Smart Energy Systems and Use of Energy Plan as an Energy and Power Generation Planning Tool

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Abstract

Energy planning and management is a requirement sustainable use of energy resources which are necessary social, economic or environment sustainability. There is need to balance electricity generation and consumption for safety, supply security and cost monument hence the need for effective modern energy models. Forecasting demand and planning for generation is one of the planning tools to ensure availability of accurate forecast and identifying management decisions. Energy plan is an energy system analysis tool and methodologies suitable for the design and evaluation of smart energy and renewable energy system alternatives. This study presents the EnergyPLAN model and describe how to use it for the design of relevant alternatives. The is an energy system analysis tool that can be used for study and research in the design of future sustainable energy solutions with a special focus on energy systems with high shares of renewable energy sources. Traditionally disparate demand sectors, such as buildings, industry and transport, are linked with supply technologies through electricity, gas, district heating and cooling grids. In this way, EnergyPLAN enables the analysis of the conversion of renewable electricity into other energy carriers, such as heat, hydrogen, green gases and electrofuels, as well as the implementation of energy efficiency improvements and energy conservation. The structure of EnergyPLAN is discussed and the essential algorithms and computational structure. The EnergyPLAN can analyse coherent energy systems on an aggregated basis and with emphasis on evaluation of potential synergies across subsectors. EnergyPLAN evaluates hourly balances of district heating and cooling, electricity and gas grids involving technologies like heat pumps, cogeneration, electrolyzers, and electric vehicles, gasification, hydrogenation, and co-electrolyzers. The model is a freeware used in many countries globally.
Key words: EnergyPLAN; Model description; Smart energy systems; Energy systems analysis; Energy modelling

Keywords
renewable energy system , Power Generation, EnergyPLAN, electrolyzers,,

Highlights

Abbreviations

CEEP: Critical Excess Electricity Production

CHP: Combined heat and power

CSP: Concentrated solar power

EEEP: Exportable Excess Electricity Production

RES: Renewable energy resources

Introduction

Concerns over greenhouse gas emissions and global climate change have generated interest in measures that not only reduce energy costs but environmental and meet other requirements like compliance to the Paris Agreement targets, energy security, renewable energies and energy efficiency by most governments. The global financial crisis brought renewed recovery policies to reduce energy dependency by increasing the penetration of renewable energy sources and promotion of energy efficiency measures. (Mendes et al. 2011),(Lund et al. 2016). During the last decade several new techniques are being used for energy demand management to accurately predict the future energy needs. In this paper an attempt is made to review the various energy demand forecasting models. Traditional methods such as time series, regression, econometric, ARIMA as well as soft computing techniques such as fuzzy logic, genetic algorithm, and neural networks are being extensively used for demand side management. Energy models are developed for sustainable progress of any nation. Energy demand models can be classified in several ways such as static versus dynamic, univariate versus multivariate, techniques ranging from times series to hybrid models(Suganthi & Samuel 2012).

To minimise carbon dioxide emissions and thereby meet the Paris Agreement targets, energy systems must transition away from being predominantly fossil fuel-based to being based on renewable energy sources (RES). This is a transition away from freely dispatchable production units towards units employing resources that are frequently of a fluctuating and possibly use-it-or-lose-it nature. The robust planning and decision-making of such a transition and the study of the implications of different choices call for advanced tools to handle the increasingly complex nature of the energy system(Lund et al. 2021).

Currently, a wide range of computer tools allow users to model and analyse energy systems at the national and regional levels to help design transition pathways. These model are often very different from one another, and therefore decision makers and researchers should choose the most suitable energy system modelling tool depending on the specific purpose and objectives of their analysis(Lund et al. 2021).

The three most common methodological approaches to energy system modelling are optimisation, simulation and equilibrium tools or models. Optimisation tools include endogenous system design optimisation; simulation tools simulate exogenously defined energy systems, and equilibrium tools include a larger econometric model of the society.Each approach has strengths as indicated by the main characteristic but also weaknesses. Thus, while optimisation tools are dominant within energy systems analysis , their complexity can cause difficulties in interpreting the results and can influence their accuracy. In their systematic analysis investigating power system optimisation models, Priesmann and co-authors even found that the higher model complexity does not guarantee higher accuracy. Likewise, it has been highlighted that uncertainties and variations in inputs for simulation models for low-carbon energy systems can have significant impact on the energy system performance. Lastly, top-down equilibrium models have shown significant sensitivity when analysing the integration of RES and potentially need to be enhanced or be used as a part of integrated mixed models(Lund et al. 2021).

One example of a widely used simulation tool is the freeware EnergyPLAN. This is one of the most commonly used tools for the evaluation of energy systems with high shares of RES. Some authors consider it the most suitable tool to identify a feasible RES integration within an energy system, e.g., in China, Denmark and Ireland. Different aspects of EnergyPLAN have been described and communicated in the scientific literature as integrated sections of the many published articles employing it. However, due to the nature and complexity of EnergyPLAN, the individual papers have found neither the space nor the necessity to describe the overall structure and details of the tool, but have typically focused on the parts pertinent to the analyses at hand(Lund et al.2021).

For a simulation tool as widely applied as EnergyPLAN, it is a significant gap in the scientific literature that there is no standard reference article describing it. Therefore, the aim of this paper is to provide this description in the hope that it will ease the writing and publication of studies applying EnergyPLAN in the future. More specifically, the goal of the paper is to demonstrate the core principles of EnergyPLAN and to document how it identifies the optimal operation of the units of the energy systems. This is based on both technical and economic simulation strategies. The paper first describes the purpose and guiding principles behind the tool along with general characteristics; then it relates the tool to the context and approach of smart energy systems. Subsequently, the structure and essential equations and procedures of its simulation approach are documented and, finally, the main conclusions are drawn(Lund et al. 2021).

There is need for global energy systems to transition from fossil fuel dominated sources to renewable energy-based sources (RES) to reduce minimise carbon dioxide emissions and meet the targets set by the Paris Agreement. The shift is from freely dispatchable power plants to that employ frequently fluctuating and possibly use-it-or loose-it nature. Advanced tools are needed to handle the increasingly complex nature of the energy system to realise a robust planning and decision-making process and analyse implications of different choices call for (Lund et al. 2021).

The EnergyPLAN model is used to analyse coherent energy systems on aggregated basis with emphasis on evaluation of potential synergies between multiple subsectors. EnergyPLAN applies hourly balances of district heating and cooling together with electricity and gas grids. And covers a wide range of technologies across multiple sectors like heat pumps, cogeneration, electrolysers, gasification, electric vehicles, hydrogenation, and co-electrolyzes (Lund 2014a).

EnergyPLAN simulation tool integrates energy systems and models within a competitive environment. However, it does not support investment optimization. Therefore, for investment optimization, hence need for a method to determine optimal combination between different sources e.g. wind and solar by running serial simulations, a method which allows only parametric runs with decision variables for energy mix optimization (Batas Bjelić & Rajaković, 2015; Lund, 2006). EnergyPLAN has been under development since 1999 and been used for substantial PhD theses and several hundreds of research papers. EnergyPLAN exploits system the synergies derived from the whole energy system, based on the smart energy system concept. EnergyPLAN enables the user to take a holistic approach focusing on the analysis of the cross-sectoral interaction(Lund 2006).

An external investment optimization tool ought to be soft-linked to the EnergyPLAN in order to prove the synergetic effect of sets of technical measures e.g. EU2030 policy goals. There is need to apply a master program to determine capital investment decisions with production costs being computed usually in a linear but not restricted to, subprogram. Under such circumstances, all operational constraints are left to the EnergyPLAN tool, like, technical minima in thermal power plants, pumped hydro storage power plants operation and inter-connection constraints for all scenarios. Hence in the total cost minimization problem, only implementation of policy goals as constraints is included(Batas Bjelić & Rajaković 2015; Mancarella 2014).

1.1. Problem

A wide range of computer tools enable users to model and analyse energy systems at the national and regional levels to identify transition pathways. A decision has to be made because the models are very different from one hence and there is need to identify the most suitable energy system modelling tool depending for specific application and objectives of the analysis(Lund 2006).

Rationale of the Study

A number of aspects of EnergyPLAN have been discussed and communicated in publications as integrated section of the many published articles employing the model. However, EnergyPLAN is complex and individual papers have rarely described the overall structure and details of the tool, other than focusing on parts pertinent to whatever is being analysed. Energy plan is a widely used simulation tool, there is need for a standard reference article describing it its structure and applications. The objective of this study is to provide the description to ease the writing and publication of studies applying EnergyPLAN by researchers. The specific goal of the paper is to demonstrate the principles of EnergyPLAN as well as document how it it works in identifying optimal operation of the various units of the energy systems.

Methods and Structure

This paper first describes the functions and guiding principles behind EnergyPLAN along with general characteristics. The tool is the analysed in the context of and approach of smart energy systems. The paper presents the structure and essential equations and procedures of the simulation approach and, with main conclusions being made from the analysis.

Smart Energy Systems

Quite a number of new new definitions and terms proposed to develop new approaches and understandings to the design future sustainable energy systems e.g. smart grid, Net Zero Energy Buildings (NZEB*)* and power to gas. These new terms and approaches are defined and applied within the limits of sub-sectors and sub-infrastructures thus represent a single-sector approach to energy planning, which is hard to analyze and fully understand unless it is placed in the context of the overall energy system(Elkamel et al. 2010),(Lund et al. 2016).
The term Smart Energy or Smart Energy Systems was defined and applied to provide the basis for a scientific paradigm shift away from single-sector approach into a coherent and integrated approach of how to identify, design, design and operate the most achievable and affordable strategies for future sustainable energy systems(Lund et al. 2017),(Moses Jeremiah Barasa Kabeyi & O A Olanrewaju 2022),(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022).

