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Review and validation of EnergyPLAN

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ABSTRACT

Energy systems analyses are integrated elements in planning the transition towards renewable energy-based energy systems. This is due to a growing complexity arising from the wider exploitation of variable renewable energy sources (VRES) and an increasing reliance on sector integration as an enabler of temporal energy system integration, but it calls for consideration to the validity of modelling tools. This article synthesises EnergyPLAN applications through an analysis of its use both from a bibliometric and a case-geographical point of view and through a review of the evolution in the issues addressed and the results obtained using EnergyPLAN. This synthesis is provided with a view to addressing the validity and contribution of EnergyPLAN-based research. As of July 1st, 2022, EnergyPLAN has been applied in 315 peer-reviewed articles, and we see the very high application as an inferred internal validation. In addition, the review shows how the complexity of energy systems analyses has increased over time with early studies focusing on the role of wind power and the cogeneration of heat and power and later studies addressing contemporarily novel issues like the sector integration offered by using power-to-x in fully integrated renewable energy systems. Important findings developed through the application of EnergyPLAN includes the value of district heating in energy systems, the value of district heating for integration of VRES and more generally the importance of sector integration for resource-efficient renewable energy-based energy systems. The wide application across systems and development stages is interpreted as inferred validation through distributed stepwise replication.

1. Introduction

Renewable energy sources (RES) are a cornerstone in the transition towards a carbon-neutral society where every effort is made to ensure that anthropogenic global warming is limited, as e.g. outlined in the Paris Agreement [1]. Energy planning deals with the issue of enabling this transition – while at the same time acknowledging the links to demographic development and to developments in prosperity [2]. In a large survey, Salvia et al. [3] investigated climate change mitigation measures in 237 European cities, finding that 78% has mitigation plans – though only 25% strive for carbon neutrality.

As outlined in e.g. Ref. [4], there are three main steps or phases in the implementation of RES in the energy system:

1. In the introduction phase, RES are merely a supplement to an otherwise fossil energy system, and RES exploitation merely decreases the production on fossil-based generation units. Any RES contribution will be fully reflected in fossil fuel savings.
2. In the high-RES phase, the RES absorption capability of the energy systems becomes strained at times and the temporal characteristics of the energy system become an issue. In this phase, the RES implementation is not fully reflected in fossil fuel savings, as timing and other system restrictions may not permit the integration of the full production.
3. In the fully RES-based phase, the temporal issues become even more prominent, aggravated by the circumstance that, in this phase, there is no fossil-based generation capacity on which to fall back, if required. The system needs to be flexible and fully adept in ensuring that all energy needs are covered at the right time using RES that often have variable or fluctuating character.

For the fully RES-based systems, concepts such as sector integration or smart energy systems [5–7] have been suggested as an integrated approach through which the exploitation of synergies between hitherto disparate energy sectors can ensure the proper integration of RES into the energy system. One key element is that storage should first be used in

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the sectors where this is economically attractive – before resorting to, e.g., electricity storage, which is expensive and typically less efficient [8].

The complexity of the transition and the integration of RES vary with the nature of the RES, and while biomass-based units or reservoir-based hydro plants have dispatch characteristics that resemble those of fossil fuel-based units, focus is often on fluctuating or variable RES. These mainly include wind power, solar power, solar thermal, wave power, and run-of-river hydroelectric power. In most geographical settings, these are the primary options due to biomass constraints or topographical restrictions. Biomass is indeed an important topic in its own right, with a wide discussion on the extent to which its use is even sustainable [9,10] and many analyses try to restrict the use to what is locally available and at the same time sustainable [11,12]. Wind power and district heating have both been key elements in the transition in, e.g., Denmark, but while adding resource efficiency, both elements have also added complexity [13,14].

With complexity follows larger demands to the analyses required for designing appropriate transition pathways and ultimately to support policymaking and investment decision-making. A large number of tools or models are currently being applied to help identify feasible or optimal transition pathways for various geographical areas or for investigating elements of the transition including TIMES [15–17], Balmorel [18,19], Homer [20,21], energyPRO [22–27], Pypsa [28–31], the LUT Energy System Transition Model [32,33] and more.

In terms of modelling approaches, Chang and co-authors therefore also identify a trend towards a more sector-integrated approach in the modelling community [34]. Johannsen and his team, on the other hand, point to the circumstance that, e.g., urban planners often do not have the competence to engage is systems analyses and scenario-making at the complexity level required for planning the transition [35]. Similarly, Rozmi et al. [36] argue for the value of immersive visualization tools in energy systems analysis.

