guio (2014)

[4] NREL (2016)

[5] Zheng et al. (2011)

[6] Chaturvedi and Isha (2016)

[7] Swasti et al. (2017)

[8] Akhavan-Hejazi and Mohsenian-Rad (2018)

[9] Wang et al. (2013)

[10] Mirakyan and De Guio (2015)

[11] Mirakyan and De Guio (2016)

[11a] IEA (2014)

[12] Alam et al. (2018)

[13] NREL (2008)

[14] Mirakyan and De Guio (2014)

[15] Madrigal and Stoft (2012)

7. Comparison of planning tools

7.1 Modelling approaches and integration of co-benefits in traditional and advanced integrated PSP (IPSP)

Upon completion of this page, you will be able to

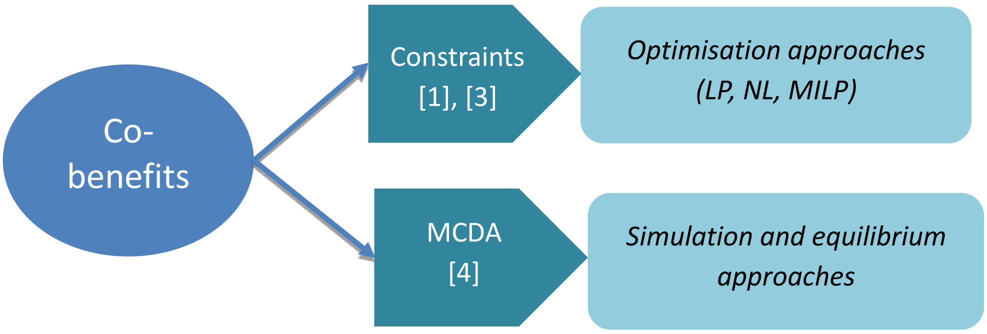
- describe different modelling approaches implemented in IPSP (both traditional and advanced IPSP),
- distinguish between the methods used for the evaluation of co-benefits in planning depending on the modelling approach implemented.

The evaluation of co-benefits in IPSP studies differs according to the modelling methodology implemented, as depicted in the figure below. The methodologies for modelling a power system can be generally divided into three main categories: simulation, optimisation and equilibrium approaches [1]:

- *Simulation (S) approaches* simulate a system using technological details. They allow the testing of various system topologies, the assessment of impacts and the development of various scenarios without algorithmic optimisation.
- *Optimisation approaches* optimise system operation and/or investments using technological details. Most optimisation models use a linear programming (LP) approach, with an objective function that is either maximised or minimised (e.g. total system cost), subject to a set of constraints (e.g. limiting emissions). Mixed-integer linear programming (MILP) additionally forces certain variables to be an integer. Optimisation models can also use non-linear programming (NP), i.e. the objective function or constraints are non-linear.
- *Equilibrium (E) approaches* take an economic approach, modelling the energy sector as a part of the whole economy, and study how it relates to the rest of the economy. Partial equilibrium (PE) models focus on balancing one energy market. In PE cases, the energy or electricity market is not modelled with the rest of the economy.

In the simulation and equilibrium approaches, the co-benefits are evaluated, and the solutions are compared using multi-criteria decision analysis (MCDA) tools. The co-benefits, such as CO_2 emissions, are evaluated and weighted in a similar way to the main benefit, such as total system costs. Finally, the solutions are compared and ranked according to the main benefit as well as to co-benefits.

In the optimisation approaches, such as LP or MILP, the co-benefits are defined as constraints. In this way the algorithm tries to minimise or maximise the main benefit, e.g. the system total cost in a constrained space. There are also multi-objective optimisation approaches, such as evolutionary algorithm [2].



Incorporating co-benefits into IPSP modelling (Sources: Ringkjøb, 2018; Ming et al., 2015; Frangopoulos, 2018; Pohekar & Ramachandran 2004)

7.2 Comparative assessment of software tools for IPSP – general features

Upon completion of this page, you will be able to

- list some general features of software tools used in IPSP,
- categorise software tools according to the planning purpose and user needs and constraints,
- identify software tools that can assess more aspects for AIPSP.

For this assessment, 15 of the most frequently used energy system planning software tools have been selected, with a focus on those used for power system planning. In our selection priority has been given to software tools that are available to use, which are updated regularly, and which offer support from the software developer, including available documentation. Specific tools that are dedicated only to network planning or demand-side management are not considered.

Focusing on the integration of decentralised VRE, the following categories have been used for the general software assessment:

- **Purpose:** the modelling tools can be used –
    - for **investment decision support** (IDS) to assess the optimal future system design and select the most relevant options for the long term,
    - for **operation decision support** (ODS) to assess the operation or dispatch of the system elements in short-term timescales. Some tools analyse the dispatch of the power generation units in approximate terms without considering ramp-up/down times or ramp rates; these can be classified as partial operation decision support (PODS).
- **Co-objectives/co-benefits**: co-objectives that can be used to assess co-benefits such as the reduction of GHG emissions – carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_X) – or pollutants such as particulate matter (PM), sulphur dioxide (SO_2), unburned hydrocarbons (UHC).
- **Temporal resolution** (TR): temporal granularity for the modelling of the energy system.

- **Modelling horizon** (MH): modelling time horizon – user-defined (UD) or no limitations (NL).
- **Availability**: Academic Version (AV), commercial (C), free demo version (DV), free (F), free for educational purposes (ED), open-source (OS), upon request (UR).
- **Published/developed by, weblink:** a link to the software developer.