According to (Lund et al. 2017), the term smart energy was systems was first introduced in the year 2012 and was later on given a specific definition as punished in the year 2014 after pre-booklet publishing in the year 2013(Lund et al. 2012). recent years, the terms “Smart Energy” and “Smart Energy Systems” have been used to express an approach that reaches broader than the term “Smart grid”. Where Smart Grids focus primarily on the electricity sector, Smart Energy Systems take an integrated holistic focus on the inclusion of more sectors (electricity, heating, cooling, industry, buildings and transportation) and allows for the identification of more achievable and affordable solutions to the transformation into future renewable and sustainable energy solutions. This paper first makes a review of the scientific literature within the field. Thereafter it discusses the term Smart Energy Systems with regard to the issues of definition, identification of solutions, modelling, and integration of storage. The conclusion is that the Smart Energy System concept represents a scientific shift in paradigms away from single-sector thinking to a coherent energy systems understanding on how to benefit from the integration of all sectors and infrastructures(Lund et al. 2017).

From literature, the term Smart Energy Systems has been applied within the field of control engineering and management simply as synonymously for Smart Grid to express that the control system has a broader application than only within the electricity sector. Other terms used for smart energy systems are integrated energy systems or integrated community energy systems(Mendes et al. 2011). The State-of the-art of power-to-gas the concept defined mainly to boost hydrogen and/or green gas and green liquid fuel production within existing limitations of transport, gas, and the electricity subsectors of energy. This creates a paradigm in which available solutions to the integration of variable renewable energy sources should be found within the key subsectors of energy. Substantial research is done within these limits and the integration of the other sectors like heating is often overlooked. The idea behind the Smart Energy Systems concept is that better solutions can be developed key sectors, like heating sectors are included(Lund et al. 2017).

In 2013,(Lund 2014b), (Connolly et al. 2013) formally defined smart energy system as “new technologies and infrastructures that create new forms of flexibility, primarily in the energy systems’ ‘conversion’ stage. Therefore, smart energy systems combine means electricity, thermal, and transport sectors to ensure that flexibility compensates for lack of flexibility across these different areas involving use of renewable energy sources. The systems is built around there infrastructure;

i.) Smart Electricity Grids
Used to connect flexible electricity demands like heat pumps and electric vehicles to intermittent renewable resources like solar and wind.

ii.) Smart Thermal Grids
Thermal grids connect district heating and Cooling to connect the electricity and heating sectors thus enabling application of thermal storage to create additional flexibility and the recovery of heat losses in the energy system.

iii.) Smart Gas Grids
Smart gas grids are used to connect electricity, heating, and transport sectors to facilitate use of gas storage to create additional flexibility.

Based these fundamental infrastructures the Smart Energy Systems are defined as approaches in which smart electricity, thermal and gas grids together with storage infrastructure are coordinated to identify synergies between them to achieve an optimal solution for each individual sector and the overall energy system(Lund et al. 2012; Lund et al. 2017).

A Smart Energy System is an approach that combines smart electricity, thermal energy and gas grids with energy storage technologies and coordinated in a way the utilises synergies between them in to achieve an optimal solution for individual sectors as well as for the overall energy system(Lund et al. 2017). A Smart Energy System is characterised by the following key principals

i.) It based on 100% renewable energy system
ii.) Consumes a sustainable level of biomass and bioenergy
iii.) Apples the synergies energy system to maximise efficiency and minimise costs

A smart energy system is affordable. Hence it does not significantly increase the cost of energy when compared to a fossil fuel based energy system, although at times it can reduce the cost and maximum increases of up to 10-15% are expected (Lund et al. 2021),(Abanades et al. 2021) A key objective of EnergyPLAN tool to assist in the design of 100% renewable energy systems. The development of EnergyPLAN that began way back in the year 2000,has added momentum to the concept of a 100% renewable energy system.(Abanades et al. 2021)

Modelling Smart Energy Systems

Common methodological approaches to energy system modelling applied are simulation, optimisation, and equilibrium tools or models. Optimisation tools include endogenous system design optimisation. The simulation tools simulate exogenously to defined energy systems, while equilibrium tools include a larger econometric model of the society. Each modelling approach has weaknesses and strengths. Optimisation tools are dominant within energy systems analysis but their complexity can cause challenges in results interpretation and can influence their accuracy. Higher accuracy is not guaranteed by model complexity. Uncertainties and variations in simulation models' inputs for low-carbon energy systems has significant impact on the performance of energy systems. Top-down equilibrium models have significant sensitivity when used to analyse renewable energy integration and therefore are best used as a part of integrated mixed models.

Smart energy systems models should provide similar and parallel analyses of gas grids, thermal and electricity systems. Examples of such models are EnergyPLAN, developed to enable an hourly basis analysis. The main role of the smart energy models is to design national energy planning strategies based on technical and economic analyses of energy and investment options. EnergyPLAN emphasises complete energy system as a whole in which electricity smart grids can be coordinated with use of renewable energy for other applications in addition to electricity production(Lund et al. 2017).

In EnergyPLAN the renewable energy is converted to other carriers like heat, synthetic gas, hydrogen, and biofuels as well as application of energy conservation and efficiency enhancements through strategies and combined heat and power which have potential to replace and reduce consumption of fossil fuels. As an effective modelling tool for smart energy systems, EnergyPLAN can compute hourly electricity balance, hourly district heating and cooling balancing and hourly hydrogen and natural gas with contributions from biogas, gasification, electrolysis and hydrogenation.(Lund 2014b).

Energy Plan

EnergyPLAN is an example a freeware widely used simulation tool commonly used for the evaluation of energy systems that have high share of renewable energy sources (RES). Energy PLAN is considered by a number of researchers as the most suitable tool for identification of RES integration within an energy system and has been applied for studies on many countries including China, Denmark and Ireland(Mancarella 2014).

Purpose of Energy Plan

The main function of EnergyPLAN is to facilitate the design of national energy planning strategies with technical and economic analyses of the consequences of different choices and investments. Its main purpose is not to provide the basis for prescribing or predicting the future energy system, instead form a basis for an informed, transparent and conscious deliberation of potential development pathways for the energy system(Lund et al., 2021). The main objective of energy plan was for nation-scale energy systems, but currently other geographical scales can be applied using EnergyPLAN(Østergaard 2015).

1.2. Guiding principles

Energy PLANs overarching guiding principle for the use and applications is establishing alternatives i.e. enable the consistent comparison of various alternative strategies of the energy system. It is based on the idea of *choice* in which energy transition pathways are in a process with a conscious and transparent evaluation of consequences of alternative measures and strategies. Ultimately, Energy PLAN is developed with capacity to consider alternative energy system combinations and also with speed, user friendliness and ease of implementing changes in mind. With respect to establishment of scenarios, the guiding principle resulted in the following objectives;

Character of technological change

Energy PLAN should facilitate users to analyse the type of technological change needed for 100% renewable energy systems. This is achieved in Energy PLAN by including a variety of new technologies like wave power, district heating and cooling, tidal power, concentrated solar power, thermal storage, biogas production, biomass gasification, and various Power-to-X technologies.

Multiple alternatives For the transport sector, Energy PLAN facilitate transparent and consistent comparison of multiple transition alternatives by quantify the impacts of many different alternatives, instead of generating a single optimal solution through endogenous energy system design optimisation. It is not easy to identify an ideal metric to quantify benefits of energy systems because an energy system may be cheap but because it relies on a high proportion of energy imports makes it less desirable than a more expensive system using primarily local or domestic resources(Lund et al., 2021). Therefore, designing an energy system on basis of optimal solution generating the lowest cost, may be overlooked. Additional, long-term projections like energy prices are prone to large uncertainties which make endogenous system designs equally uncertain. In Energy PLAN, a scenario simulation may be completed in less than 10 seconds with implication that users can demonstrate the impacts of various alternatives quickly(Batas Bjelić & Rajaković 2015).

Free of institutional inertia

The existing institutional and market frameworks should not limit alternatives designed in and analysed in Energy-PLAN which is a real issue within the electricity system, with some models which are constructed based on the design of the day-ahead markets in current, markets. Future energy system may not be ideal for current design of electricity markets for 100% renewable energy systems, particularly technologies with zero marginal production costs. Energy-PLAN has various operation strategies, like market simulation strategy based on the design of existing European electricity markets, and a technical simulation strategy. In Energy-PLAN, the technical simulation strategy does not depend on market designs and temporal market prices and operates the energy system for the system to minimise fuel.

1.3. Geographical Scope And Resolution

Energy-PLAN is mainly used for the design of national energy system analysis, and is therefore widely used to investigate energy systems and energy transitions in countries such including Germany, Denmark, Ireland, Norway. Hungary, Romania, Portugal, Singapore Hong Kong, Jordan, Chile and China. Energy-PLAN has also been applied to some large extent, to other geographical units like islands and cities like ands regions.