Lund and co-authors distinguish between denominated simulation and optimisation models [37], where optimisation models are characterised by an endogenous system design optimisation and simulation models only model systems described explicitly by the user. System design is thus an endogenous process using simulation models. Another main characteristic of the different modelling tools is their temporal resolution, i.e., whether they use hourly data for a full year or more, use time-slicing or even do not use any sub-yearly modelling to model the energy system.

The geographical target of transition pathway development ranges from cities and islands over countries to entire continents. Islands represent a particular and novel focus for transition planning research, and regarding the use of models in this context, Prina et al. [38] find that national-scale models are often applied in these cases. This is despite such cases requiring particular constraints due to, e.g., challenges arising from spatial and temporal resolution. They also note that compared to unit commitment models, models like EnergyPLAN rely on a simplified representation of system stability.

In a comparison of models, Klemm and Vennemann [39] address which models are suitable for multi-energy systems in mixed-used districts. Based on a survey of 145 models, they identify 13 models – including EnergyPLAN, energyPRO, HOMER, Markal, oemof and TIMES – as having the required characteristics for modelling such systems. In another comparison, Bouw et al. [40] identifies a gap in existing models in terms of their representation of buildings and retrofitting opportunities as well as in general lack in equal representation of heat and electricity sectors – though acknowledging that, e.g., EnergyPLAN as a general purpose model *"do treat all sectors with the same degree of detail"*.

EnergyPLAN is an example of one the more prominent modelling tools in the scientific literature [41]. It is a tool that has been under continuous development at Aalborg University since the turn of the millennium, and the first publications even precede the use of the name [42–44]. EnergyPLAN has been developed with the explicit purpose of designing and simulating high-RES energy systems. Thus, it operates with a 1 h temporal resolution for a full year and it has sectorial integration in its core to act as an enabler of the integration of RES into the energy system. It is a simulation model [37] based on *analytical programming* implying that EnergyPLAN employs pre-coded priorities and procedures to handle the behaviour of all units in each time step. It is thus, for instance, not based on the numerical solving of a series of connected balance equations, as in modelling tools based on linear programming.

A previous survey from 2015 showed that, at that time, EnergyPLAN had been applied 95 times to simulate case studies published in the journal literature [41]. Primary energy consumption, carbon dioxide emissions, costs, and excess generation were the most dominant characteristics that were applied to assess to which extent a given energy system was favourable.

Since that survey, the field in general and EnergyPLAN applications in particular have gained even further traction. This combined with the magnitude of the investments required for the energy transition increases the need for validation of EnergyPLAN. Rehman and Andersen [45] argue for two important elements of validation; internal and external. The former addresses the computational ability and the latter the appropriateness of the model under given circumstances. External validation is usually performed in the modelling-tool selection phase of the analysis in question, while internal validation regards the actual mathematical procedures of the tool in question. EnergyPLAN is documented in the manual [46] as well as in Ref. [47], but even so, strictly speaking, this does not constitute a validation.

In Ref. [48], the authors argue, with respect to the energyPRO modelling tool, that the sheer number of applications can function as an internal validation; what may be labelled *inferred internal validation*. The rationale being that the more a modelling tool is used, the lower is the likelihood that misrepresentations or actual programming errors are left unnoticed.

The aim of this article is to strengthen the internal validation of EnergyPLAN through a review of its application, and thus also to form a reference for further work applying EnergyPLAN. This review is based on analyses of journal articles which apply EnergyPLAN or refer to EnergyPLAN in other ways, as well as analyses on the geographical scale of the cases studied. Secondly, in a more in-depth part, a selection of case articles is analysed with a view to illustrating the evolution in types of analyses conducted and results gained using EnergyPLAN.

In its essence, the article is a synthesis article as it synthesises the application of EnergyPLAN from a quantitative as well as from a qualitative perspective. The quantitative element supports its validation, and the qualitative element synthesises some of its impacts on the energy systems analysis field. The qualitative element also serves to support the article's supposition of model validation through distributed stepwise replication. It is the first article to address the inferred validation of the EnergyPLAN model through such a synthesis of its application.

The article proceeds with an overview of the approach used for identifying studies applying EnergyPLAN in the literature in Section 2, and quantitative analyses of the usage of EnergyPLAN in Section 3. Section 4 presents a discussion of validation approaches including calibration, replication, and model comparisons, while Section 5 is a review of types of EnergyPLAN applications and the results of these over time. Lastly, conclusions are presented.

