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Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations

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HIGHLIGHTS

- All applications of the EnergyPLAN model in journal articles are investigated.
- All references to the EnergyPLAN model in journal articles are investigated.
- All applications of criteria for systems analyses are investigated.
- New performance criteria for energy system simulation are suggested.

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ABSTRACT

Energy systems with high degrees of renewable energy integration require on the one hand energy scenario making and energy system analyses for the optimal design of systems and pathways and on the other hand well-established criteria for decision-making and for characterisation of energy system suitability. This article has a threefold objective, it reviews the application of a given energy system simulation model – EnergyPLAN – analysing its application on geographic level as well as the types of simulations or scenario analyses performed on the model. Secondly, it reviews the types of performance indicators applied in said energy systems simulations and thirdly it reviews and details existing advanced energy system performance indicators and proposed additional indicators.

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1. Introduction

Climate change mitigation, energy supply security and foreign exchange cost are all driving factors behind a situation where many national and local governments are planning large transitions in the energy system. The significant transitions can be the result of various different policy goals, however they are all towards the direction of the utilisation of more environmentally benign and often also locally available energy sources – typically in the form of renewable energy sources – RES.

From an energy systems perspective, one common characteristic of many of the occurring, planned or envisioned transitions is a shift away from storable fuels towards energy systems relying on energy sources fluctuating beyond human control. A second characteristic is a shift in complexity from systems with a relatively limited number of fuel sources towards a system with the utilisation of many complementary energy sources. A third characteristic is a move towards more integrated energy systems where synergies are exploited and e.g., waste heat from energy conversion processes is utilised for heating or even cooling purposes. In Denmark for instance, district heating has been a cornerstone in the country's attempts of curbing energy demand growth [1].

The transitions may thus go from traditional energy systems where residents are having electricity needs covered by condensing mode coal-fired power plants, transport needs covered by diesel-powered vehicles and heating demands covered by residential oil boilers to energy systems with electricity demands covered by wind and solar power combined with biomass-fueled cogeneration of heat and power (CHP) plants, transportation demands covered by synthetic fuels produced on the basis of hydrogen from electrolytic converters and carbon dioxide from the CHP units and heat supplied from CHP plants, waste heat from electrolytic converters and heat pumps utilising low-grade heat reservoirs.

Such systems are envisioned by researchers, decision makers, and progressive energy companies in many countries, and the literature holds numerous examples of highly integrated RES-based energy systems with cases from Denmark, Ireland, Croatia, Jordan, Norway and many more.

Denmark holds the world record in the integration of wind power, and while facilitated through strong interconnectors to neighbouring countries [2], this will not suffice in the future where policy objectives include the transition to 100% RES supply by 2050. High utilisation of fluctuating RES will set its own agenda for the rest of the country's energy system which all together will be highly complex.

For traditional energy systems, optimisation criteria are relatively simple with for instance cost of energy (CoE) and yearly unavailability, but design of highly complex energy systems require performance indicators that aptly capture the quality of a given system. A simple CoE is for instance more appropriate when there is a clear separation between energy streams than when streams mingle and synergies are exploited and CoE is a matter of choice and definition rather than a matter of simple logic. Where load following capability for simple energy systems is a simple matter of dispatch and sufficient generation capacity, load following capability of complex energy systems is a complex optimisation of a number of production, conversion, storage and demand technologies – and load following capability is not necessarily a certainty in energy systems simulation. More criteria are therefore required to capture the simulated or actual performance of complex high-RES energy systems. Likewise, proper tools are required to handle energy scenario design and simulations. The next section probes deeper into the nexus of energy system simulation schools and the application of optimisation criteria.

2. Simulations and outputs

Østergaard [3], listed a number of optimisation criteria, but mainly based on the overall objective of a given strategic energy systems change – i.e., carbon dioxide emission reductions, primary energy supply minimisation and societal cost – but also criteria touching upon the performance of an energy system in terms of integration renewable energy supply – measured for instance in import and export of electricity.

Tarroja et al. [4] identified a range of metrics detailing the operation of dispatchable power producers as a consequence of renewable energy integration into the given energy system. Their focus was the electricity system, and it was not treated as a system integrated with other parts of the energy system – notably the heat and transport systems – which as deliberated will be one of the main characteristics of future high-RES energy systems. As Lund et al. state; *"electricity smart grids should be seen as part of overall smart energy system"* [5], thus the set of metrics does not fully capture the full complexity of future energy systems.

Scott et al. [6] performed a literature review of the use of multi-criteria decision variables in bioenergy systems, with the five most oft used criteria being Technology Selection, Policy, Sustainability, Operations, and Economic criteria.

This article probes deeper into the characterisation of good renewable energy integration. It investigates what performance indicators and criteria are being used in the scientific body of literature and identifies relevant performance indicators. The following definitions apply in terms of energy planning and energy systems modelling in this article:

- Objectives refer to general goals to be met. These may be in the form of quantitative as well as qualitative measures.
- Outputs refer to energy modelling results in general
- Criteria refer to the specific categories of quantitative objectives as well as their quantification in terms of finite values, minimum or maximum values
- Performance indicators characterise energy system performance without requiring a certain value as for criteria

A specific characteristic of an energy system may of course be more than one of the above-mentioned four terms.

Different types of simulation and analytical models usually have different criteria and performance indicators. In the following, a selection of the main modelling schools and their potential outputs, criteria and indicators are deliberated.