Additionally, even within the system like country, region or island covered by the model, Energy-PLAN simulates the electricity and the gas supplies with no spatial representation of supply and demand. In Energy-PLAN, connection to the outside world is modelled as a single transmission line but by using add-ons, individual models can be built of a number of countries or regions and analyse the electric transmission lines between them(Batas Bjelić & Rajaković, 2015).

1.4. Type Of Applications

EnergyPLAN forms the modelling basis for energy transition strategies, and is frequently applied in the analysis of the role of various technologies or technological systems which among other includes the role of Compressed Energy Storage, and hydro power, biogas and biomass, the role of district heating as heating infrastructures , pumps, and V2G ,the energy system value of flexible electricity demands, future energy market prices, and market designs buildings and energy efficiency and comparison of integrated and non-integrated energy systems. As a result of its versatility, EnergyPLAN has acquired a wide range of applications(Lund et al. 2021).

1.5. Sectorial Aggregation

For high computational speed, and setting up of models, Energy PLAN is aggregated in the system description and does not model each individual station and component. For example, district heating systems are, aggregated and defined as three principal technology groups and while RES technologies are aggregated into one stock of wind turbines having common characteristics. This also applies to power plants and waste incineration plants as well as to all demands.

For district heating, three different types of district heating system can be e modelled since they have different behaviours in the district heating system. These are:

i.) District heating systems based on fuel boilers
ii.) District heating systems based on backpressure CHP plants
iii.) District heating systems based on extraction CHP plants

These three typologies are referred to as district heating Groups 1–3(Lund et al., 2021).

1.6. Fundamental Modelling Approach

Energy PLAN applies "analytical programming "rather than establishing a series of balance equations solved numerically as in optimisation and equilibrium models. Energy PLAN applies a series of endogenous priorities and pre-defined procedures for simulating the operation of freely dispatchable units, with the approach being purely deterministic with no stochastic elements(Lund et al. 2021).

Energy PLAN simulates user-defined systems without making endogenous system optimisation. Various simulation strategies define the concrete optimisation criterion applied in an Energy PLAN simulation e.g. energy balance, primary energy consumption, operational expenditure but in design of scenarios, the user can apply any of the outputs of Energy PLAN or derivatives. Users can employ total system costs, renewable energy shares, job creation, emissions and other in exogenous system optimisation(Lund et al. 2021).

It is possible to combine Energy PLAN with other tools for exogenous scenario design based on various objectives. Such work may apply genetic algorithms to identify optimal scenarios based on multiple criteria(Lund et al. 2021).

1.7. Coding and execution

The programming and maintenance of Energy PLAN is done in Delphi Pascal. Energy PLAN is a freeware and users can engage on a semi open-source basis in which independent add-ons and help tools can be added by users. EnergyPLAN can include add-ons based on any type of coding but should provide an exe-file. The tool can be executed from other platforms like Excel or MATLAB, that allow multi-execution(Lund, 2014a),(Lund et al. 2021).

1.8. Considerations regarding time

Energy PLAN can be used to simulate one leap-year time period in total and for longer-spanning analyses, several simulations should be run. Within the one-year period, Energy PLAN can simulate the energy system on an hourly resolution level within one year. Therefore, all demands and productions should be exogenously defined using hourly time series. The reason is that the integration of renewables is a key focus for Energy PLAN. Therefore, the user should adequately factor in energy resource associated intermittencies. The hourly simulation is contrary to some scenario tools that simulate the system on an annual basis as well as some optimisation tools which are based on time slicing, where hourly sample periods are identified for more in-depth analyses(Lund et al. 2021). Energy PLAN's hourly resolution facilitate investigation hourly, daily, weekly and seasonal differences in power and heat demands and generation e.g. water inputs to large hydropower systems(Batas Bjelić & Rajaković 2015).

1.9. Grid stability

One objective of Energy PLAN is to balance power generation and demand based on an hourly resolution. Because of this, stability of active power and frequency are considered at this time step. However, Voltage stability and short-circuit power are not explicitly modelled but , Energy PLAN gives option of requiring certain units to have a minimum production at all hours to ensure that a minimum share of the power production comes from ancillary service-providing units, and that the share of each production category that should be interpreted as providing ancillary service should be defined(Batas Bjelić & Rajaković 2015).

1.10. Inputs and outputs

EnergyPLAN comes with a graphical user interface where the user can type in inputs and maintain an overview of the model. An overview of and outputs of the model are shown in Fig. 1

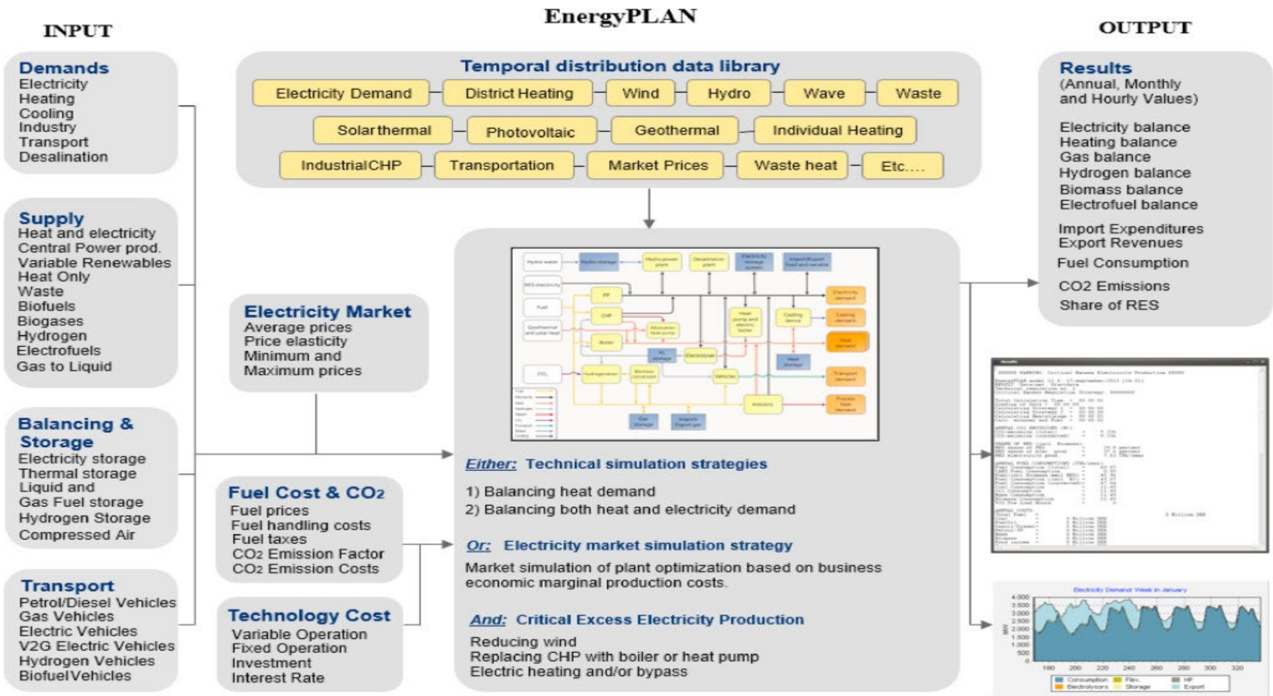

Figure 1. Data inputs and outputs of Energy PLAN.

The input structure of Energy PLAN refers to the aspects of an energy system:

i.) Energy demands including transport, heat and electricity,
ii.) Energy generation units and resources e.g. turbines, boilers, power plants, storage , energy conversion units like electrolysers, biogas plants, and gasification plants hydrogenation units, etc
iii.) Simulation i.e. defining the simulation and operation of generating units and power system and technical limitations like transmission capacity, etc.
iv.) Costs for fuel costs, gas, taxes variable and fixed operational costs and investment costs

The generated by EnergyPLAN include

i.) Energy balances and annual production
ii.) Electricity import and export
iii.) Fuel consumption,
iv.) Total costs including income derived from exchange of electricity.
v.) Results can be presented to resolution of 1 hour,
vi.) An export facility can enable the imported of results into a spreadsheet for further investigation, analysis or illustration.

Results are presented in monthly and yearly overviews of production and demands within different technology categories, additionally as gas and electricity imports and exports. Annual aggregates also include money flows, to and from an external electricity market, carbon dioxide emissions, and fuel consumption.

1.11. The Smart Energy Systems Approach of Energy PLAN

Energy PLAN was developed alongside the concept of smart energy systems as defined. Therefore, the design Energy PLAN emphasises the option of examining the complete energy system as a whole. Therefore the challenge of RES-based power integrating variable into the electricity grid via the smart grids is not looked upon as an isolated issue, instead be looked at as one out of various means and challenges of approaching sustainable energy systems in general(Lund et al. 2021).

Energy PLAN is therefore designed as a tool in for coordination of smart grids with the utilisation of renewable energy systems (RES) for other purposes than electricity production.