Note that there is no single generally preferred ideal tool, rather that the optimal tool depends on the purpose, co-objectives, required time resolution or modelling horizon etc. The most frequently used tools are presented in italics in the table below.

Tools	Purpose	Co-objectives	Temporal resolution	Modelling horizon	Avail-ability	Published/developed by Weblink
AURORAxmp	IDS, ODS	Any	Hourly	50+ years	C (DV, AV)	EPIS, http://epis.com
BALMOREL	IDS, PODS	CO_2, SO_2, NO_x	Hourly	Long-term	OS	Hans Ravn, www.balmorel.com
Calliope	IDS, ODS	Any	Hourly	50+ years	OS	ETH Zürich – Stefan Pfenninger, www.callio.pe
EMMA	IDS, ODS	No	Hourly	Long-term	OS	Neon Neue Energieökonomik – Lion Hirth, www.neon-energie.de/en/emma
EnergyPLAN	IDS	CO_2	Hourly	1 year	F	Sustainable Energy Planning Research Group – Aalborg University, www.energyplan.eu
Enertile	IDS, ODS	CO_2	Hourly	2050	C	Fraunhofer ISI, www.enertile.eu/enertile-en/index.php
ENTIGRIS	IDS, ODS	CO_2	Hourly	2050	C	Fraunhofer ISE – Christoph Kost, www.entigris.org
HOMER-pro	IDS, ODS	CO, CO_2, NO_x, PM, SO_2, UHC	Minutes	UD	C, DV	National Renewable Energy Laboratory and HOMER Energy LLC, www.homerenergy.com/
LEAP	IDS, PODS	Any	Hourly	Long-term UD	ED, C	Stockholm Environment Institute, www.energycommunity.org
LIPS OP/XP	IDS, ODS	CO_2	Hourly	Long-term UD	C, DV	Lahmeyer, Tractebel, Department of Energy Economics, https://tractebel-engie.de/

Tools	Purpose	Co-objectives	Temporal resolution	Modelling horizon	Avail-ability	Published/developed by Weblink
MESAP/ PlaNet	IDS	Any	Hourly	Long-term UD	C	seven2one, www.seven2one.de
MESSAGE	IDS	Any	Multiple years	Long-term UD	UR	International Institute for Applied Systems Analysis, www.iiasa.ac.at
Oemof (SOLPH)	IDS, ODS	Any	Seconds to years	UD	OS	Oemof developing group (Reiner Lemoine Institute/ZNES Flensburg/OVGU), www.oemof.org
PLEXOS	IDS, ODS	Any	Usually hourly	50+ years	C	Energy Exemplar, https://energyexemplar.com
TIMES	IDS, PODS	Any	UD time-slices	Long-term UD	C, DV	International Energy Agency, ETSAP https://iea-etsap.org/index
WASP	IDS	CO_2, NO_x, SO_2	Monthly	Up to 30 years	C	International Atomic Energy Agency, www.iaea.org.

Comparative assessment of IPSP tools – general features (Sources: Ringkjøb, 2018; Zeng et al., 2011; Debnath and Mourshed, 2018)

7.3 Comparative assessment of software tools for IPSP – specific features

Upon completion of this page, you will be able to

- state and distinguish between specific features of software tools used in IPSP,
- categorise software tools according to the diverse needs of VRE integration,
- identify software tools capable of assessing more detailed aspects for AIPSP.

For this assessment the tools are characterised according to several detailed categories:

- The underlying **methodology**: the modelling methodology can be simulation, optimisation or equilibrium approaches, or a combination of them – simulation (S), linear programming (LP), mixed-integer linear programming (MILP), non-linear programming (NP), equilibrium (E) or partial equilibrium (PE).
- **Consideration of renewable energy technologies** (Renewable generation): whether the software tool can model renewable technologies – hydropower (HP), wind power (WP), wave power (WaP), geothermal (GT), tidal power (TP), solar power (SP), or all of them.

- **Storage**: whether the tool can model storage technologies – pumped hydro storage (PHS), batteries (B), compressed air energy storage (CAES), hydrogen (H), thermal energy storage (TES), or all of them.
- **Grid**: the modelling tools considered here are not specifically dedicated to network planning. However, the assessment of load flow between regions and consideration of investment in network expansion are important in IPSP. Four approaches are followed: alternating current (AC) flow, direct current (DC) flow, net transfer capacities (NTC), or just import/export (IE) of energy without detailed network specification.
- **Intersectoral coupling** (ISC): whether the software tool can model the coupling of energy-using sectors – demand response (DR), power-to-gas or hydrogen (PtG), power-to-electrical vehicle (PtV), or power-to-heat (PtH) are used to shift loads to hours when demand is lower than supply. This allows better balancing of VRE.
- **Power system**: whether the integrated power system (IPS) can be modelled, i.e. demand and supply, or only the supply side (SSD) based on an exogenously defined aggregated load curve.