Linear programming optimisation models are based on single objectives where the objectives may encompass more criteria, but where everything is converted to one single unit of measure such as monetary value. Any undesirable behaviour may thus be assigned a penalty and desirable behaviours may be assigned a reward and the quantification of these penalties and rewards will direct the solution space in a certain direction.

Multi-criteria decision analysis (MCDA) where a set of criteria are measured, scaled, weighed and aggregated to form a final score measuring the relative fulfilment of a series of objectives, is a way to capture criteria that are not congruous along a uniform scale of measure as opposed to the monetization of linear programming models. While MCDA may be incorporated into existing energy simulation models, it is more often included in dedicated models [7] or applied outside energy systems simulations models [3]. A review of the literature in the field does not reveal other articles than [3] where hourly simulations of high-RES energy systems are evaluated with MCDA.

Multi-objective (MO) analyses where different objectives are incorporated are less typical in energy planning and as opposed to linear optimisation models, these models require more novel heuristics for finding solutions such as evolutionary algorithms where a population of potential solutions are left to mate and form offspring that are evaluated according to any criteria applicable. MO analyses are seldom combined with high temporal resolution models for simulation and design of high-RES energy systems. One exception is the work by Mahbub et al. [8], which combines a genetic algorithm with the energy systems simulation model EnergyPLAN [9] to create and evaluate scenarios according to several criteria.

A partial equilibrium investment optimisation model like TIMES MARKAL has also been applied together with EnergyPLAN to model Portugal towards 2050 [10], thereby providing performance simulations of externally generated scenarios.

Apart from these last examples, in which scenario design is automated, there are also cases of what might be denoted ‘‘manual heuristics‘‘, where energy scenarios are simulated, assessed and adapted in an iterative process with the purpose of designing energy systems with certain characteristics.

Models with few outputs or investment optimising models that optimise according to a single economic criterion are not the target for this article's assessment of the application of criteria and performance indicators.

For the purpose of evaluating high-RES energy systems, a high temporal resolution is required. Connolly et al. has performed a survey of computer tools for energy system analysis [11] and categorises the models into a number of segments. 19 models are indicated as simulation models, and of these, ten are indicated as national or regional time-step simulation models with time steps of one hour or less. Of these, only TRNSYS16, HOMER, and EnergyPLAN are listed as having many or very many users. The models STREAM and H2RES are also indicated as national or regional time-step simulation models with time steps of one hour or less, but the use of these are not monitored by their developers. Searching Sciencedirect for an indication of the model usage, TRNSYS16 gives 30 articles, EnergyPLAN 204 articles, and H2RES 68 articles as of May 6th 2015. The model names HOMER and STREAM are ill-chosen for such searches, but searching for the model developer NREL *and* HOMER gives 316 articles, and Ea Energy Analysis *and* STREAM gives 10 articles. While none of these search results are checked for contents or relevance, they do give an indication that EnergyPLAN, H2RES and HOMER have active user communities across several users.

EnergyPLAN is one of the models applying manual heuristics in terms of finding optimal energy systems configurations. This has the implication that any model output or derivate thereof may be applied as criterion or performance indicator. The model is capable of performing hourly simulations with a time frame of one year. It does so with the entire energy system and includes synergies arising from sector integration by including:

(a) all demands (heating and cooling demands, flexible and inflexible electricity demands, transportation demands in the form of fossil fuel demands, electricity demands, and synthetic fuel demands)
(b) RES-based power units (on and off-shore wind power, wave power, photo voltaics (PV), run-of-river hydro, hydro power with reservoirs, geothermal power)
(c) RES-based district heating units (geo-thermal)
(d) Energy conversion technologies (individual and district heating-connected fuel boilers, electric boilers, heat pumps, solar collectors, and CHP units. Condensing mode power plants. Electrolysers and synthetic fuel producers)
(e) Energy storage technologies (individual and district heating connected heat storage. Electric storage. Vehicle-to-Grid (V2G). Compressed Air Energy Storage (CAES), hydrogen and other fuel storages).

While being able to model high-RES systems and simulate e.g. strategies for optimal use of otherwise curtailed RES-based power production in heating, hydrogen or CAES, it does so with a limited resolution in terms of production, conversion and demand units where all categories of technologies are aggregated into one representative unit.

Due to many different model outputs, the manual heuristics, the active energy systems modelling community and the author's close knowledge of the model, EnergyPLAN is selected as case for the review of optimisation criteria and performance indicators in this article.

3. Scope and structure

The primary objective of this article is twofold; to assess the application of the EnergyPLAN model in peer-reviewed journal articles and to determine current use of optimisation criteria and advanced performance indicators in peer-reviewed journal articles applying the EnergyPLAN model. The secondary objective is to suggest further advanced performance criteria for energy systems analyses.

Section 4 presents the methodology applied in the review procedure, and Section 5 the results of the review of current practise within energy systems simulation using the EnergyPLAN model. Section 6 presents main findings from a selection of the EnergyPLAN analyses reviewed. Section 7 reviews already applied advanced performance indicators as well as suggests additional performance indicators, and finally Section 8 concludes the article.