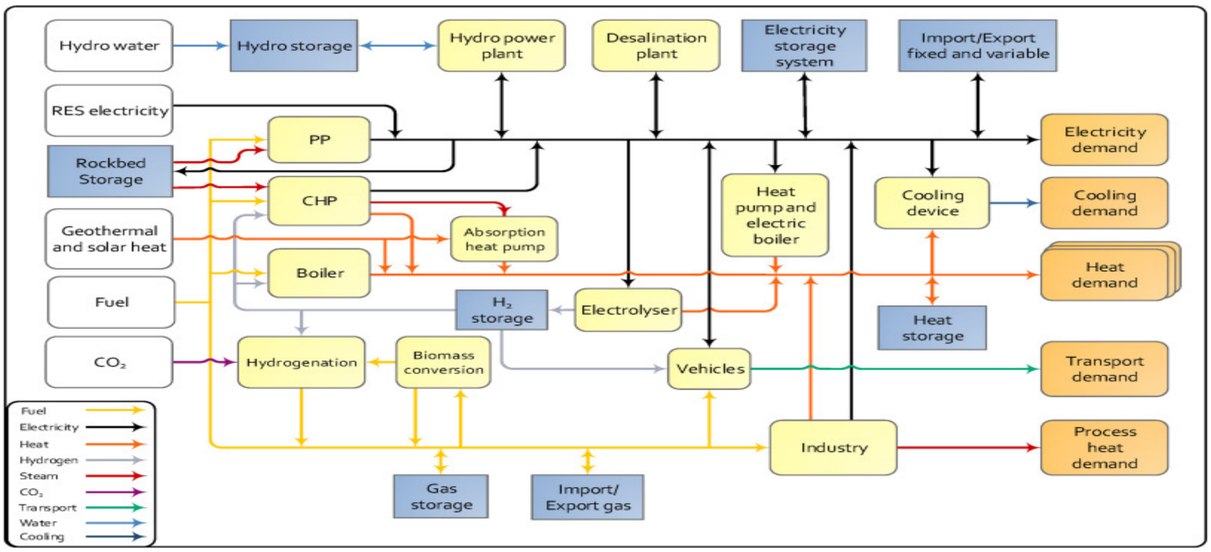

Figure 2. The overall technology and flow model on which Energy PLAN is based (Lund et al. 2021)

In Energy PLAN, renewable energy sources are converted into other forms of energy carriers than electricity via different power-to-x technologies\like heat, hydrogen, e-gases and electro fuels. EnergyPLAN can also be used to model renewable energy systems by considering energy conservation and efficiency improvements e.g. cogeneration (CHP) and fuel cells(Lund et al. 2021).

The measures taken have the potential to substitute fossil fuels or increase fuel efficiency of the system. A good energy system should in the long term take measures like energy conservation and system efficiency improvements. Consequently, Energy PLAN can be used for analyses which illustrate, e.g., why electricity smart grids should be seen as part of overall smart energy systems.(Lund et al. 2021)

EnergyPLAN can calculates an hourly electricity balance, balances of district heating, cooling, hydrogen and natural gas, including contributions from biogas, gasification as well as electrolysis and hydrogenation(Lund et al. 2021).

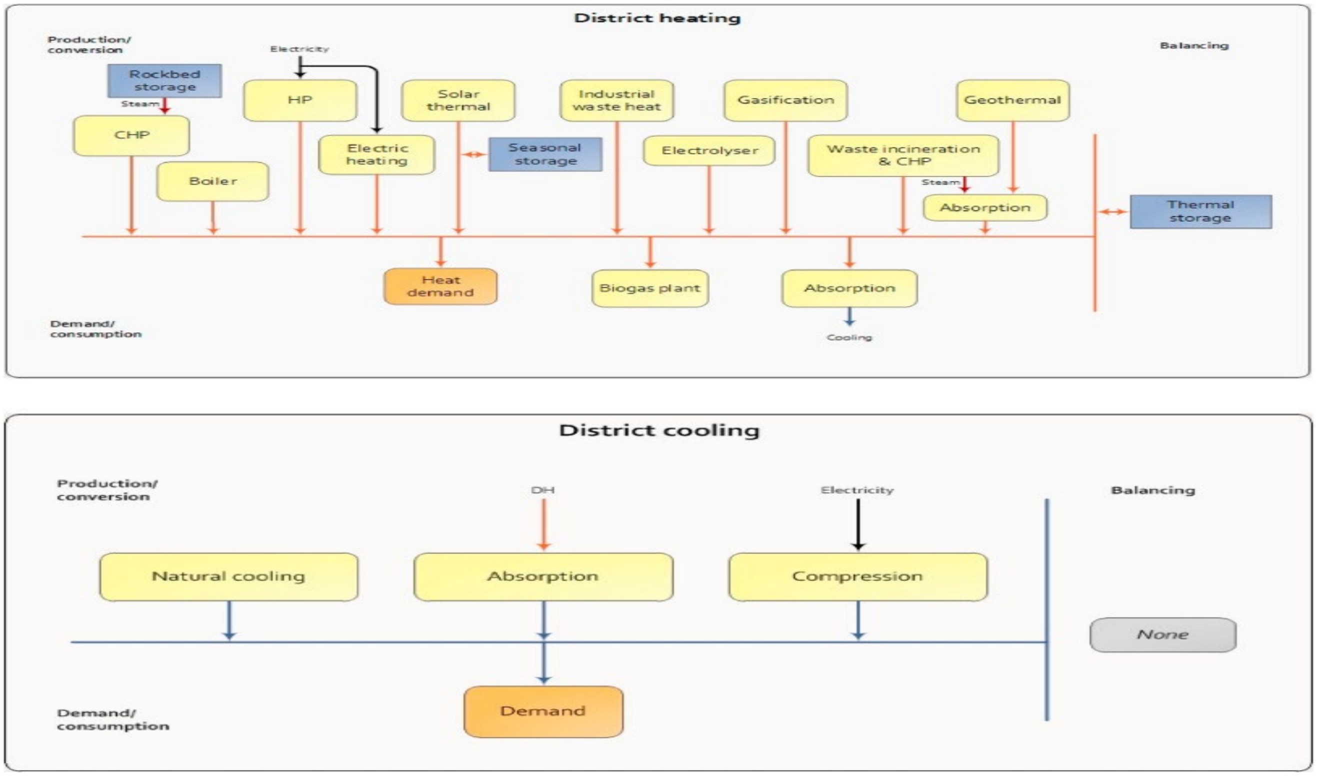

Figure 3. Units involved in Energy PLAN's simulation of the hourly balancing of the District Heating and Cooling system including interactions with other parts of the entire system.

District heating is divided into three separate systems in Energy PLAN, one for boiler-only systems, another one for small CHP systems, and one for large extraction CHP plant-based systems.

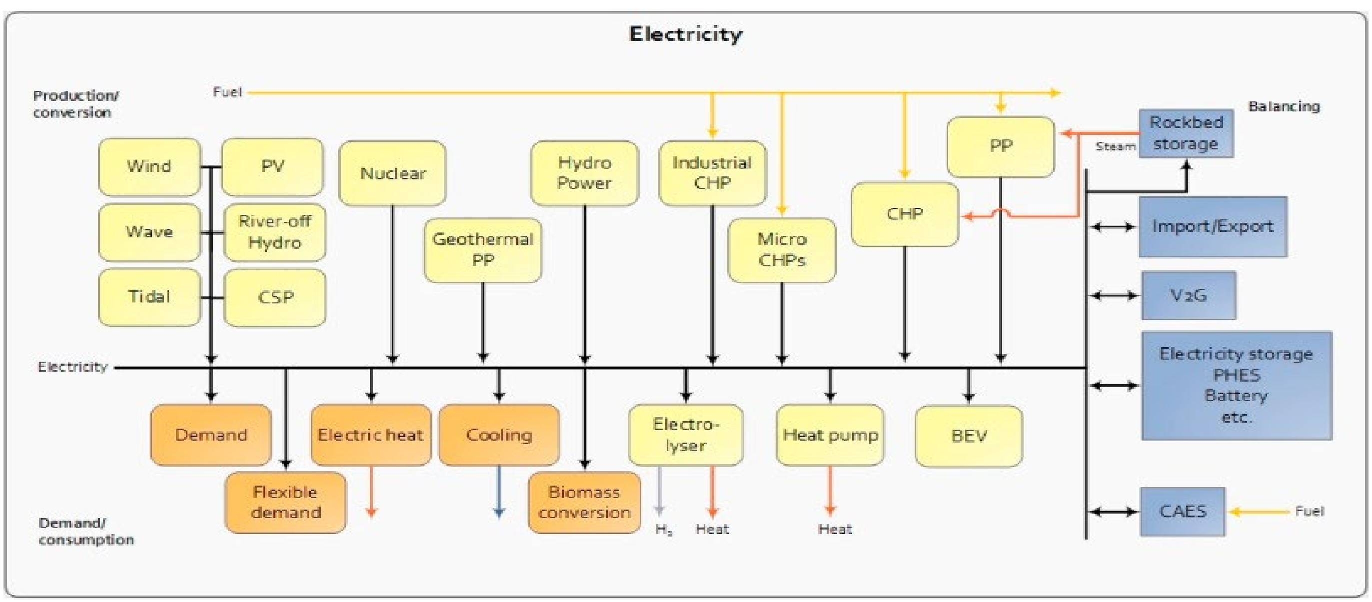

Figure 4. Units involved in Energy-PLAN's simulation of the hourly balancing of the Electricity system including interactions with other parts of the whole system.