	Methodology	**Renewable generation**	**Storage**	**Grid**	**ISC**	**Power system**
AURORAxmp	S, LP, MILP , PE	All	All	IE, NTC, DC load	DR, PtH	IPS
BALMOREL	PE/LP (MIP)	HP, SP, WP, WaP	All	NTC	DR	SSD
Calliope	LP (MIP)	All	All	NTC	DR, PtG	IPS
EMMA	LP	WP, SP, HP	PHS	NTC	None	SSD
EnergyPLAN	S	All	All	IE	PtG, PtV, PtH	IPS
Enertile	LP	All	PHS, TES, B	NTC	PtH	IPS
ENTIGRIS	LP	HP, WP, SP, CSP	PHS, B, TES	NTC	None	SSD
HOMER-pro	S and LP	All	B, CAES	IE	DR, PtH	SSD
LEAP	S and LP	ALL	None	IE	All	IPS
LIPS OP/XP	PE/LP (MILP)	All	PHS	NTC	DR	SSD
MESAP/PlaNet	S and LP	All	None	IE	All	IPS

	Methodology	Renewable generation	Storage	Grid	ISC	Power system
MESSAGE	LP	All	All	IE	None	IPS
Oemof (SOLPH)	LP, MILP, PE	ALL	All	IE, NTC	DR	IPS
PLEXOS	NP, MILP, MIQP*, PE	All	All	IE, NTC, DC load, AC load	DR	SSD
TIMES	LP/MILP, PE	All	All	NTC	All	IPS
WASP	LP, PE	HP, WP, WaP	PHS	IE	None	SSD

*Mixed integer quadratic programming

Comparative assessment of integrated power system planning tools – specific features (Sources: Ringkjøb, 2018; Pohekar & Ramachandran, 2004; Zeng et al., 2011)

7.5 Chapter endnotes

[1] Ringkjøb et al. (2018)

[2] Ming et al. (2015)

[3] Frangopoulos (2018)

[4] Pohekar & Ramachandran (2004)

[5] Zeng el al (2011)

[6] Debnath & Mourshed (2018)

8. Power system planning case studies with and without co-benefits

8.1 Overview of international practice on IPSP and general description of studies

Upon completion of this page, you will be able to

- list the objectives and co-benefits analysed in the planning studies,
- classify studies according to different temporal resolutions and modelling horizons,
- identify studies that assessed multiple co-benefits.

This section mainly discusses those studies that have conducted IPSP (sometimes also called "master planning") in developing countries. The studies also need to be available online for further reading. With regard to the integration of VRE, and for the assessment of co-benefits, the following six categories have been used for the general classification and assessment of studies:

- **Institutions involved:** which institutions or consulting companies were involved in the planning (only the first institution is listed in the table).
- **Planning document and online reference:** the name of the document presenting the planning results, the source of online reference.
- **Co-objectives or co-benefits:** Implemented co-objectives that have been used to assess the co-benefits such as Diversity Index (DI), Energy Security Index (ESI), Expected Un-served Energy (EUE), GHG emissions or air pollutants, loss-of-load probability (LOLP), Network planning criteria (N-criteria).
- **Renewable energy (RE) penetration:** type and share of renewable energy technologies in the total planned power generation.
- **Temporal resolution (TR):** time granularity performed by the modelling.
- **Modelling horizon (MH):** time horizon implemented in scenario analysis.

Country	Institution	Planning document, weblink	Co-objectives or co-benefits	RE penetration	Temporal resolution	Modelling horizon
Afghanistan 2013	Fichtner GmbH & Co. KG	"Islamic Republic of Afghanistan: Power Sector Master Plan" [1]	Poverty, employment, land use, air quality, climate	54% HP by 2032	Weekly	20 years
Bangladesh 2016	Tokyo Electric Power Services Co., Ltd.	"Power System Master Plan 2016" [2]	Reduction of CO_2, ESI	10–20% RE by 2041	Daily	20 years
Bihar 2011	SNC-Lavalin International	"Developing the Power System Master Plan for Bihar" [3]	LOLP, EUE	-	Monthly	10 years

Country	Institution	Planning document, weblink	Co-objectives or co-benefits	RE penetration	Temporal resolution	Modelling horizon
Ghana 2012	Lahmeyer, Tractebel	"Renewable Energy Development Plan for Ghana" [4]	LOLP, ENS	PV 9%, WP 36.3%, HP 19 % by 2026	Hourly	15 years
Mauritius 2013	SNC-Lavalin International	"Making the right choice for a sustainable energy future 2013" [5]	Affordability, security of supply, CO_2, SO_2, ash biodiversity, land use, health etc.	PV and WP 10% by 2020	-	20 years
Myanmar 2015	IES – Intelligent Energy Systems	"Myanmar Energy Master Plan"[6]	LOLP, CO_2	PV 6%, HP 56%	Monthly	15 years
Kenya 2018	Lahmeyer, Tractebel	"Updated Least Cost Power Development Plan" [7]	LOLP, ENS, N-criteria	PV 8.6%, Wind 8.5 %	Hourly	20 years
Pakistan 2011	SNC-Lavalin International	"National Power System Expansion"[8]	LOLP, ENS, N-criteria	Wind 5.5%, HP 35.7 %	Yearly	20 years
Panama 2017	University of Toronto, Department of Civil Engineering	"Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector" [9]	CO_2-eq, DI	Wind 25%, PV 6% by 2026	Yearly	26 years
Sri Lanka 2017	Ceylon Electricity Board	"Long Term Generation Expansion Plan" [10]	CO_2, DI, LOLP, EUE	PV 9 %, WP 10% by 2037	Hourly	20 years
South Africa 2016	Department of Energy	"Integrated Energy Plan" [11]	Job creation, CO_2-eq, water consumption, energy access, DI	WP 18.8%, PV 19.5% by 2050	Year	37 years