4. Methodology

In order to identify articles applying the model EnergyPLAN, full-text searches of articles are required. Thus, publishing portals with this facility are required. Five portals are used in this survey:

- Sciencedirect with approximately 2500 journals
- Taylor and Francis Online with 2022 journals
- Hindawi Publishing Corporation with 434 journals
- Springer Link with 5.2 million articles
- Open Access Journals at Aalborg University with 11 journals (of which the developers behind EnergyPLAN are involved in one journal)

All articles with the search term EnergyPLAN are subsequently sorted according to contents into five different categories:

1. Irrelevant articles. Articles where the search term is present for other reasons such as the presence of links to an energy plan for British Columbia (www.energyplan.gov.bc.ca), the company Energyplan.com, an energy plan for New York (energyplan.ny.gov), energy plans for Halifax as well as for New Foundland and Labrador. The category also includes certain articles without full-text access but which are all published 1971–2000 and thus without relevance in the context of the EnergyPLAN model which has only been developed since 1999 [12]. The first article applying the EnergyPLAN model [13] was published in 2000, however at this point the model name was not even applied.
2. Duplicates. This refers to the journal Fuels and Abstracts that contain duplicates of relevant EnergyPLAN abstracts. The original articles are included in the assessment where relevant
3. Articles that refer to analyses based on EnergyPLAN
4. Articles that refer to EnergyPLAN as an example of a model, compares modelling characteristics or contemplates applying EnergyPLAN
5. Articles where EnergyPLAN is applied for analyses

Categories 3 and 4 are not necessarily easily distinguishable in as much as references to EnergyPLAN model characteristics may encompass references to modelling results and references to modelling results may encompass references to model characteristics. In the characterisation of the different articles, it has been assessed whether the primary objective is to present results within a specific area or whether the primary objective is to characterise one or more energy models.

Focus of the survey is on the last category where modelling and result sections have been inspected for use of criteria or performance indicators. A number of articles such as [14–16] validate scenarios or the combination of model and scenario through comparison between known and modelled parameters – but this is not considered optimisation criteria.

For the characterisation of the scope of EnergyPLAN articles, the scope of individual articles may span across more of the defined potential scopes listed in Section 5. The decision has been made according to what the authors have stressed most prominently in abstract, keywords or ultimately the title of the article.

5. Application, references and characterisation of EnergyPLAN

The EnergyPLAN model has been applied in 95 different peer reviewed journal articles, additionally, results have been referred in 45 other articles and the model has been characterised in 40 articles as of May 26th 2015 – see Table 1.

Table 1
Occurrence of the term energyplan in journal articles between 1971 and 2015 in the databases mentioned in Section 3 as of May 26th 2015.

Category	Result of article survey
Irrelevant	7 Publications prior to 2002: [17–23] 14 Publications containing energyplan in URL: [24–37]
Duplicates	19 Publications (not referenced for space reasons)
References to analyses	45 Publications [4,38–77,76,78–81]
References to model characteristics etc.	40 Publications [82–120,121]
Application of EnergyPLAN	95Publications 2003–2010 [2,3,11,122–151] 2011–2013 [10,152–184] 2014–2015 [14–16,185–202,203–209]

Their publication over time is shown in Fig. 1 demonstrating an increasing tendency though with some changes particularly in 2012–2013 as well as in 2004. Upon closer inspection, two of the articles with publication year stated as 2003 were in fact submitted and published in 2004, however the journal back-dated the relevant issue.

The EnergyPLAN model has mainly been applied on country or state level, with 76 articles presenting analyses at this level – See Fig. 2. 43 articles present analyses of Denmark or Western Denmark, while four articles present analyses on Ireland [11,170,183,185] and three Portugal [10,14,200]. Macedonia [173,176], Jordan [190,195], Jiangsu [152,180], Italy [166,169],

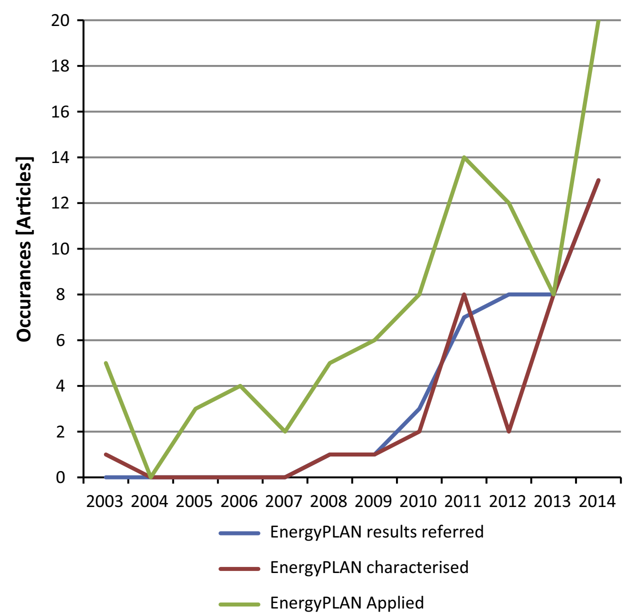

Fig. 1. Evolution of the application and reference to EnergyPLAN in peer-reviewed journal articles from 2003 until 2014. Inconclusive data for 2015 are not shown. Updated with data up until May 26th 2015 to account for possible back-dating.

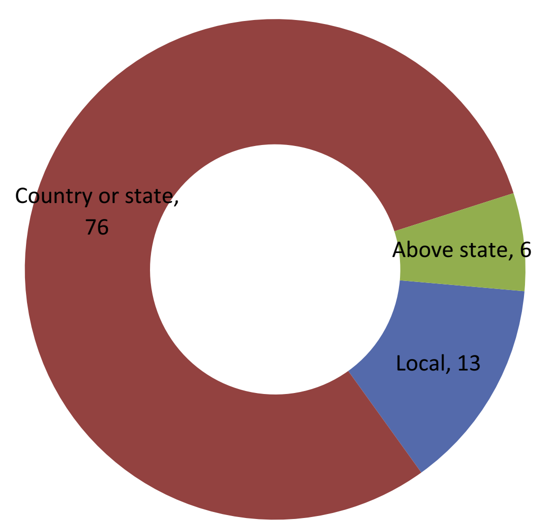

Fig. 2. Geographic scale of EnergyPLAN analyses 2003–2015 (as of May 26th 2015). Country or state level includes states and provinces in Canada, China and the United States. "Above state" include EU27, China, and analyses of several states in the US, China or global.