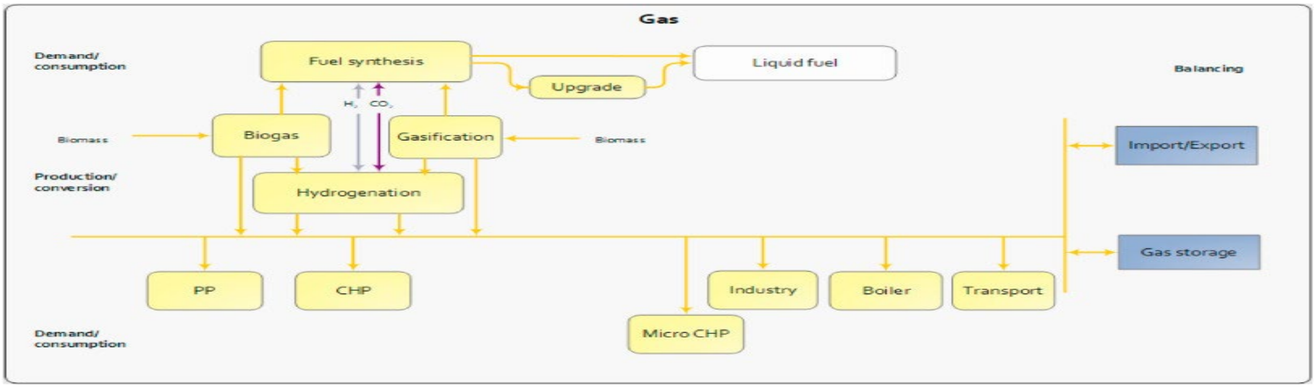

Figure 5. Units involved in Energy PLAN's simulation of the hourly balancing of the gas system including interactions with other parts of the whole system.

5. Computational Approach

5.1. General computational strategy

The very first calculations are made as entered in Energy PLAN, for example if wind capacity is entered, and hourly distribution is provided, and distribution file is chosen from the library, Energy PLAN computes annual and the hourly power generation(Østergaard 2015). This is demonstrated in figure 6

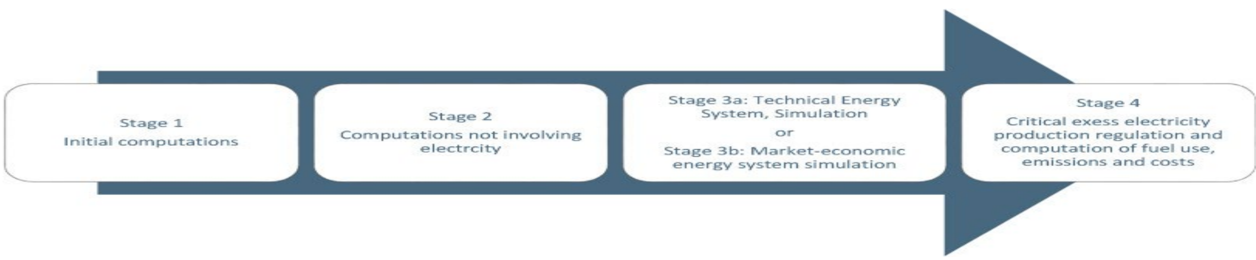

Figure 6. Overall structure of the energy system simulation procedures.

In stage 2, Energy PLAN finishes a number of initial computations not involving electricity balancing, like quantity of heat provided by industry, the hourly demand of heat in the three district heating systems and the hourly non-flexible electricity demand. Energy PLAN then branches based on user-specified simulation strategy, for the technical simulation Energy PLAN identifies the least fuel-consuming solution, and for the market-economic simulation Energy PLAN identifies the consequences of operating each unit on the electricity market with the aim of optimising the business-economic profit.

Energy-PLAN will then finish by computing socio-economic consequences of the system i.e. total energy systems costs and carbon dioxide externality in both simulation strategies, with the entire process taking s a few seconds. Both simulation strategies can be completed and compared. The technical and market-economic simulations are further detailed.

5.2. Technical simulation strategy

In technical energy systems simulation strategy by Energy PLAN the steps undertaken are summarised in figure 7 below. After each step, Energy PLAN establishes condensing mode power and import/export including CEEP (Critical and Exportable Excess Electricity Production).and EEEP (Exportable Excess Electricity Production

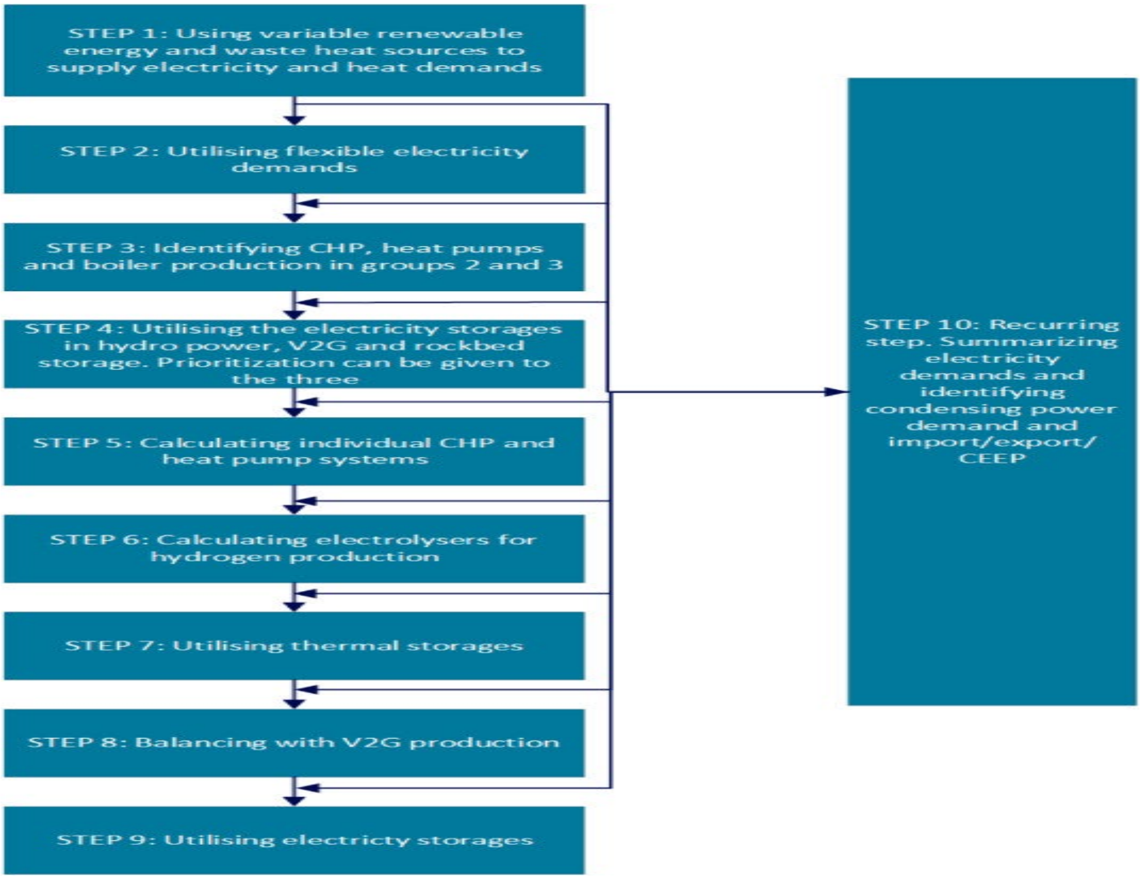

Figure 7. Graphical representation of Stage 3A: Technical Simulation Strategy in EnergyPLAN.

Figure 7 demonstrates the steps followed by Energy PLAN to carry out the technical simulation strategy. These steps are calculation sequence and not necessarily the importance of each measure and technology. The user can It is possible for the user to prioritise the measures(Lund, 2006).

Step 1

In the step, EnergyPLAN computes electricity and heat productions for units in district heating supply systems by beginning with , all heat units producing solely according to the heat demand, and these units are given priority on an hourly basis according to the following sequence:

a.) Solar Thermal

b.) Industrial excess heat incl. electrolysers and thermal gasification

c.) Heat production from waste fuel

d.) Heat plant CHP

e.) Heat pumps

f.) Peak load boilers

The hourly electricity generation from variable RES are already calculated in Stage two.

i.) Step 2

At this stage, Energy Plan identifies the potential use flexible electricity demand if available and specified in the input. Demand for electricity can be made flexible, , or within short periods according to four time horizons. The modeller can choose to stipulate an annual demand which may be shifted within three timeframes – 24 hours 1week or 4weeks within a capacity constraint.