Country	Institution	Planning document, weblink	Co-objectives or co-benefits	RE penetration	Temporal resolution	Modelling horizon
Indiana, US 2015	Wabash Valley Power	“Integrated Resource Plan” [12]	CO_2, NO_x, SO_2, LOLP	-	Hourly	18 years

Selected studies conducting IPSP – an overview (Source: Fichtner, 2013; JICA, 2016; SNC-Lavalin, 2011a,; Lahmeyer, 2012; NEC, 2013; IES, 2015; ERC, 2018; SNC-Lavalin, 20011b; McPherson and Karney, 2014; CEB, 2017; DOE, 2016 and WVP, 2015)

8.2 Review of international practices on IPSP – specific description of studies on VRE integration

Upon completion of this page, you will be able to

- Name the software tools implemented in the planning studies,
- Distinguish between studies conducting operation and investment optimisation,
- Identify studies that assessed more detailed AIPSP aspects.

- **System analysis**: Studies are categorised according to whether they conducted:
  - **Operation optimisation** – optimising the operation of a given energy system according to cost, with at least hourly time resolution, and considering the availability of the system elements and other restrictions. This is important on the one hand to assess the potential flexibility of large power generation stations, and on the other to allow exploitation of the highly cost-effective power generated by VRE.
  - **Investment optimisation** – optimising the system design (i.e. which power generation stations, transmission lines etc. are best) in the long run. This is important for assessing (a) the real benefits of cost-intensive investments in the coming decades and (b) the optimal future system design, selecting the investments most relevant in the long run.
- **Grid**: whether transmission (T) or distribution (D) network planning were conducted in the studies together with generation system planning.
- **Intersectoral coupling (ISC)**: whether any of the following were considered – demand response (DR), power-to-gas or hydrogen (PtG), power-to-electric vehicle (PtV) or power-to-heat (PtH), which are used to shift loads from hours when demand is lower than supply.
- **Storage**: Whether storage technologies were considered in the study or not: pumped hydro storage (PHS), batteries (B), compressed air energy storage (CAES), hydrogen (H) or thermal energy storage (TES).
- **Software tools applied:** The power system modelling software that was applied.

Country	Operation optimisation	Investment optimisation	Grid	ISC	Storage	Software
Afghanistan 2013	Yes	Yes	T	-	-	PSSE®
Bangladesh 2016	-	Yes	T	-	-	PDPAT
Bihar 2011	Yes	Yes	T, D	-	PHS	SYPCO
Ghana 2012	Yes	Yes	T	-	PHS	LIPSOP/XP
Mauritius 2013	Yes	Yes	T	DR	B, PHS	HOMER
Myanmar 2015	-	Yes	T	-	-	WASP
Kenya 2018	Yes	Yes	T	-	-	LIPSOP/XP
Pakistan 2011	-	Yes	T, D	-	-	SYPCO, YMDIST
Panama 2017	-	Yes	-	-	-	LEAP
Sri Lanka 2017	-	Yes	T	-	PHS	SDDP, MAED, WASP, OPTGEN
South Africa 2016	-	Yes	-	PtG	B, PHS	-
Indiana, US 2015	Yes	Yes	-	DR	-	Plexos

Selected studies conducting IPSP – detailed consideration (Source: Fichtner, 2013; JICA, 2016; SNC-Lavalin, 2011a,; Lahmeyer, 2012; NEC, 2013; IES, 2015; ERC, 2018; SNC-Lavalin, 20011b; McPherson and Karney, 2014; CEB, 2017; DOE, 2016 and WVP, 2015)

8.3 Lessons from the review of international practices

Upon completion of this page, you will be able to

- Summarise the key aspects addressed in the planning and modelling studies,
- Learn in an example that the main objective "lowest system marginal costs" can be reached together with positive co-benefits, i.e. a low GHG emission scenario.

The main lessons from the review of international practices can be summarised as follows:

- In the last decade studies have mostly used reliability criteria such as LOLP or ENS as co-objectives, along with the minimisation of power generation costs as the main planning objective. Few studies also considered CO_2 emissions or SO_2 pollutants as co-objectives. Two studies considered more co-objectives such as affordability, security of supply, land or water use etc.
- More than half of the studies conducted planning based on weekly, monthly or yearly temporal resolution, which is not sufficient for the integration of VRE, particularly wind and PV systems.
- Most of the studies included transmission planning as part of IPSP. Distribution planning was also considered in two studies.
- The planning and modelling of aspects that allow the assessment of system flexibility and integration of VRE – such as intersectoral coupling (demand response, power-to-gas, or power-

to-electric vehicle), detailed unit commitment/economic dispatch or storage technologies such as batteries – are not commonly applied yet.

- Despite the availability of sophisticated modelling tools on the market, some studies use software developed in-house or commercially available software, which do not allow detailed analysis to be conducted.

An example of various levels of renewable energy integration and co-benefits assessment is presented in the figure below [2]. This kind of assessment allows to choose the best technological mix according to different objectives and preferences of decision makers.