2. Methodology

One issue when identifying relevant work is that search facilities like Scopus [49] and Directory of Open Access Journals [50] do not enable users to perform full-text searches of journal articles. Thus, whether an article is identified properly using databases depends on where the authors have used the term EnergyPLAN in the given work. Observing Table 1, for instance, it is clear that there are many more occurrences of the term "EnergyPLAN" when making full-text searches in Elsevier's journals using ScienceDirect [51], than in a Scopus search where only

Table 1
Examples of differences in number of search results depending on search facility. Data as of June 1st, 2022. Results are neither checked for relevance nor type of publication. Scopus searches are made using the search string "TITLE-ABS-KEY (energyplan) AND DOI (10.xxxx/*)" where xxxx is the DOI root for the individual publisher.

Journal or publisher	Search results in Scopus (Title, Abstract & Keywords)	Search results using journal full-text search
IEEE	19	22
IJSEPM	12	12
Elsevier	169	781
MDPI (e.g., Energies)	25	27

titles, keywords and abstracts are included.

On the other hand, full text searches are also more likely to generate irrelevant matches that require manual evaluation. In the 2015 survey [41], 18% of the ScienceDirect results were thus not relevant in the context.

Therefore, the process needs to be split into more steps; screening of journals and in-depth search within these. This section details how articles have been identified for inclusion in the analyses and are subsequently analysed in a three-step approach, as outlined in Fig. 1. These steps are detailed in the following subsections.

2.1. Identification of journals and full-text search facilities

Using Scopus [29] and Directory of Open Access Journals [30], a series of journals may be identified where the term EnergyPLAN appear in the data indexed by these – typically in titles, keywords and abstract. This results in the journals listed in the second column in Table 2.

In many cases, these journals are but one of multiple journals of the publisher; however, using the journal identification as an entry point to identify the publishers' proprietary search engines enables the wider full-text search across the publishers' range of journals.

2.2. Article identification and characterisation

The identification of journal articles for inclusion in the analysis involves a selection of the type of publications for inclusion and an evaluation of the articles. First and foremost, only peer-reviewed journal articles are included in this survey. Some of the publishers' search facilities enable the inclusion or exclusion of different categories of work, which can assist in this regard. Taking ScienceDirect as an example, several categories may be selected or deselected, as shown in Table 3, which details the application.

Secondly, some peer-reviewed journal articles apply the term "EnergyPLAN" – though some in contexts irrelevant for this article. Here, the same labelling as used in Ref. [41] is applied:

1. Irrelevant in the context – e.g., through the reference to various websites containing the word energyplan or from articles preceding the tool in focus in this article
2. Duplication – mainly copies of article abstracts published separately from the main article
3. Referencing results – work that mentions results from EnergyPLAN analyses, but without detailing or describing the modelling tool

Table 2
Journals and publishers publishing EnergyPLAN work identified through Scopus and DOAJ.

Publisher	Journals	Publisher's full-text search facility
Econ Journals	Int. J of Energy Economics and Policy	https://econjournals.com/
Elsevier	Applied Energy, Energy, Smart Energy, Energy Policy - and more	https://www.sciencedirect.com/
IEEE	IEEE Access	https://ieeexplore.ieee.org/search/advanced
MDPI	Applied System Innovation; Energies; Sustainability	https://www.mdpi.com/
SAGE	Energy and Environment	https://journals.sagepub.com/
SDEWES	J of Sustainable Development of Energy, Water and Environment Systems	(No proprietary search engine – searched via Scopus and Google Scholar)
Serb. Soc. of Heat Transfer Eng.	Thermal Science	(No proprietary search engine – searched via Scopus and Google Scholar)
Springer	J of Modern Power Systems and Clean Energy – and more	https://link.springer.com/
Taylor & Francis	International Journal of Sustainable Energy	http://www.tandfonline.com
Wiley	Wind Energy - and more	https://onlinelibrary.wiley.com/search/advanced
WITPress	WIT Transactions on Ecology and the Environment	https://www.witpress.com/
AAU Press	Int. J of Sustainable Energy Planning and Management	https://journals.aau.dk/index.php/sepm

Table 3
Article categories used in ScienceDirect and application in the identification of work.

Included	Disregarded
Research articles, Review articles, Short communication	Conference papers, Books, Book chapters, Encyclopaedia, Conference abstracts, Book reviews, News, Editorials, other (Acknowledgements, Indexes, Contributor descriptions)

4. Characterisation – papers that consider EnergyPLAN as a candidate for analytical tool, characterises it, compares to other modelling tools or similar, or mentions it as an example of a model
5. Application – papers that present analyses where EnergyPLAN has been applied to one or more case studies.

Category 5 articles typically also contain elements of categories 3 and 4, while Category 4 articles also typically contain elements of Category 3 articles. However, here they are only characterised according to the highest category number.