Table 2
Distribution of articles applying the EnergyPLAN model according to general scope as of May 26th 2015.

General scope/topic	Articles	References
Integration of RES into the energy system	30	[2,3,11,15,135,138,140,144,145,147,148,155,158,164–166,168,169,174,180,183,184,189,197,198,200] [164,204,206,209]
High-RES scenarios	15	[14,122,132,141,146,152,159,160,167,170,173,176,185,187,192]
General methodological issues within energy systems modelling and simulation	7	[10,129,151,171,179,199,208]
Low-RES scenarios	6	[16,153,161,186,188,205]
Transport	6	[139,142,143,154,193,210]
District heating	6	[124,128,191,196,202,207]
The role of energy savings and the systems impacts hereof	5	[130,172,175,194,203]
Life-cycle assessment	3	[126,149,177]
Grid stability	3	[134,137,162]
Transmission issues	3	[127,133,136]
Biomass usage	2	[156,178]
Desalination	2	[190,195]
Waste as an energy resource	2	[123,150]
Carbon Capture and Storage (CCS), PV, Market structures, thermoelectric generators, CHP	1	[125,163,181,182,201]

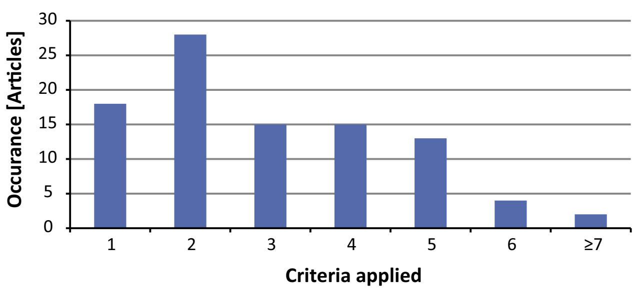

Fig. 3. Number of criteria applied per article using the EnergyPLAN model as of May 26th 2015.

Croatia [167,198], Mexico [194,208], Finland [206,209] and Britain [15,164] have all been the object of analysis for two articles, Serbia [155], Romania [161], Ontario [196], Norway [197], Inner Mongolia [154], Hungary [16], Hong Hong [187], South Korea [205], Iran [199], and Alberta [186] have all been the subject of one article each as of May 26th 2015.

Somewhat fewer articles – 13 – have addressed local areas – regions (South-West Region in Ireland [192]) municipalities (Aalborg [122,158,174] and Frederikshavn [160,175] in Denmark), islands (Mljet in Croatia [151], Flores in Portugal [171], Corvo in Portugal [204], Bornholm in Denmark [162]), towns (Corinaldo, Italy [188]), neighbourhoods (Loviisa, Finland [207]) or even a congregation of buildings [172] while even fewer – six – have addressed large scale system comprising more countries or states (10 US states [181], EU27 [191], China [153,165,198,202], 13 electricity markets in Oceania, North America, and Europe [168]).

The circumstance that the model has been and is under continuous development at a Danish university, shows in the data with 49 articles about energy systems for the entire country down to municipal level,

While the articles address the energy system of the noted geographic levels, they do not necessarily do so in a holistic manner. Some focus on the entire energy system while others only focus on specific sectors of the energy system. The largest fraction of the articles address integration of RES into the energy system, i.e., focus on what amounts may be integrated using various means. This applies to 30 articles with focus on how storage (thermal, electric or compressed air), heat pumps, CHP operation, flexible power plants, optimal ratios of RES capacity, flexible demand, electric vehicles, integration across sectors may assist the

Table 3
Criteria use in articles applying EnergyPLAN for energy systems analyses as of May 26th 2015.

Criteria	References
PES	[3,11,15,16,123–125,128,130,132,141,146,150–152,154,157,159–161,163,165–167,170,173,175,178–180,182–192,194,197,198,202] [204,206]
CO2	[3,15,16,123–125,128,134,135,139,143,146,147,150,152–155,159,161,164,165,167,173,175,176,179,180,182,186–188,194–196,198,200,202] [205,206,209]
Excess	[11,15,125,129,131,132,134,135,139–141,143,144,151,154,155,157,160,162,164,165,167,180,181,183,184,187,188,190,195,197,198,200]
Cost	[3,11,123,128,135,138,139,142,147,148,150,154,156,158,163,164,167,168,173,176,179,182–184,186,191–193,198,201,202] [203–206,209]
Duration	[10,122,144,148,155,160,164,182,189,196,198] [204]
Configuration	[3,127,133,136,156,158,174,177,196,199,202]
RES Share	[3,152,153,155,159,166,169,192,197] [206]
Mix	[126,149,156,171,172,185,188,192,197,201,202]
Import	[3,14,167,175,189,197,198] [206]
Export	[3,161,167,187,189,197]
COMP	[11,154,165,170,173,183,184]
Socioeconomics	[3,146,152,159,178,197]
Condensing	[2,3,137,160,189]
Ramping	[11,180,183,184]
Employment	[128,159,179,211]
Fossil share	[152,169,195]
Hourly	[199,204,207]
Fiscal	[128,179]
Emissions	[126,181]
Commercial	[146,159]
Transmission	[186,189]

integration of RES or simply how the present energy system configuration limits the integration of RES.