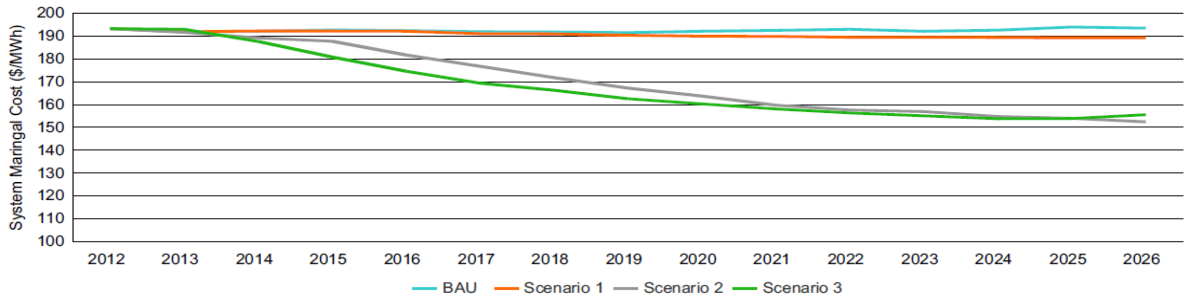
Scenarios with share of renewables	Composition [MW base]	Economy [US cent/kWh]	Environment [US cent/kWh]	Energy security [US cent/kWh]	Total [US cent/kWh]
Scenario No RE	Gas 35%, Coal 35%	12.1	5.7	8.2	26.0
Scenario RE10	Gas 35%, Coal 25%	16.0	5.0	6.9	27.9
Scenario RE20	Gas 25%, Coal 25%	19.2	4.7	6.2	30.2

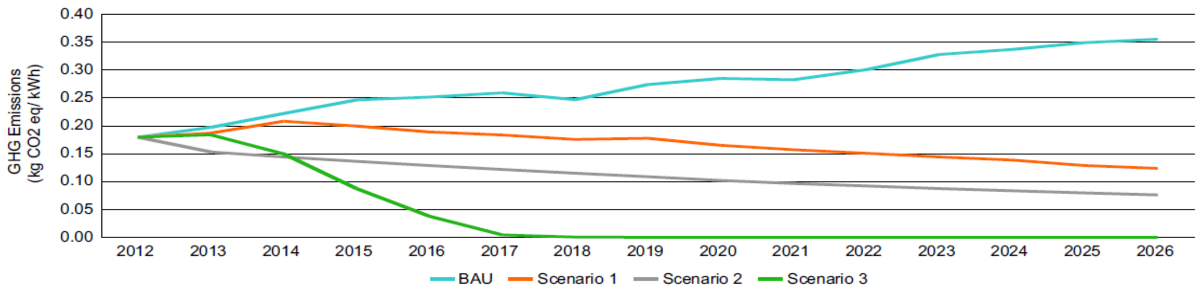
Note: RE10 or RE20= power system having 10% or 20% power generation by RE

Power development scenarios for Bangladesh, results comparison (Source: JICA, 2016)

Considering only the economic aspect, the most favourable system is the “Scenario No RE”, i.e. no renewable energy sources. However, if co-benefits are additionally considered, this scenario’s total cost advantage is significantly reduced. Moreover, the study [JICA, 2016] states that if the cost of renewables integration can be reduced by 5%, e.g. through innovation, the scenarios with higher shares of renewable energy become more favourable.

The study for Panama [9] shows several scenarios comparing system costs versus GHG emission quantities. The multi-objective assessment allows a scenario with complementary options to be identified where the costs and GHG emissions are the lowest (Scenario 3, green line)





Long-term scenario alternatives for Panama[2] *(Source: McPherson and Karney, 2014)*

Scenario 3 (green line) postulates the decarbonisation of the entire electricity system. Existing fossil fuel generation and incremental demand are met by wind, geothermal, solar, and additional hydro resources. In this scenario CO_2 emissions from the electricity sector can be reduced from 0.18 kg CO_2-eq/kWh in 2012 to zero in 2026. At the same time the system marginal costs ($/MWh) are the lowest compared to the other scenarios with less renewable energy.

8.4 Chapter endnotes

[1] Fichtner (2013)

[2] JICA (2016)

[3] SNC-Lavalin (2011a)

[4] Lahmeyer (2012)

[5] NEC (2013)

[6] IES (2015)

[7] ERC (2018)

[8] SNC-Lavalin (2011b)

[2] BAU (Business As Usual) : meet increasing demand primarily with fossil and some hydro power plants.
Scenario 1: meet increasing demand primarily with hydro; maintain fossil levels, without exploring different technologies.
Scenario 2: maintain fossil and hydro levels, meet increasing demand with geothermal and wind.
Scenario 3: replace fossil and meet increasing demand with wind and geothermal.

[9] McPherson and Karney (2014)

[10] CEB (2017)

[11] DOE (2016)

[12] WVP (2015)

9. Summary

The main lessons learned from the online course can be summarised as follows:

The energy system is in a period of transition. The number and diversity of power generation technologies, in particular decentralised systems based on variable renewable energy (VRE), are consistently increasing in many countries. Power is no longer flowing only in one direction, from centralised power plants to the consumer, but now also flows from one consumer to another. In addition, interest in and demand for sustainability are growing, particularly in respect of reducing greenhouse gases and local pollutants.

The planning and analysis of such systems require a system-wide approach to power system planning (PSP) to improve overall efficiency and reliability with high proportions of VRE, additionally considering multiple objectives for the assessment of co-benefits.