Contrary to the analyses in Ref. [41], Categories 1 and 2 are excluded already in the initial article selection process.

Search results are harvested for storage in an Excel database depending on the facility of the journal in question. While for instance Scopus can export directly in CSV (comma-separated values) format, exports from ScienceDirect are in BibTeX format [52] which are subsequently converted to CSV using JabRef [53].

Since this is a very dynamic field in publishing, the article database

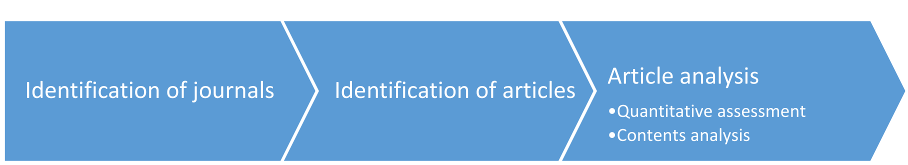

Fig. 1. Analytical approach for EnergyPLAN article analysis.

requires maintenance, which is a manageable task for most publishers due to their slow publication rate of EnergyPLAN articles. Specifically for Elsevier journals, however, the automated search and notification facility offered by ScienceDirect is used whereby an e-mail may be received when a new article containing a given search term is published.

3. Quantitative EnergyPLAN usage

This section provides an overview of the use of and reference to EnergyPLAN in the journal literature from a quantitative and geographical scope perspective, thus providing bibliometric data on its ability to model a variety of different systems.

3.1. Character and temporal evolution of EnergyPLAN references

The first usage of EnergyPLAN was found around the turn of the millennium, and the first published results were from an analysis of the interplay between wind power and cogeneration of heat and power (CHP) and the impacts on the transmission system from different operation strategies [43]. At this time, however, the tool had not yet received its name; thus, the first articles referring to the name were not published until 2003.

Applying the characterisation from Section 2 gives the tabular overview found in Table 4 –shown graphically in Fig. 2.

Not surprisingly, the first articles were applications only, and only later were results or the tool referenced in the literature. Fig. 2 shows a sustained increase by all three measures over the last two decades. Also, in the later years, reference to results or to EnergyPLAN itself has increased and has overtaken the application of the tool in the literature. This points towards a larger awareness of the tool as well as a focus on the results gained from EnergyPLAN modelling.

As seen in Fig. 3, as of July 1st, 2022, 39% or 315 of the articles demonstrate an actual application of EnergyPLAN; another 42% offer some level of characterisation of EnergyPLAN, and 19% refer to results without going more into detail about the tool itself. It should be noted, of course, that this survey does not capture any work that refers to EnergyPLAN analyses with a complete disregard for which tool was used in the referred work. Taking for instance the five highest cited articles in Scopus which both apply EnergyPLAN *and* use the term EnergyPLAN in title, abstract or keywords [10,65,71,97,122], as of July 1st, 2022, these are cited 1924 times in the literature – though they can of course be referenced for information not relating to the EnergyPLAN analyses and results. All five articles are EnergyPLAN application articles.

Table 4
Character of EnergyPLAN reference and temporal evolution in the journal literature. Updated up until July 1st, 2022.

	Application	Characterisation	Reference
2003	[54–58]	[59]	–
2004	–	–	–
2005	[60,61]	–	–
2006	[62–66]	–	–
2007	[67,68]	–	–
2008	[69–72]	[73]	[74]
2009	[75–81]	[82]	[83]
2010	[18,84–91]	[92]	[93,94]
2011	[95–107]	[108–115]	[116–121]
2012	[122–134]	[135,136]	[11, 137–141]
2013	[12,142–148]	[149–156]	[157–162]
2014	[163–181]	[182–195]	[196–207]
2015	[208–230]	[41,231–242]	[5, 243–250]
2016	[10,251–269]	[25,270–300]	[301–310]
2017	[311–327]	[328–363]	[364–370]
2018	[371–398]	[28,399–435]	[436–452]
2019	[16,453–483]	[31,33,36,484–518]	[519–540]
2020	[541–576]	[20,577–624]	[625–646]
2021	[647–686]	[34,38–40,47,48,687–700] [701–720] [721–739]	[740–757]
2022	[1,2,4,9,10,12, 758–783]	[3,5–8,11, 784–815]	[816–824]

In general, EnergyPLAN has seen a substantial application in the journal literature. This is discussed further in relation to validation of EnergyPLAN in Section 6.