15 articles address more holistically the development of high-RES scenarios, seven articles address general methodological issues within energy systems modelling and simulation, six articles present low-RES scenarios as well as district heating, five articles investigate the role of energy savings and the systems impacts hereof, three articles treat each of grid stability and transmission issues. Two articles each of waste as an energy resource, biomass as an energy resource and desalination, while one article address each of Carbon Capture and Storage (CCS), PV, Market structures, CHP, and thermoelectric generators – See Table 2 for references.

This application of the model fits appropriately to the general purpose of the model which is to "*assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments*" and in terms of RES and CHP "*has emphasised the analysis of different regulation strategies with a focus on the interaction between combined heat and power production (CHP) and fluctuating renewable energy sources*" to quote the model documentation [9].

6. Optimisation criteria in EnergyPLAN simulations

The 95 articles applying the EnergyPLAN model employ a variety of criteria. As the model has several options, the majority employ a small range of criteria, while others employ a single criterion as shown in Fig. 3. The survey distributed on articles is shown in Table 3.

- The most frequently applied criterion is primary energy supply (PES); the sum of fuel usage and fuel equivalents for non-fuel energy sources as shown in Fig. 4. This is applied in 46 articles or approximately half of the articles where EnergyPLAN has been applied. Some articles focus on specific primary energy sources whilst others address the sum of the entire range of the given energy system. See also Mix below.
- Greenhouse effect enhancing carbon dioxide emissions are assessed in 42 articles
- Excess power generation is assessed in 35 articles. Excess power generation reveals the ability of a given energy system to properly integrate fluctuating power sources by showing the quantity which cannot be used in the system with the given configuration. The measure can be in terms of exportable excess – excess which may be exported from the given system constrained by interconnection capacity or critical excess – excess beyond the interconnection capacity. In the case of the 34 articles, the excess is critical. Exportable excess is included under the category export.
- Business economic costs are assessed in 35 articles though in a variety of different shapes and forms depending on the particular focus of the authors – e.g., total annual costs, net present values, fuel costs, O&M costs
- Duration of various units either graphically as duration curves or quantitatively as operating hours of various units are investigated in 12 articles. This category also includes capacity factor – i.e., the ratio between actual production and production at full nominal load throughout the year.
- The general system configuration is the main output of 12 articles. This is not so much a criterion as an output; typically used for further analyses of more specific topics in designated models
- The RES share is assessed in 11 articles
- The production mix across all primary energy sources is assessed in 11 articles
- Export and/or import of electricity is assessed in eight articles (see also excess power generation above)
- Seven articles use the COMP factor (see Section 7 for details on the COMP factor)
- Socioeconomic costs are assessed in six articles
- Condensing mode power generation – the power generation mode with the highest electric yet poorest total efficiency - is assessed in six articles
- Ramping – the changes from hour to hour in the dispatch of dispatchable units is assessed in four articles. This underlines the versatility of a model such as EnergyPLAN, since ramping is not one of the outputs but with all hourly production, consumption and storage data being available for the modeller, such analyses may easily be performed.
- Employment effects of given energy scenarios are assessed in four articles.
- The fossil share is assessed in three articles
- Three articles look into hourly results
- Fiscal effects – effects on public finances – are assessed in two articles
- Emissions are assessed in two articles. The emissions are additional to the CO_2 emissions calculated endogenously in the model and include other pollutants
- Commercial effects in the form of technology export opportunities are assessed or rather estimated in two articles
- The required transmission system to operate a given energy system is assessed on two articles. This is related to import/export addressed previously.

Finally there are a few criteria which are only applied once. This includes e.g., the amount of fresh water that might be saved for irrigation if hydro power is substituted by other RES production, income of different electricity producers under different market constructs, CHP share, foreign dependency and land use. A number

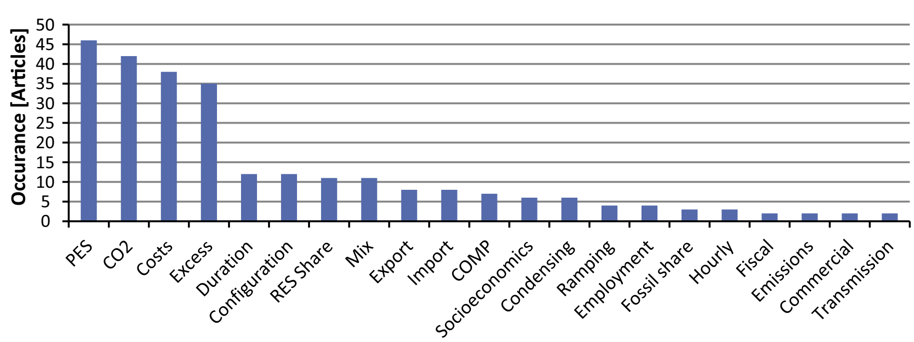

Fig. 4. Application of different criteria in articles applying the EnergyPLAN model as of May 26th 2015.

of advanced performance indicators applied in EnergyPLAN analyses or applicable for EnergyPLAN analyses are addressed in Section 8 while Section 7 gives an overview of some indicative results from EnergyPLAN simulations.