Traditional integrated power system planning (TIPSP) generates system expansion solutions that match the anticipated peak power demand with high reliability. The objective is to minimise the total costs at a very high temporally and spatially aggregated level, without sufficient consideration of the flexibility issues that are inherent to the integration of VRE. In contrast, advanced integrated power system planning (AIPSP) seeks to find comprehensive system solutions (demand, supply, or network design) considering co-benefits alongside the minimisation of total costs. AIPSP add further planning processes, such as flexibility analysis and modelling with high temporal resolution and detailed geospatial representation. AIPSP becomes a multi-objective assessment that also covers co-benefits, such as reduced emissions and other environmental impacts, and improved living and health conditions.

TIPSP and software tools supporting this process remain the common approach in many developing countries. Certain developing countries are implementing aspects of AIPSP but are yet to conduct the full AIPSP process. Software tools are available on the market to support the AIPSP process.

10. Further reading

Borbonus, S. (2017), "Generating socio-economic values from renewable energies: An overview of questions and assessment methods", IASS Working Paper, Institute for Advanced Sustainability Studies, www.iass-potsdam.de/sites/default/files/files/iass_2017_cobenefits_assessment_methods.pdf.

Connolly, D. et al. (2010), "A review of computer tools for analysing the integration of renewable energy into various energy systems", *Applied Energy*, Vol. 87(4), pp. 1059–82, www.sciencedirect.com/science/article/pii/S0306261909004188.

DOE (Department of Energy) (2013), *The Integrated Resource Plan (IRP) 2010–30*, www.doe-irp.co.za/.

Hamilton, K. et al. (2017), "Economic co-benefits of reducing CO_2 emissions outweigh the cost of mitigation for most big emitters", London School of Economics and Political Science, www.lse.ac.uk/GranthamInstitute/news/economic-co-benefits-of-reducing-co2-emissions-outweigh-the-cost-of-mitigation-for-most-big-emitters/.

Hannan, M. A. et al. (2018), "Review of baseline studies on energy policies and indicators in Malaysia for future sustainable energy development", *Renew. Sustain. Energy Rev.*, Vol. 94 , www.sciencedirect.com/science/article/pii/S1364032118304799.

Helgenberger, S. and M. Jänicke (2017), "Mobilizing the co-benefits of climate change mitigation: connecting opportunities with interests in the new energy world of renewables", IASS Working Paper, Institute for Advanced Sustainability Studies, http://publications.iass-potsdam.de/pubman/item/escidoc:2348917:7/component/escidoc:2666888/IASS_Working_Paper_2348917.pdf.

IEA (International Energy Agency) (2017), *Getting Wind and Sun onto the Grid*, OECD/IEA, Paris, www.iea.org/publications/insights/insightpublications/Getting_Wind_and_Sun.pdf.

Mohamad, F. and J. Teh (2018), "Impacts of energy storage system on power system reliability: a systematic review", *Energies*, Vol. 11(7), 1749. https://doi.org/10.3390/en11071749.

Mougouei, F. R. and M.-S. Mortazavi (2017), "Effective approaches to energy planning and classification of energy systems models", *International Journal of Energy Economics and Policy*, Vol. 7, Issue 2, http://dergipark.gov.tr/download/article-file/361729.

Schill, W.-P. (2013), *Residual Load, Renewable Surplus Generation and Storage Requirements in Germany*, DIW Berlin, German Institute for Economic Research, www.diw.de/documents/publikationen/%E2%80%8C73/%E2%80%8Cdiw_01.c.429202.de/%E2%80%8Cdp1316.pdf.

Seifi, H. and M. S. Sepasian (2011), *Electric Power System Planning: Issues, Algorithms and Solutions*, Springer Science & Business Media.

Shahnia, F., A. Arefi and G. Ledwich (2018), *Distribution Network Planning*, Springer Nature Singapore Pte Ltd., www.springer.com/de/book/9789811070556.

Streimikiene, D. (2005), "Indicators for sustainable energy development in Lithuania", *Natural Resources Forum*, Vol. 9, Issue 4, https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1477-8947.2005.00144.x.

Todoc, J. L. et al. (2005), "Indicators for sustainable energy development in Thailand", *Natural Resources Forum*, Vol. 29, Issue 4, https://doi.org/10.1111/j.1477-8947.2005.00146.x.

11. References (cited)

ACEEE (American Council for an Energy-Efficient Economy) (2014), *Integrated Resource Planning for State Utility Regulators*, www.raponline.org/document/download/id/817.

Akhavan-Hejazi, H. and Mohsenian-Rad, H. (2018), "Power systems big data analytics: An assessment of paradigm shift barriers and prospects", *Energy Reports*, Vol. 4, pp. 91–100, www.sciencedirect.com/science/article/pii/S2352484717300616.

Alam, S. et al. (2018), Fault Current Limiters in Power Systems: A Comprehensive Review, *Vol. 11*(5), 1025, https://www.mdpi.com/1996-1073/11/5/1025

Bagheri, A. and Hjorth, P. (2007), "Planning for sustainable development: a paradigm shift towards a process-based approach", Sustain. Dev., Vol. 15(2), pp. 83–96, https://onlinelibrary.wiley.com/doi/abs/10.1002/sd.310.

CEB (Ceylon Electricity Board) (2017), *Long Term Generation Expansion Plan*, www.pucsl.gov.lk/english/wp-content/uploads/2017/05/LTGEP_2018-2037.pdf.

Chaturvedi, D. K. and Isha (2016), "Solar power forecasting: a review", *International Journal of Computer Applications*, Vol. 145, No. 6, https://pdfs.semanticscholar.org/a679/0993e18db1b5d488b161194fa07a3d5c139f.pdf.