3.2. Geographical coverage

EnergyPLAN is applied to various scales in the literature, ranging from urban neighbourhoods to continents. For this overview, three different levels are included:

- Local
- Country
- Multi-country

For certain cases, adaptions are made compared to normal geographical understanding. Due to size, states or provinces in the USA, China, India, and Australia are treated as countries. Thus, a paper dealing with 10 US states [133] is not treated as a "local" geographical scale, but rather as a multi-country geographical scale.

In general, there is a prevalence for studies of countries, as seen in Fig. 4 and Table 5, and within this category, a certain prevalence of European case studies. However, as also seen, all inhabited continents are represented in the case studies conducted using EnergyPLAN in the journal literature. Africa is the continent with the least application of EnergyPLAN.

Fig. 5 shows a graphical representation of where EnergyPLAN has been applied in the journal literature, indicating that, e.g., all EU member countries have been analysed. The application in general has been global, albeit with a clear underrepresentation in Africa as well as Central and South-East Asia.

Different scales of applications provide different settings for energy systems analyses where small systems are more sensitive to issues of granularity in the modelling environment whereas the modelling of very large systems in single-node models like EnergyPLAN run the risk of not capturing internal bottlenecks and of evening out fluctuations from geographically disparate regions.

4. Approaches to model validation

This section presents an overview of different theoretical considerations to model validation as well as a discussion on calibration and model comparisons as part of validation and finally considerations regarding open source as a part of validation.

4.1. Theoretical considerations regarding validation

The validation of models and modelling tools is a recurring issue in the scientific literature. According to the Oxford Advanced Learner's Dictionary, validation is "to prove that something is true" [825], which is not possible to do with any scientific hypothesis; whereas the Oxford Learner's Dictionary of Academic English elaborates slightly with the definition "to prove that something is true or accurate" [826] and Merriam-Webster's defines validation as "to support or corroborate on a sound or authoritative basis" [827].

Sargent [828] argues that "*model verification and validation are critical in the development of a simulation model as a model and its results need to be 'correct'* ". However, as pointed out by Smiatek et al. *"Validation Is Not Verification"* [829], which is based on the fact that *"if the simulation model output data and the real world output data are consistent with each other, the simulation model is not rejected, but neither is it accepted or 'proven true'. It is provisionally accepted as 'valid' because it has not been falsified"* [830]. Both Wang & Grant and Rykiel forward the notion that validation *"means that a model is acceptable for its intended use because it meets*

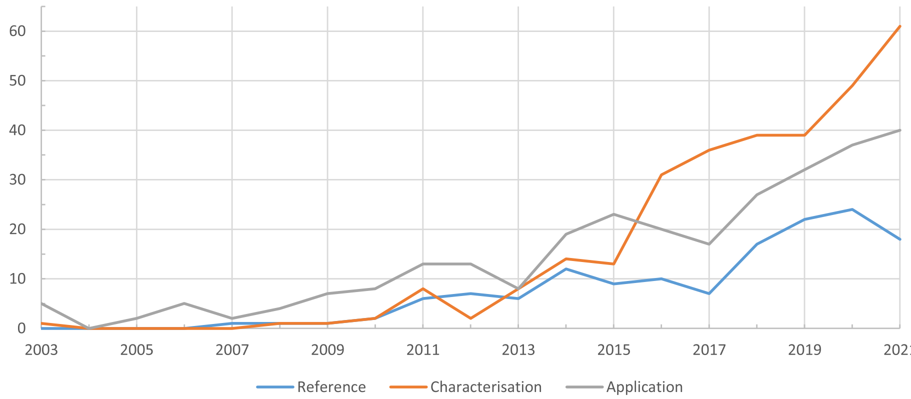

Fig. 2. Character and temporal evolution in the use of EnergyPLAN 2003–2021 in the journal literature. Partial data for 2022 are not shown.

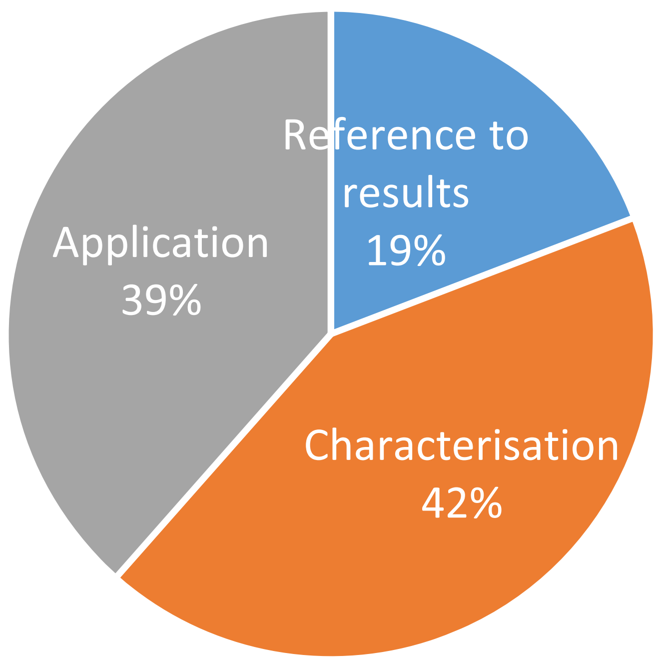

Fig. 3. Character of EnergyPLAN reference in the journal literature. Updated up until July 1st, 2022.