7. Findings from EnergyPLAN simulations

Using manual heuristics, EnergyPLAN optimises the hourly operation of a user-defined energy system over the course of one year, thus it will not endogenously determine optimal systems configuration. The work performed in EnergyPLAN can be characterised as a bottom-up approach, and as Wilson & Swisher [212] pointed out in 1993, *"The top-down analyses support politicians who have taken a wait and see stance in the greenhouse debate. Bottom-up analyses support politicians who have taken a do something now stance toward stabilizing, and eventually reducing, greenhouse gas emissions."* While hybrid modelling combining bottom up-and top-down approaches has emerged since then, bottom-up models such as EnergyPLAN are also widely used, showing favourable economic outcomes of transitions to high-RES energy systems. This is the case for Aalborg Municipality, Denmark [122], where results showed annual expenses at lower/comparable levels for a 100% RES and a fossil-based business-as-usual alternative. In another case, Mathiesen et al. [159] investigated the socio-economic effects of a similar transition for Denmark at large, revealing that *"implementing energy savings, renewable energy and more efficient conversion technologies can have positive socio-economic effects, create employment and potentially lead to large earnings on exports. If externalities such as health effects are included, even more benefits can be expected."* Cho and Kim [205] employs EnergyPLAN to investigate the economic feasibility of different ways of attaining a 20% RES contribution in primary energy supply (PES) for electricity generation in South Korea, finding wind power being the most feasible option. Hong et al. [180] and Cerovac et al. [198] use EnergyPLAN simulations to point towards the importance of flexible power plants to accommodate the fluctuating nature of RES; in these cases wind power in Croatia and China. This is in line with the logic of Lund et al.'s [213] analyses of excess power generation in Denmark.

In a series of three articles on Compressed Air Energy Storage, a team of researchers concluded *"even in energy systems with very high shares of wind power and CHP, neither the historical nor the expected future price variations on the spot market alone can justify the investment in CAES systems"* [148], that uncertainty will mean that they will not operate optimally, and at best earn 80–90% of what would be attainable with full market foresight [147] and that in terms of effects on a high-RES Danish energy system, even *"with an unlimited CAES plant capacity, excess power production is not eliminated because of the high percentage of CHP production"* [144]. Likewise, Connolly et al. concluded regarding pumped hydroelectric storage (PHES) that *"Considering the 40-year lifetime of PHES, even with low investment costs, a low interest rate, and a suitable electricity market, PHES is a risky investment without a more predictable profit"* [168].

One the other hand, electricity storage may have a role to play as investigated by Edmunds et al. who conclude that *"Increasing the levels of interconnection and energy storage has significant technical benefits in the potential future GB systems considered"* [15]. Likewise, when taking the step to electric vehicles which supply storage and possibly Vehicle to Grid (V2G) capability at a negligible marginal investment costs, Lund and Kempton find that *"adding EVs and V2G to these national energy systems allows integration of much higher levels of wind electricity without excess electric production, and also greatly reduces national CO2 emissions"* [143]. Staying with EVs, Nunes et al. find that in a future Portuguese energy system with substantial PV, charging of electric vehicles should occur in the day time [200].

Several analyses point towards an important role of heat humps. Hedegaard et al. go as far as stating *"In terms of reducing fuel consumption of the energy system, the installation of heat pumps is the most important step"* and high-RES plans for Aalborg [122], Frederikshavn [160], Denmark [159], Croatia [167], Ireland [170,185] and the European Union [191] all include heat pumps as important elements in district and/or individual heating.

Fernandes & Ferreira find that *"100% renewable requires strengthening of storage and interconnection capacity"* [14] – in line with Edmunds et al. [15] while other work finds positive effects of distributed general technologies such as wind power and CHP [133,136] on transmission requirements and grid losses for less RES-intensive energy systems.

Ridjan et al. investigated the role of synthetic fuels in in future 100% energy systems, finding that *"synthetic fuel pathways reduce the demand for biomass, while simultaneously increasing the flexibility of the energy system by enabling a high share of wind energy. The most interesting finding is that the production costs of synthetic fuels are comparable with petrol production costs once the associated CO_2 emissions are included."* [193]

One last case is flexible electricity demand. Kwon and Østergaard [189] investigated the potential role of flexible electricity demand for RES integration in Denmark. One the one hand, they investigated the amount of flexible electricity demand in the Danish energy system (amounts at different potential time shifts) and on the other hand, they investigated what amounts it would require to make an impact.). Using international exchange as an indicator of how well the system integrates RES, they found that *"the level of flexible demand which can decrease international connection by half would need to be approximately 13 TW h of flexible demand within a month. This is more than a quarter of the classic electricity demand and such long time frame of flexible demand is rarely found in practice. Flexible demand within the classic demand can thus not contribute sufficiently if this level of reduction in international exchanges is required."* Thus, flexible demand within the classic electric demand is not the answer to integration of fluctuating RES, which underlines the need for integration between the electric, heating and transportation sectors.

8. Advanced performance indicators

This section present a review of existing advances performance indicators from the literature as well as suggest additional.

8.1. Metrics

As mentioned in Section 2, Tarroja at al. [4] have written an article on *Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing*, which in terms of scope, resembles the current article. Their metrics take a starting point in the net load defined as the difference between total load and the non-dispatchable RES-based power production. Below is a list of their nine different metrics, where terms are verbatim from the authors and descriptions are paraphrased.