EnergyPLAN establishes the best use of flexible demands to achieve a balance between electricity demand and supply with two limitations i.e. should be positive at any time and it should be below the stipulated capacity constraint. The average demand for period should equal average demand for the year by normalisation of the variation(Lund 2006).

ii.) Step 3

At this stage, the modeller can choose operation of CHP and heat pumps as input. Energy PLAN will seek to balance the electricity supply and demand of the overall system. If this strategy is chosen, Step 1 calculations are replaced by a strategy to minimise electricity export by use of heat pumps at CHP plants thus increasing electricity demand to the heat pumps and decrease the electricity generation by CHP units. By making use of unused capacity at the CHP plants in the given hour combined with heat storages, any production at condensing-mode plants is minimised and replaced by CHP production.

iii.) Step 4

Hydropower can be used to replace replacing the condensing-mode plants and decreasing, first, Critical Excess Electricity production (CEEP) and, secondly, Exportable Excess Electricity production (EEEP). In this case, first is establish the potential of replacing the condensing-mode power plant ($e_{Hydro\text{-}Inc}$) which is minimum value of the production of the condensing unit and the difference between hydropower capacity and hydropower production.$e_{Hydro\text{-}Inc} = MIN\ (e_{PP}, (C_{Hydro} - e_{Hydro}))$

Hydropower production, e_{Hydro}, is identified from stage 1. The potential to reduce hydropower in the case of CEEP ($e_{Hydro\text{-}Dec\text{-}CEEP}$) is established as a minimum value of the CEEP and the hydropower generation. The hydropower potential is limited by the fact that the hydropower plant potentially forms part of grid stabilisation:

$e_{Hydro\text{-}Dec\text{-}CEEP} = MIN\ (e_{CEEP}, e_{Hydro}) e_{Hydro\text{-}Dec\text{-}CEEP} \leq e_{Hydro} - e_{Hydro\text{-}Min\text{-}Grid\text{-}Stab}$

For reverse hydropower, i.e., a pump and both a lower and a higher water reservoir, the potential to further decrease CEEP ($e_{Hydro\text{-}Pump\text{-}Dec\text{-}CEEP}$) is established as the minimum value of the CEEP (minus the share that is already dispatched), pump capacity, and the content of the lower water storage,

$s_{Hydro\text{-}PUMP}: e_{Hydro\text{-}Pump\text{-}Dec\text{-}CEEP} = MIN\ [(e_{CEEP} - e_{Hydro\text{-}Dec\text{-}CEEP}), C_{Hydro\text{-}PUMP}, s_{Hydro\text{-}PUMP} / \mu_{Hydro\text{-}PUMP}\ ]$

The potential to decrease hydropower in the case of EEEP ($e_{Hydro\text{-}DEC\text{-}EEEP}$) is determined by knowing the potentials to increase and decrease the hydropower generation, a balance is determined to maintain annual generation. The reduction of CEEP is given priority over the reduction of EEEP.$\Sigma\ e_{Hydro\text{-}Inc} = \Sigma\ e_{Hydro\text{-}Dec\text{-}CEEP} + \Sigma\ e_{Hydro\text{-}Dec\text{-}EEEP}$

Hydropower generation (e_{Hydro}) is modified in line with the generator capacity, hourly distribution of the water supply, and the storage capacity as follows:

Hydro storage content

$= \text{Hydro storage content} + w_{Hydro} e_{Hydro} = e_{Hydro} + e_{Hydro\text{-}Inc} - e_{Hydro\text{-}Dec\text{-}CEEP} - e_{Hydro\text{-}Dec\text{-}EEEP} e_{Hydro\text{-}Input} \leq (\text{Hydro storage content} - S_{Hydro}) * \mu_{Hydro} e_{Hydro\text{-}Input} \leq C_{Hydro}$

Errors may arise at the end of the computations in form of differences in the storage content at the beginning and at the end which can be corrected by identifying a solution in which the storage content at the end is the same as at the beginning. Initial storage content can be defined as 50% of the storage capacity. At end of first iteration, a new initial content is defined as the resulting content at the end of the calculation. The modeller may as input specify a start and end value of the hydro storage(Lund et al., 2021).

iv.) Step 5

Computation of individual CHP and heat pump systems is based on stage 1 computation in which solar thermal (if any) is given priority. EnergyPLAN will exploit the option of using the electricity generation and demands of these units to balance the electricity supply and demand for entire system if heat storage capacity is specified, this will then update the generation on the individual CHP and heat pump systems(Lund, 2014a),(Lund et al., 2021).

v.) Step 6

Four electrolyser systems ,two of these are systems which are assumed to be located next to the district heating based on backpressure units and extraction plants, respectively, along with the CHP units, heat pumps and boilers. Waste heat production of the electrolysers can be used for the district heating supply. Other system produce hydrogen for micro CHP systems or for transport and hydrogenation. The electrolyser is generally assumed to be producing hydrogen, but it may be used for modelling any kind of equipment converting electricity into fuel and heat(Lund et al. 2021).

Computation is based on Stage 1 results in which the minimum capacity of the electrolyser is determined together with the electricity demand, d_{ElcM}. Production is reorganised EnergyPLAN to avoid CEEP/EEEP and condensing-mode power generation.

a.) First, Energy PLAN establishes the potential to increase the production at hours of excess generation,

$d_{ElcM\text{-}inc\text{-}pot}$, is established as lower value of CEEP and while the difference between capacity is, C_{ElcM}, and while generation of the electrolyser:

$d_{ElcM\text{-}inc\text{-}pot} = \text{Min}\ [\ e_{CEEP}, (C_{ElcM} - d_{ElcM})]$

b.) Secondly, the potential to to reduce generation at hours of power-only production, $d_{ElcM\text{-}dec\text{-}pot}$, is define/identified minimum of the power production, e_{PP}, while electrolyser demand is: $dElcM_{\text{-}dec\text{-}pot} = \text{Min}\ [\ e_{PP}, d_{ElcM}\ ]$

A balance is then created where either the potential to increase or the potential to decrease is reduced to achieve the same level as annual potentials:

If $D_{ElcM\text{-}dec\text{-}pot} > D_{ElcM\text{-}inc\text{-}pot}$ then $d_{ElcM\text{-}dec\text{-}pot} = d_{ElcM\text{-}dec\text{-}pot} * D_{ElcM\text{-}inc\text{-}pot} / D_{ElcM\text{-}dec\text{-}pot}$If $D_{ElcM\text{-}inc\text{-}pot} > D_{ElcM\text{-}dec\text{-}pot}$ then $d_{ElcM\text{-}inc\text{-}pot} = d_{ElcM\text{-}inc\text{-}pot} * D_{ElcM\text{-}dec\text{-}pot} / D_{ElcM\text{-}inc\text{-}pot}$

Then an optimal temporal distribution of demand for electrolyser electricity producing exactly the same annual fuel as before is computed :

$d_{ElcM}{:} = d_{ElcM} - d_{ElcM\text{-}dec\text{-}pot} + d_{ElcM\text{-}inc\text{-}pot}$

Finally, the temporal distribution is measured against hydrogen storage capacity by first computing changes in storage content.

If computed storage content is below zero, production of the electrolyser is increased, but if computed storage content exceeds storage capacity, electrolyse production is reduced.

vi.) Step 7

Thermal storage in district heating systems is applied to improve the possibilities for minimising the electricity export. Heat storage capacity is included in EnergyPLAN for each of the district heating groups 2 and 3. Energy storage capacities are applied to minimise excess and condensing mode power generation in the system(Lund, 2014a).

vii.) Step 8

For electric vehicles which include the concept of vehicle to grid (V2G) through a smart charge and smart discharge, an important input in Energy PLAN is hourly distribution of the transport demand (δ_{V2G}), which is the basis of computation. It is important to determine the number of V2G battery electric vehicles which are driving and consequently not connected to the grid in the hour in question which together with the $V2G_{Max\text{-}Share}$ or the maximum share of V2G battery electric vehicles driving during peak demand hour and the $V2G_{Connection\text{-}Share,}$ establishes the fraction of the V2G fleet that is available to the electrical system in any given hour. The other reason for defining

δ_{V2G} is to determine battery storage by driving(Lund 2014a). The hourly transport demand, and hence discharging of the battery (t_{V2G}), is computed using

$t_{V2G} = [D_{V2G} * \delta_{V2G} / \Sigma \delta_{V2G}] * \eta_{CHARGE}$

The grid connection capacity of the total V2G fleet on an hourly basis (c_{V2G}) is calculated as follows:

$c_{V2G} = C_{Charger} * V2G_{Connection-Share} * ((1- V2G_{Max-Share}) + V2G_{Max-Share} * (1 - \delta_{V2G}/Max(\delta_{V2G})))$

There are three factors in the equation i.e. first factor is $C_{Charger}$, which is power capacity of the entire V2G fleet., multiplied by $V2G_{Connection-Share}$, which is the fraction of parked vehicles assumed to be plugged and the third factor, in parentheses, determines the fraction of vehicles on the road in each hour which is based on the sum of two terms. The first term, (1- $V2G_{Max-Share}$), is the minimum fraction of packed vehicles. The 2nd term is the additional fraction of vehicles parked during non-rush hours. The fraction representing vehicles packed per hour is derived from the known input of hourly energy demand for the fleet. The equation yields c_{V2G}, which is capacity of vehicles connected to the grid in any given hour. The model calculates the following per hour;

The V2G battery will start charging at the time of excess electricity generation (e_{CEEP}) and available battery capacity ($S_{V2G-Battery}$ - $s_{V2G-Battery}$) within limits power capacity of the grid connection (c_{V2G}) for that specific hour. The minimum of three values is expressed as; $e_{Charge} = \min [e_{CEEP}, (S_{V2G-Battry} - s_{V2G-Battery}) / \mu_{Charge}, c_{V2G}]$

Charging is forced in the case where the transport demands of the present and the next “y” hours cannot be serviced by the battery content. Initially, the “y” value is set to 1 h. If this leads to lack of battery content, the value is raised in steps of 1 h.