specified performance requirements." [831,832]

Helfenbein and DeSalle introduce the term corroborate, stating that *"Hypotheses, other than tautologies, that have been tested and not falsified have been corroborated"* [833].

Refsgaard & Henriksen [834] split the model validation into three elements – the conceptual model, the coding and the site-specific model, stating that a *"conceptual model is subject to confirmation or falsification like scientific theories. A model code may be verified within given ranges of applicability and ranges of accuracy, but it can never be universally verified. Similarly, a model may be validated, but only with reference to site-specific applications and to pre-specified performance (accuracy) criteria"*. Based on this, they arrive at the finding that a *"model's validity will always be limited in terms of space, time, boundary conditions and types of application."* [834]

A similar, disaggregated and more operational approach is given by Rykiel [832], saying that the *"validation process can be decomposed into several components: (1) operation, (2) theory, and (3) data."*

Finally, as pointed out by Kleindorfer et al. [835], there seems to be no way to validate a tool and a model in a traditional scientific understanding. Applying a courtroom analogy, the model and tool designers are left with the option of arguing for the credibility *"beyond reasonable doubt"*. Applying such approach to the EnergyPLAN tool and energy systems models made in EnergyPLAN, one may argue that the large application in the scientific literature shown in Section 3 lends credibility to EnergyPLAN and that is it validated through its application. In the case of EnergyPLAN, this is further supported by its shown ability to replicate a diversity of different energy systems across nations and energy system development stages.

4.2. Replication and calibration

From a more practical stance, some articles touch upon the issue of validation of EnergyPLAN through a discussion on calibration as in Refs. [375,547]. Focus is thus on the tool's ability to replicate systems described with existing statistical data. In the latter reference, this is the overall topic of the paper, where they first show that EnergyPLAN can replicate a given year and secondly suggest approaches to modelling multiple years despite, e.g., climatic differences between years. Other work provides a more integrated approach, addressing validation from a model theoretical perspective as well from a calibration/data perspective; e.g. Ref. [134].

Replication through calibration is useful for documenting the ability to model existing systems appropriately – thereby validating the output – however, it will by nature be limited as suggested by Ref. [834] to certain boundary conditions or as phrased by Kerr and Goethel *"Operational validation of the model using independent data may not be possible when the simulated scenario extends outside the realm of observed conditions"* [836] in a publication on fish stocks.

Energy planning models, however, are frequently applied to analyse future scenarios based on significant changes in the composition of the energy system. Thus, while a tool through a proper calibration may replicate a given system to match actual statistics, it is not per se a given that future systems will also match. Here, the situation is of course, that there is no statistics or measurements to match against. However, with a tool like EnergyPLAN that has been used to replicate multiple systems in the literature, a large variety of different systems have already been replicated as shown in Section 3. Thus, to take an example, a reference model for a given country with only individual boilers for heating may be set up and calibrated to adequately replicate the existing system. While this replication and calibration in the given case does not necessarily lend credibility to district heating analyses of that country, replication in other countries or systems with district heating will. Thus, analyses across different energy system development stages will support a model's validation – particularly for systems not at the forefront of development. This may be labelled validation through distributed stepwise replication.

Additional to the discussion of replication with the aim of validation is also the issue of replication by other researchers. In principle, the results of the use of tools for energy system analysis should be replicable