- Maximum net load value – corresponding to the minimum required dispatchable power production capacity
- Minimum net load value – minimum production dispatchable power production thus indicating the either partial load or units to be curtailed
- Net load value range – the difference between the two and thus an indication of the range they are required to operate within
- Net load capacity factor – the aggregated relative use of the dispatchable power production units

- Surplus renewable fraction – the aggregated curtailment of RES-based power producers relative to potential production
- Load duration curves – use vs duration of various productions units
- Daily occurrence of maximum and minimum net load values – the times of the day with minimum and maximum net loads
- Generator duration counts – frequency of the usage of different types of dispatchable power producers
- Power spectral density – the frequency of variations in net load

The authors of [4] focus on the electricity system, though nothing prevents the metrics from being applied to other sectors of the energy system. All is based on the net load, which is treated as an exogenous signal to act on and the metrics focus on the resulting requirements of dispatchable power producers.

8.2. Mismatch compensation factor

Lund et al. [172] developed the term Mismatch compensation factor f_{MMC} in relation to zero energy buildings, defined as

$$f_{MMC} = \frac{C_{\text{Cost Balance}}}{C_{\text{Energy Balance}}},$$

where $C_{\text{Energy Balance}}$ is the installed RES capacity balancing aggregated annual imports to and exports from the system and $C_{\text{Cost Balance}}$ is the installed RES capacity where import costs and export income balance.

The mismatch factor is intended for small systems where it determines how well energy balance translates into economic balance of such energy systems.

8.3. Emissions reduction effectiveness

Ouelette et al. [186] defined the term emissions reduction effectiveness in an assessment of cogeneration of heat and power (CHP) in the exploitation of oil sands in Canada's Alberta province. From a starting point in a business as usual (BAU) scenario, they investigated how effectively changes in CHP capacity translated into changes in emissions. The Emissions Reduction Effectiveness ε was defined as

$$\varepsilon = \frac{E_{\text{BAU}} - E_{\text{Scenario}}}{|\text{CHP}_{\text{BAU}} - \text{CHP}_{\text{Scenario}}|}$$

With E indicating emissions under BAU conditions as well as in the scenario under inspection and CHP correspondingly indicating installed CHP capacity.

8.4. Compromise coefficient – COMP

Connolly defined the term Compromise Coefficient or COMP in an analysis of the maximum possible wind penetration and associated energy costs for Ireland [11]. The COMP is defined as the ratio between the marginal primary energy supply (PES) to the marginal Critical Electricity Export (CEEP); simulated electricity export beyond transmission capacity.

$$\text{COMP} = \frac{\Delta\text{PES}}{\Delta\text{CEEP}}$$

The COMP factor has later been applied in other works by Connolly [165,170,183] as well as in the works of Liu et al. [165], Hedegaard et al. [184] and Ćosić et al. [173].

8.5. Marginal export

Kwon and Østergaard [156] determined the ratio between marginal export and marginal changes in biomass-based PES to determine how changes in available fuel for dispatchable power and heat production affect electricity export.

$$\frac{\Delta\text{Export}}{\Delta\text{PES}}$$

The term is correlated to Connolly's COMP though in effect the value is inverse and all exports are included-critical as well as exportable as opposed to Connolly's COMP.

8.6. Relocation coefficient

Blarke defined the term relocation efficiency as a measure for comparing different technologies' ability to supply system flexibility [145]. Defined as the *"statistical correlation between net electricity exchange between plant and system (e), and the electricity demand minus intermittent electricity production (d)"* [145], the relocation coefficient reads:

$$R_C = \frac{\sum(e-\bar{e})(d-\bar{d})}{\sqrt{\sum(e-\bar{e})^2\sum(d-\bar{d})^2}}$$

This coefficient is clearly based on the sample correlation coefficient or Pearson's correlation coefficient indicating in this case the linear dependence between dispatchable power needs and the flexibility rendered from a given flexible unit. Blarke follows up by defining the relocation cost effectiveness as the relative increase in net present value of the system of increasing the relocation coefficient by one percentage point.

In later work, Blarke applied the term intermittency-friendliness coefficient for the Relocation Coefficient [214–216].

8.7. Biomass system efficiency

In [156], Kwon and Østergaard defined the biomass system efficiency

$$\eta = \frac{\text{Output of all plants fueled by biomass} - \text{Output from synthetic fuel}}{\text{Input bio mass amount} - \text{biomass used for transportation}}$$

which is basically applied to assess the usefulness of biomass in the energy system – disregarding the transportation system.

8.8. Intermittent RES use with lowered base-load production

Franco and Salza [169] proposed determining how reduction in base load production influences the integration of intermittent RES through the factor ΔE_{IR}, without naming the term. The term is defined as

$$(\Delta E_{\text{IR}})_{ij} = \frac{(E_{\text{IR}})_{ij} - (E_{IR})_{i0}}{(E_{\text{IR}})_{i0}}$$

where E_{IR} is the production from intermittent renewable energy sources and subscripts i and j annotate respectively an installed capacity of renewables of i [MW] and a reduction in base power of j [MW]. The term thus indicates how much more intermittent renewable energy production that might be integrated with varying amounts of capacity and with varying amounts of base power production. If base power plants are given a high production a priori, then there is little room for intermittent renewable energy production and vice versa.