Needed minimum battery content is computed as follows:

Charging of the battery is adjusted to achieve: $_{Charge} \geq [s_{V2G-battery} - s_{V2G-Battary-min}] / \mu_{Charge}$

In case eCharge is higher than the capacity of the grid connection, c_{V2G}, hours, y, is raised by one, and the computation start again. The new battery content is established by adding the above charging and subtracting the discharging caused by driving

(t_{V2G}): $sV_{2G-Battery}: = s_{V2G-Battery} - t_{V2G} + (e_{Charge} * \mu_{Charge})$

V2G battery vehicles are simulated supplying the grid as a potential replacement of production from power plants (e_{PP}) and available stored electricity in the battery after the supply of the transport demand:

$e_{Inv} = \min [e_{PP}, ((s_{V2G-Battery} - s_{V2G-Battery -min}) * \mu_{Inv}), c_{V2G}]$

The resulting new battery content is then calculated as follows$s_{V2G-Battery}: = s_{V2G-Battery} - (e_{Inv} / \mu_{Inv})$

The above computation is repeated until the storage content at the end is the same as at the beginning.

viii.) Step 9

The electricity storage can be a hydro storage consisting of the following components:

i.) Pump for converting electric energy to potential energy defined by a capacity and an efficiency
ii.) Turbine used to converting potential energy to electricity and defined by a capacity and an efficiency
iii.) Storage for storing energy and is defined by a capacity.

Hydro storage can be applied for modelling any kind of electricity storage, like batteries. Storage simulation is used to avoid critical excess electricity production. The regulation of storage is as follows;

In case of critical excess production, the pump charges the storage, $e_{CEEP} > 0$. In this case, the available capacity in the storage ($S_{CAES} – s_{CAES}$) is calculated and the electricity demand of the pump (e_{Pump}) is identified as the minimum value of the following three values:

$-e_{CEEP}$, the critical excess production

$(S_{CAES} - s_{CAES})/\alpha_{Pump}$ available storage capacity divided by the pump efficiency

C_{Pump}, the maximum capacity of the pump.

If $e_{CEEP} > 0$ **then** e_{Pump}: = min [e_{CEEP}, $(S_{CAES} - s_{CAES}) / \alpha_{Pump}$, C_{Pump}]$s_{CAES} = s_{CAES} + e_{Pump} / \alpha_{Pump}$

The turbine is used to discharge storage, first by replacing import and then power plant production if $e_{PP} > 0$. In this case, the content of the storage (s_{CAES}) is identified and the electricity production of the turbine ($e_{Turbine}$) is identified as the minimum value of the following three parameters:

e_{import}, e_{PP}, import or electricity generation of the power plant, respectively

$s_{CAES} * \mu_{Turbine}$, turbine efficiency multiplied by the storage content

$C_{Turbine}$, Represents maximum capacity of the turbine.

If $e_{import} > 0$ **then** $e_{Turbine1}$: = min [e_{import}, $s_{CAES} * \mu_{Turbine}$, $C_{Turbine}$]**If** $e_{PP} > 0$ **then** $e_{Turbine2}$: = min [e_{PP}, $s_{CAES} * \mu_{Turbine}$, $(C_{Turbine} - e_{Turbine1})$]$e_{Turbine} = e_{Turbine1} + e_{Turbine2}$$s_{CAES} = s_{CAES} - e_{Turbine} / \mu_{Turbine}$

The above computation is repeated till storage content at the end of the year is the same as at the beginning.

ix.) Step 10
The last step involves several measures to reduce Critical Excess Electricity generation, e_{CEEP}, computation depends on input specification where the modeller can choose between:
i.) Reducing electricity generation from wind, photo voltaic, wave power, etc.
ii.) Reducing CHP production by replacing with peak load fuel-based boilers
iii.) Substitute fossil fuel-based boiler production with electric heating
iv.) Increase carbon dioxide (CO_2) hydrogenation
v.) Part-loading nuclear power generation or nuclear power is simulated following an exogenously given temporal distribution curve

5.3. Market economic simulation strategy

If market-economic simulation is chosen, EnergyPLAN distinguishes between business economy including taxes and socio-economy *not* including taxes., EnergyPLAN seeks to establish the least-cost solution of power system operation, assuming an electricity market in which all plant operators seek to optimise their business-economic profit. The market-economic modelling is based on establishment of electricity market price at each hour resulting from demand and supply of electricity. Actual generation level of various units resulting from the market price being equal to the marginal production price is established. Marginal consumption prices are established for electricity-consuming units like heat pumps and electrolysers. Net import is the difference between electricity demand, d_{Total}, and electricity supply, e_{Total}. The market price on the external market, p_X, is found as follows:$p_X = p_i + (p_i / p_o) * Fac_{depend} * d_{Net\text{-}Import}$where p_i is the system market price.

Fac_{depend} is the price elasticity (Currency/MWh/MW)

p_o is the basic price level for price elasticity (input),

$d_{Net\text{-}Import}$ is the trade on the market.

By sign convention, electricity import is calculated as positive and export as negative, leading to an increase in the market price in the case of import and a decrease in the case of export(Al-Sulaimi et al. 2022).

The production level at a prevailing market price is equal to marginal generation cost of a generating unit, the system is identified as an integrated part of the procedure. The following is used as an illustration for a geothermal power plant;

In the first incident, net-import, $d_{Net\text{-}Import}$, is computed as well as market price, p_X, when geothermal generation is zero. The alance production is computed as

$$BalanceProduction_{Geothermal} = - [(VEPP_{Geothermal} - p_X) / (Fac_{depend} * p_X / p_o) - d_{Net\text{-}Import}]$$

where $VEEP_{Geothermal}$ is the marginal production cost of geothermal power production.

p_x is the market price before geothermal production

Fac_{depend} is the price elasticity (Currency/MWh/MW)

p_o is the basic price level for price elasticity (input)

$d_{Net\text{-}Import}$ is the trade on the market before geothermal production

The equation is typically subject to the limitations on the power plant capacity.

The modeller may stipulate whether or not to limit dNet-Import by the transmission line. Setting EnergyPLAN to 'Transmission capacity limits the effect on the system price' limits dNet-Import to the transmission line capacity of the system, expressed in absolute values. However, if EnergyPLAN is set to "Transmission capacity does not limit the effect on the system price", the transmission line capacity does not limit dNet-Import. The simulation is done in steps shown in figure 8

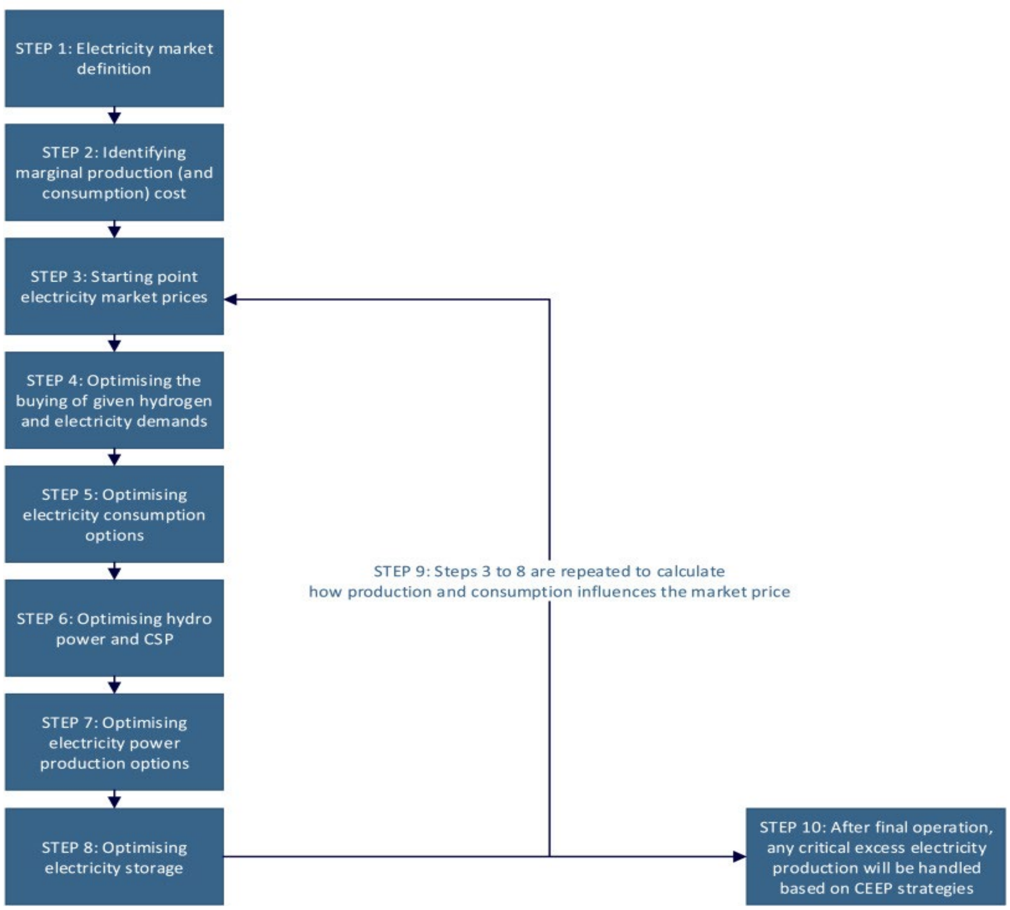

Figure 8. Graphical representation of Stage 3B: Market-Economic Simulation Strategy in Energy-PLAN.

Process description

i.) Step 1

In the first step, the hourly prices for external electricity market is defined as model input. Fluctuating electricity market prices are presented as hourly distribution file. Influence of import/export on the external market prices is expressed as dependence factor i.e. price elasticity and a basic price level for the price elasticity. Upon identification of the best business-economic operation strategy for each power plant, the influence on the market price is taken into consideration.

ii.) Step 2

Marginal generation or production costs are computed on the basis of fuel costs, taxes, CO_2 costs and variable operational costs. For cogeneration and heat pumps and other units connected to district heating plants , power stations and individual micro CHP, marginal costs are expressed in currency/MWh of electricity generation or consumption. The modeller can choose currency. The marginal costs are provided based on a multiplication factor together with an addition factor for storage units like hydrogen CHP and pump storage systems.