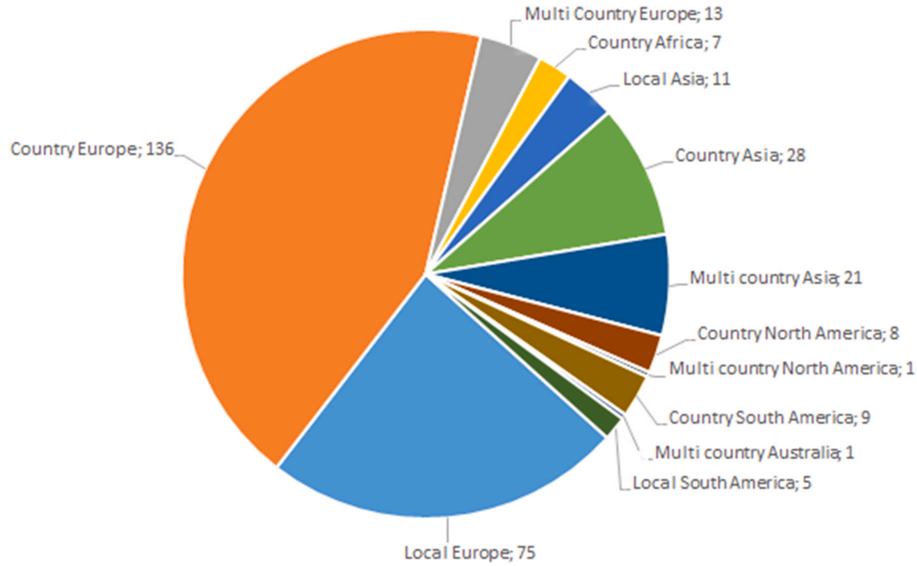

Fig. 4. Geographical coverage of EnergyPLAN applications in the journal literature. Updated up until July 1st, 2022.

Table 5
Characterisation of journal papers applying EnergyPLAN according to geographical scale. Updated up until July 1st' 2022.

	Local	Country	Multi-Country
Europe	[4, 68,86,91,96,98,99,101,123,126,127,148,171,173,174, 209,211,221,224,252,253,263,264,267,311,315,316], [371–374], [380,382,390,392,398,454,460,461,464,469,473,476,477, 480,544,545,547,551,554,557,558,560] [562,565–567,651, 652,659,660,668,670,672,681,684,761,772,775,778]	[1,9,10, 12,16,54–58,61–67,69–72,75–81,84,85,87–90,95,97, 100,102,103,105,107], [122,124,125,128–131,134,145–147, 168–170,178–181], [208,210,213–215,217–220,222,225,226, 229,254,256–258,261,262,266], [317–320,323,324,326,375, 378,379,385–387,389,395,397,453,457–459,463,465,468, 470,472] [474,479,482,483,542,546,549,555,561,568,571,573,575, 656,657,663,665,667,671,675,677,680,682,683,766,769,770, 774,780]	[10,106,177,255,259,265,322, 391,393,649,673,679,782]
Asia	[216,268,313,325,327,396,462,475,563,653,686,762]	[12, 132,142,144,164,166,172,176,227,230,269,312,314,383, 481,559,574,654,655,662,664,666,669,764,767,768,771,776]	[2, 104,143,228,251,260,321, 376,384,466,467,471,541,548, 550,552,569,650,674,758,765]
Africa		[570,576,647,648,777,781,783]	
North America		[163,165,167,212,223,381,388,478]	[133]
South America	[676,678,685,759,763]	[377,456,564,658,760,773,779]	
Australia			[553]

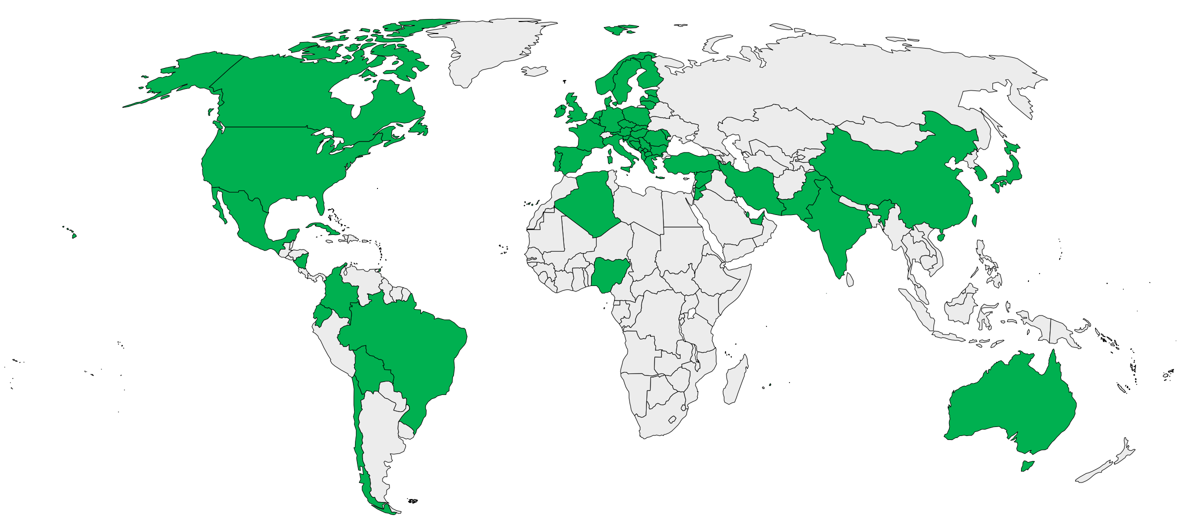

Fig. 5. Global application of EnergyPLAN applications in peer-reviewed journal articles. The map shows countries in which EnergyPLAN has been applied, though in many cases the application has not been to the entire country. Updated up until July 1st, 2022.

for other researchers. This requirement means that the tools and models as well as the data should be accessible for others to replicate.