Debnath, K. B. and M. Mourshed (2018), "Challenges and gaps for energy planning models in the developing-world context", *Nature Energy*, Vol. 3(3), pp. 172–84, www.nature.com/articles/s41560-018-0095-2.

DOE (Department of Energy) (2016), *Integrated Energy Plan*, South Africa, www.energy.gov.za/files/IEP/2016/Integrated-Energy-Plan-Report.pdf.

EPRI (Electric Power Research Institute) (2016), *Electric Power System Flexibility: Challenges and Opportunities*, EPRI, www.naseo.org/Data/Sites/1/flexibility-white-paper.pdf.

ERC (Energy Regulatory Commission) (2018), *Updated Least Cost Power Development Plan*, www.erc.go.ke/wp-content/uploads/2018/09/Updated-Least-Cost-Power-Development-Plan-2017-2022.pdf

Fichtner (2013), *Islamic Republic of Afghanistan, Power Sector Mater Plan*, Asian Development Bank, www.adb.org/sites/default/files/project-document/76570/43497-012-afg-tacr.pdf.

Frangopoulos, C. A. (2018), "Recent developments and trends in optimization of energy systems", *Energy*, doi: 10.1016/j.energy.2018.08.218, www.sciencedirect.com/science/article/abs/pii/S0360544218317547.

Greacen, C. et al. (2013), *An Introduction to Integrated Resources Planning*, International Rivers, www.internationalrivers.org/sites/default/files/attached-files/intlrivers_irp.pdf.

Howell, S. et al. (2017). "Toward the next generation of smart grids: semantic and holonic multiagent management of distributed energy resources", *Renew. Sustain. Energy Rev.*, Vol. 77, pp. 193–214, www.sciencedirect.com/science/article/pii/S1364032117304392.

IAEA (International Atomic Energy Agency) (2005). “Energy indicators for sustainable, development: guidelines and methodologies”, IAEA, Vienna, www-pub.iaea.org/MTCD/Publications/PDF/Pub1222_web.pdf.

IEA (International Energy Agency) (2018), *Status of Power System Transformation: Advanced Power Plant Flexibility*, OECD/IEA, Paris, doi: 10.1787/9789264278820-en, https://webstore.iea.org/download/summary/1041.

IEA (International Energy Agency) (2014) “The Power of Transformation, Wind, Sun and the Economics of Flexible Power Systems”, Paris, https://webstore.iea.org/the-power-of-transformation

IES (Intelligent Energy Systems) (2015), *Myanmar Energy Master Plan*, www.burmalibrary.org/docs22/2015-12-Myanmar_Energy_Master_Plan.pdf.

IRENA (International Renewable Energy Agency) (2017), “Planning for the renewable future: Long-term modelling and tools to expand variable renewable power in emerging economies”, IRENA, Abu Dhabi, www.irena.org/-media/Files/IRENA/Agency/Publication/2017/IRENA_Planning_for_the_Renewable_Future_2017.pdf.

IRENA (2018), *Power System Flexibility for the Energy Transition*, Part 1: Overview for policy makers, IRENA, Abu Dhabi, https://www.irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition

JICA (Japan International Cooperation Agency) (2016), Power System Master Plan, Government of the People’s Republic of Bangladesh, https://powerdivision.portal.gov.bd/sites/default/files/files/powerdivision.portal.gov.bd/page/4f81bf4d_1180_4c53_b27c_8fa0eb11e2c1/(E)_FR_PSMP2016_Summary_revised.pdf.

Lahmeyer (2012), *Renewable Energy Development Plan for Ghana*, www.lahmeyer.de/en/projects/energy/solar-energy/single/article/renewable-energy-development-plan-for-ghana/.

Luo et al. (2015), “Overview of current development in electrical energy storage technologies and the application potential in power system operation”, *Applied Energy*, www.sciencedirect.com/science/article/pii/S0306261914010290.

Madrigal, M. and Stoft, S. (2012), *Transmission Expansion for Renewable Energy Scale-Up, Emerging Lessons and Recommendations*, The World Bank, https://openknowledge.worldbank.org/handle/10986/9375.

Mayrhofer and Gupta (2016), “The science and politics of co-benefits in climate policy”, *Environmental Science and Policy*, Vol. 57, pp. 22–30, www.sciencedirect.com/science/article/pii/S1462901115301064.

McPherson, M. and Karney, B. (2014), “Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector”, *Energy Policy*, Vol 68, pp. 146–57, www.sciencedirect.com/science/article/pii/S0301421514000330.

Ming, M. et al. (2015), “Multi-objective optimization of hybrid renewable energy system using an enhanced multi-objective evolutionary algorithm”, *Energies*, Vol. 8(4), pp. 2924–49, https://doi.org/10.3390/en8042924.

Mirakyan, A. (2013). “Integrated energy planning in cities and territories: A review of methods and tools”, *Renew. Sustain. Energy Rev.*, Vol. 22, pp. 289–79, www.sciencedirect.com/science/article/pii/S1364032113000646.

Mirakyan, A. and R. De Guio (2016), *Three Domain Modelling and Uncertainty Analysis, Applications in Long Range Infrastructure Planning*, Springer International Publishing. www.springer.com/de/book/9783319195711#aboutAuthors.