The simulation is as follows:

$p_{sell} > p_{buy} * f_{MUL} + f_{ADD}$In where

p_{sell} is the market electricity price when selling (Currency/MWh)

p_{buy} represents market electricity price when buying (Currency/MWh)

f_{MUL} is multiplication factor (always higher than 1).

f_{ADD} is addition factor (Currency/MWh)

iii.) Step 3

The simulation starts by calculating the prices of electricity based on;

i.) The electricity demand which includes the flexible demand
ii.) The production for renewable energy sources (RES)
iii.) Generation from RES affected by the "RES influence on system electricity price" setting, which offers two options:

a.) Zero bidding price (RES can stop)

If this option I applied, the Variable RES electricity generation is curtailed at negative system electricity market prices.

b.) Negative bidding prices (RES cannot stop)

Where such an option is applied, the Variable RES won't be curtailed as a result of negative electricity market prices.

All district heating is defined as delivered by boilers as a starting point while the sequence for individual plant optimisation is then identified by the subsequent procedure.

iv.) Step 4

At this step, the identification of the least-cost solutions of buying the minimum amount of needed power to meet the following demands for producing hydrogen and for charging electric and production of hydrogen for micro-CHP vehicles are identified, at given market price fluctuations and limitations on storage capacities, etc. For situations of high electricity prices, the option of producing heat using less hydrogen than the CHP is considered in the identification of least-cost solution for the hydrogen micro-CHP systems. While for the case smart charging electric vehicles(EV) and V2G, optimal business-economic option for buying and selling are determined on the basis of multiplication and addition factors identified as an input.

v.) Step 5

In this step, power consumption options are sorted in the order of marginal consumption costs:

i.) Replace boiler with heat pumps for district heating Group 2

ii.) Replace boiler with heat pumps for district heating Group 3
iii.) Replace the boiler with electrolysers in district heating Group 2
iv.) Replace boiler with electrolysers for district heating Group 3
v.) Replace electric heating with heat pumps for individual houses
vi.) Replace boiler with electric boiler for district heating Group 2
vii.) Replace boiler with electric boiler for district heating Group 3
viii.) Producing steam for thermal storage at high-temperature when the price of electricity lower than the cost of fuel needed for the condensing-mode and extraction mode CHP power generation in DH Group 3 with efficiency considerations (Lund et al., 2021).

Each pathway is then optimised based on market electricity prices, by starting with options with highest marginal costs and with due regard to the fact that each change in consumption impacts on market price(Lund, 2006).

vi.) Step 6

At this stage, the e best business-economic generation from concentrated solar power (CSP) is identified with due regard to the limitations on generation and storage generator capacities, and a similar computation is done for hydropower. For pumped hydro storage option, the optimal business-economic solution of buying and selling is identified next(Lund, 2006).

vii.) Step 7

The generation options are then sorted out in order of starting with those having lowest marginal costs of production: Nuclear production, geothermal generation, generation by condensing-mode power plants, generation from individual small-scale CHP units, power production from individual biomass CHP, generation from CHP substituting boilers in district heating Group 2, production from CHP resubstituting boilers in district heating Group 3, production from CHP replacing the heat pumps in district heating Group 2, generation by CHP as a substitute for heat pumps in district heating Group 3, production from CHP replacing electrolysers in district heating Group 2, and generation by CHP replacing electrolysers in district heating Group 3(Lund et al. 2021).

Optimisation is then done for option in order of market prices of electricity, beginning with those options with lowest marginal costs and while considering the fact that each change in consumption has an influence on the market price by reducing the market price. Transmission line limitations on transmission are considered by setting a limit on the generation by each unit, export does not exceed export will not exceed the transmission capacity. Import limitations are computed with regard to the condensing power plants, which are simply activated in the case that the import transmission capacity is exceeded(Lund et al. 2021).

viii.) Step 8

The above-mentioned multiplication and addition factors are used as basis to establish the optimal business-economic solution of selling and buying and selling is identified

ix.) Step 9

To compute the impact on the simulation of the consumption units after the market price is influenced by the production options, repeat Steps 3 to 8.

x.) Step 10

Critical excess generation is removed based on technical simulation procedure Step 10 in section 3.

2. Results and Discussion

EnergyPLAN enables users to make consistent and comparative analyses of energy systems based on renewable energy, fossil fuels, and nuclear power. Energy demand and generation management is necessary for proper allocation of energy resources and infrastructure. The energy tool considers all e energy system sectors i.e. heat. Transport, electricity and industry and transport and considers a wide range of energy technologies. Energy PLAN can enable quick modelling without losing coherence for wide variety of energy system like the fossil fuel based and those with radical technological changes like 100% renewable energy systems.

Modellers can apply Energy PLAN, to differentiate between a technical simulation, which ignores existing electricity market constructions and price levels, and a market-economic simulation, is adjustable using taxes. Energy PLAN can calculate the costs of the total system divided into fuel costs, investments costs, operation costs, CO_2 costs and other taxes. Therefore, EnergyPLAN can generate data for further socio-economic feasibility studies, like balance of payment and job creation.

EnergyPLAN is an energy system analysis tool created for the study and research in the design of future sustainable energy solutions with a special focus on energy systems with high shares of renewable energy sources. It has been under development since 1999 and has formed the basis for a substantial number of PhD theses and several hundreds of research papers. EnergyPLAN is designed to exploit the synergies enabled from including the whole energy system, as expressed in the smart energy system concept. Thus, with EnergyPLAN, the user can take a holistic approach focusing on the analysis of the cross-sectoral interaction. Traditionally disparate demand sectors, such as buildings, industry and transport, are linked with supply technologies through electricity, gas, district heating and cooling grids. In this way, EnergyPLAN enables the analysis of the conversion of renewable electricity into other energy carriers, such as heat, hydrogen, green gases and electrofuels, as well as the implementation of energy efficiency improvements and energy conservation. This article describes the overall structure of EnergyPLAN and the essential algorithms and computational structure(Lund et al. 2021)

2.1. Advantages of EnergyPLAN

As a freely available tool, it is easily downloaded with detailed documentation about its operation, which enable debate on its functionality and methodologies for improvement.

The main advantages of EnergyPLAN are;

- i.) Ability to model the entire system with all sectors related to the system
- ii.) The aggregation of units into representative units limiting the data requirement
- iii.) EnergyPLAN has ability to quickly simulate a user-defined scenario,
- iv.) High transparency in how scenarios are developed
- v.) The one hour (1h) temporal simulation step and the ability to simulate a whole year with seasonal variations.

Energy PLAN is continuously undergoing development to meet the future modelling requirements Currently, to future energy systems for example latest improvement is to on its ability to identify suitable flexible use of electrolysers and ability to handle different assumptions impact of variable renewable generation on the electricity market prices.

Energy PLAN is particularly ideal option if the key objective to analyse impacts of long-term alternatives, more so in relation to renewable energy, for distinct scenarios analysis without endogenous system optimisation. Energy PLAN can also be used in combination with other tools to take care of additional objectives in an energy system analysis. Latest model development include developing its ability to identify suitable flexible use of electrolysers and proper handling of different assumptions on influence of variable renewable electricity productions on electricity market prices(Lund et al. 2021).

2.2. Limitations of Energy-PLAN

The model has some inherent limitations worth noting too. Energy-PLAN focuses on the entire system and the aggregation employed cannot capture detailed operation of individual units in the energy system. Additionally its exogenous and transparent system design and its fast computational time comes at the expense of larger requirements of the user which requires experience to identify favourable scenarios for analysis(Lund et al. 2021).

3. Conclusion

Energy management a very important function for world to achieve economic prosperity and environmental security. EnergyPLAN is a freeware that can support independent add-ons and help tools and it and can be executed from other platforms like Excel or MATLAB, thus enabling multi-execution. Energy-PLAN can compute hourly operation for an energy system which enables reliable matching of demand and supply even with introduction of intermittent and variable renewable energy sources in the system. Energy-PLAN is used to simulate the operation of national energy systems on an hourly basis, capturing heating, cooling, electricity, industry, and transport sectors. The model was developed and is maintained by the Sustainable Energy Planning Research Group at Aalborg University, in Denmark. The users of Energy-PLAN include researchers, policy makers, and consultancies, worldwide. The model is widely used and accessible due to the key focus on free sharing the model during its development making it to have user-friendly interface. The Energy-PLAN model has been used in many studies, reports, and hundreds of scientific publications.

Energy-PLAN is limited to some extent in that it focuses on the entire energy system and with the aggregation employed, it is not possible to carry out a detailed analysis of the operation of individual units. Additionally, the exogenous and transparent system design which leads to fast computational time comes at the expense of larger requirements of the user hence, some; experience is required to identify favourable scenarios.

The appropriateness of Energy -PLAN depends on the individual user's objectives, but EnergyP-LAN is particularly suitable when the main objective is to analyse the impact of long-term alternatives, especially with relation to renewable energy, and specific scenarios are analysed without endogenous system optimisation. Energy plan can be used in combination with other tools for additional objectives when undertaking an energy system analysis.

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