8.9. Thermal plant PES reduction with lowered base-load production

Similarly, Franco and Salza [169] proposed the term ΔE_{TP} for the reduction in PES caused by lowering base load production defined as

$$(\Delta E_{TP})_{ij} = (E_{TP})_{ij} - (E_{TP})_{i0}$$

where E_{TP} is the PES of conventional thermal plants production and subscripts i and j annotate respectively an installed capacity of renewables of i [MW] and a reduction in base power of j [MW]. The term indicates how much PES may be saved at a given installed RES capacity with a reduced base-load-requirement compared to a situation with the same given RES capacity but with a defined standard base load production. In EnergyPLAN modelling terms, this corresponds to the fuel savings of thermal power plants by decreasing the grid stability requirements if the defined standard base-load is expressed in relative terms or by decreasing the minimum production on the central CHP if the defined standard base-load is expressed in absolute terms.

8.10. Synergy from the inclusion of electric vehicles

As Franco and Salza [169] and others point out, introducing electric vehicles has an immediate effect on PES due to a higher efficiency of the propulsion system. In addition, there may be secondary effects on the energy system as charging patterns affect the operation of the energy system, and optimal charging patterns may results in additional savings. Thus, Franco & Salza calculate the PES reduction additional to the immediate reduction due to improved efficiency of electric vehicles over vehicles with internal combustion engines.

$$\Delta E_{EV} = \Delta E_{EV,Total} - \Delta E_{EV,Vehicles}$$

where ΔE_{EV} is the additional saving caused by electric vehicles (EV), $\Delta E_{EV,\ Total}$ is the entire energy systems PES savings and), $\Delta E_{EV,\ Vehicles}$ is the PES saving based on kilometres driven and efficiencies of the traction system - internal combustion engine on the one hand and electric traction system including power production and transmission on the other hand.

8.11. Flexibility factor or system flexibility

Nunes et al. [200] apply the Flexibility factor or System Flexibility in their EnergyPLAN simulations of Portugal. This factor is defined by Denholm and Margolis [217] as *"the fraction of peak load below which conventional generators can cycle"*. When taken as a simulation output rather than input, it is thus empirically found by the lowest hourly value over the year divided by the maximum hourly value.

8.12. Marginal primary energy supply

The marginal PES indicates how the marginal PES of the system is affected by a marginal change in PES from RES, i.e.,:

$$\text{Marginal PES} = \frac{\Delta \text{PES}}{\Delta \text{PES, RES}}$$

Thus, if the marginal PES factor is less than one, it indicates that at the given penetration of RES, the system cannot fully integrate the marginal RES production. This factor is primarily useful for energy systems modelled in island mode as PES otherwise ought to be adjusted for import and export.

This term is relevant for comparisons between different RES where the factors may be determined for the marginal effect on the PES from the range of RES included in the system.

The factor should be determined for un-curtailed RES production as curtailment is one of the means for the energy system to handle integration of fluctuating RES – and thus one of the factors that the indicator should capture.

8.13. Curtailment fraction

The curtailment fraction indicates the percentage of production that is lost from a given RES-based production technology as a consequence of the system not being able to handle excess productions calculated over a given period of time

$$\text{Curtailment fraction} = \frac{\text{Curtailed RES production}}{\text{Potential RES production}} = \frac{\text{Potential RES production} - \text{Realised RES production}}{\text{Potential RES production}}$$

The curtailment fraction may also be calculated as the marginal curtailment fraction which emphasises the marginal effect of adding additional RES by determining the marginal curtailment of the additional capacity which will be larger than the overall curtailment fraction.

Alternatively, a System Integration Efficiency may be calculated as 1-Curtailment fraction where 1 (or 100%) thus indicates that all RES-based production from a given technology may be integrated.

8.14. Marginal economic efficiency

The marginal economic efficiency is defined as the ratio between marginal total system costs and marginal RES costs – each measured in marginal annual annualized costs for investments, operation and maintenance and fuels.

$$\text{Marginal Economic Efficiency} = \frac{\Delta \text{Total System Costs}}{\Delta \text{RES Costs}}$$

The term reflects how well additional RES expenditures translate into total system costs. If the ratio exceeds unity, it may e.g., indicate that additional integration cost will be incurred. This may be in the form of additional storage capacity, heat pump capacity or electrolysis capacity to accommodate the extra RES production assuming the energy system is operated in island mode and there is no curtailment.

9. Conclusion

This article has reviewed the use of the EnergyPLAN model, characterised its application and investigated which general criteria or optimisation criteria are applied in energy systems analyses, energy systems simulations and energy system scenario design. EnergyPLAN has been applied in 95 analyses, has been considered for application and/or has been characterised in 40 articles, modelling results have been referenced in 45 articles – not including articles where it has not been stressed that the referred analyses were performed using EnergyPLAN.

The survey furthermore revealed that most analyses are performed on a country or state level, that the main focus is on the development of high-RES scenarios or on the simulation of the integration of high levels of RES into the energy system, while fewer articles focus on modelling methodology or the inclusion of other technologies into the energy system.

In terms of performance indicators, most analyses apply more than one indicator with PES being dominant closely followed by CO_2 emissions, Excess power and costs. PES, CO_2 and costs are in line with official goals of countries seeking to minimise impacts on the climate.

Of indicators probing more into the technical workings and feasibility of a given energy system or a given energy scenario, excess power is by far the most dominant indicator with duration of given units, import, export, Compromise Coefficient (COMP), condensing mode power generation and ramping following. These are indicative of the types of production technologies being applied in climate-friendly energy systems; non-dispatchable production which potentially lead to power balancing problems and thus excess, import, export of condensing mode power generation.

Lastly, a series of advanced performance indicators are reviewed. These are typically ratios between optimisation criteria or ratios between marginal changes in optimisation criteria.

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