Mirakyan, A. and De Guio, R. (2015). “Modelling and uncertainties in integrated energy planning”, *Renew. Sustain. Energy Rev.*, Vol 46, pp. 62–9, www.sciencedirect.com/science/article/pii/S1364032115001161

Mirakyan, A. and De Guio, R. (2014), “A methodology in innovative support of the integrated energy planning preparation and orientation phase”, *Energy*, Vol. 78, pp. 916–27, www.sciencedirect.com/science/article/abs/pii/S0360544214012390.

NEC (National Energy Commission) (2013), *Making the Right Choice for a Sustainable Energy Future 2013*, http://publicutilities.govmu.org/English/DOCUMENTS/NEC%20FINAL%20REPORT.PDF.

NREL (National Renewable Energy Laboratory) (2008), Transmission System Performance Analysis for High-Penetration Photovoltaics, NREL/SR-581-42300, NREL, Golden, https://www.nrel.gov/docs/fy08osti/42300.pdf.

NREL (2012), Renewable Electricity Futures Study: Exploration of High-Penetration Renewable Electricity Futures, NREL/TP-6A20-52409-1, NREL, Golden, CO, www.nrel.gov/docs/fy12osti/52409-1.pdf.

NREL(National Renewable Energy Laboratory) (2016), *Forecasting Wind and Solar Generation: Improving System Operations*, NREL, Golden, CO, www.nrel.gov/docs/fy16osti/65728.pdf.

Perras, S. (2014), “Electricity transmission line planning: Success factors for transmission system operators to reduce public opposition”, University Dresden, Faculty of Business and Economics, PhD thesis, www.qucosa.de/fileadmin/data/qucosa/documents/16177/140220_Dissertation_Stefan_Perras_FINAL_Qucosa.pdf.

Pohekar, M. Ramachandran (2004), “Application of multi-criteria decision making to sustainable energy planning – A review”, *Renew. Sustain. Energy Rev*., Vol. 8, pp 365–81, https://pdfs.semanticscholar.org/c605/9af177503e0a2c9f7f25cfcc8689266f3861.pdf.

Pöller, Markus (2012), “Assessing the impact of increasing shares of variable generation on system operations in South Africa”, Flexibility Study, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, www.ee.co.za/wp-content/uploads/2018/05/GIZ-M.P.E.-2017-Flexibility-Study-Report.pdf.

Ringkjøb, H. et al. (2018), “A review of modelling tools for energy and electricity systems with large shares of variable renewables”, *Renew. Sustain. Energy Rev.*, Vol. 96, pp. 440–59, www.sciencedirect.com/science/article/pii/S1364032118305690.

SNC-Lavalin (2011a), *Developing the Power System Master Plan for Bihar*, Asian Development Bank, www.adb.org/projects/documents/developing-power-system-master-plan-bihar-0

SNC-Lavalin (2011b), *National Power System Expansion for Pakistan*, http://climateinfo.pk/frontend/web/attachments/data-type/PSEP%2001%20Main%20Report.pdf.

Swasti, R. et al. (2017), "Smart asset management for electric utilities: big data and future", Proceedings of 12th World Congress on Engineering Asset Management (WCEAM) 2017, https://arxiv.org/abs/1706.09711.

Swisher, J. N.et al. (1997), "Tools and methods for integrated resource planning", United Nations Environmental Programme, Roskilde, https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=29031683.

Ueckerdt, F. et al. (2015), "Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves", *Energy*, Vol. 90, Part 2, pp. 1799–814, www.sciencedirect.com/science/article/abs/pii/S0360544215008993.

Utilities Commission (2013), "Network technical code and network planning criteria", www.powerwater.com.au/__data/assets/pdf_file/0012/3441/network_technical_code_and_network_planning_criteria.pdf.

Vera, I. and L. Langlois (2007), "Energy indicators for sustainable development", *Energy*, Vol. 32(6), www.sciencedirect.com/science/article/abs/pii/S0360544206002337.

Wang, L. et al. (2013), "A data warehouse architecture supporting energy management of intelligent electricity system", Proceedings of the 2nd International Conference on Computer Science and Electronics Engineering, www.researchgate.net/publication/266646757_A_Data_Warehouse_Architecture_supporting_Energy_Management_of_Intelligent_Electricity_System.

Willis, H. L. (2004), *Power Distribution Planning Reference Book*, 2nd edn, CRC Press, https://books.google.de/books/about/Power_Distribution_Planning_Reference_Bo.html?id=9EShPwTRnoUC&redir_esc=y.

Wilson, R. and B. Biewald (2015), *Best Practices in Electric Utility Integrated Resource Planning*, Synapse Energy Economics, www.raponline.org/knowledge-center/best-practices-in-electric-utility-integrated-resource-planning/.

WVP (Wabash Valley Power) (2015), *Integrated Resource Plan*, www.wvpa.com/wp-content/uploads/2015/08/WVPA-2015-Integrated-Resource-Plan-Executive-Summary.pdf.

Zeng, Y. et al. (2011), "A review on optimization modelling of energy systems planning and GHG emission mitigation under uncertainty", *Energies*, Vol. 4, pp. 1624–56, doi:10.3390/en4101624, www.mdpi.com/1996-1073/4/10/1624.

Zheng, Z. W. et al. (2011), « An overview: development of prediction technology of wind and photovoltaic power generation", *Energy Procedia*, Vol. 12, pp. 601–8, www.sciencedirect.com/science/article/pii/S1876610211019072.