4.3. Validation through comparison

Models may also be validated though comparisons to other models. Thus, in more cases, the same case study is investigated in EnergyPLAN and another modelling tool to validate the model outcomes. R Lund et al. [254] compare EnergyPLAN outcomes with a Modest-based model to investigate large-scale heat pumps in district heating, finding that the *"comparison does not show any significant differences"*, albeit a tendency for lower optimum of heat pumps and lower system costs for the EnergyPLAN-based model.

H Lund et al. [68] compare results from EnergyPLAN with H2RES (see model description in Ref. [837]) to evaluate the renewable energy transition of the island Mljet in Croatia. The two models had different scopes and coverage – EnergyPLAN targeting holistic systems and H2RES electricity systems only for instance – thus the comparison was for electricity-only systems. The article identified different approaches in the modelling of, e.g., hydrogen storage and minimum ancillary service provision, but the two models arrived at *"more or less the same results"* when analysing the island of Mljet.

Liao et al. [321] compare outcomes from their modelling tool with EnergyPLAN to assess results on North-West China. They find that EnergyPLAN underestimates wind and PV curtailment as a consequence of overestimating the flexibility of the system as it excludes *"the unit commitment constraints"*. It should be noted that EnergyPLAN does not exclude unit commitment constraints – though not all of the constraints in Ref. [321] are included. Thus, power balance, reserve capacity, and maximum generation are for instance included while ramping, minimum on and offline time constraints and inter-system constraints are not to address a sample of the constraints from Ref. [321]. Unfortunately, is not clear which of the mentioned constraints in particular have caused the deviations in the result.

In a comprehensive model analysis of Bolivia, Lopez et al. [773] compared the LUT Energy System Transition model and EnergyPLAN. They found that EnergyPLAN arrived at a 30% higher system costs due to differences in the modelling of synthetic natural gas – a major constituent in the LUT scenario. For the same reason, the use of EnergyPLAN would not lead to the same role of synthetic natural gas. Subsequently, EnergyPLAN's modelling of this sector was improved to address the identified issue.

Perkovic et al. [269] use EnergyPLAN as comparison for their analyses of desalination in Jordan, finding good agreement between the results from EnergyPLAN and from their proposed Mixed Integer Linear Programming model. Similarly, Laitinen et al. use EnergyPLAN to validate their tool EnFloMatch [651] for a system with a battery, an electricity demand, PV and wind power. They found *"very similar results"* from the two model runs. Lastly, Lyden et al. [815] use EnergyPLAN to compare with simulation results from the use of their PyLESA model on a case having PV, heat pump and thermal storage, showing *"similar overall results"*.

These model comparisons corroborate EnergyPLAN's credibility. Also, the fact that researchers find it valuable to use EnergyPLAN to validate new models and compare results with other models is a testament to the wide applicability range of EnergyPLAN and the years of development.

4.4. Open source as validation

EnergyPLAN is not an open-source model but rather open access. Thus, users do not have access to the actual implementation of the algorithms. This is opposed to initiatives such as OseMOSYS, where the first 2011 presentation [838] stressed a compact and accessible coding, or the PyPSA [29] environment.

Stokes [839] point to the challenge of validating open source models with no well-defined "software vendor" and thus possible uncontrolled evolutions but Groissböck [31] argue that, e.g., *"OseMOSYS, and pyPSA are mature enough based on a function comparison with commercial or proprietary tools for serious use"*. Interestingly, this is assessed based on functionality rather than, e.g., an internal validation of the coding. Likewise, in one of the early PyPSA application articles, validation was not so much considered with a view to the coding but rather *"through replication and extreme input testing"* where the extreme input testing shows whether changes in inputs provide expected results.

Open access will provide the expert user the opportunity to probe into the coding and with more users utilising a given model and possibly adapting it, it must be assumed that this does provide a high degree of internal validation of the coding. This is not an option for a model like EnergyPLAN where instead it may be argued that there is a case of distributed extreme input testing. For non-expert users, whether the source is open access or not does not per se offer validity or not.

5. EnergyPLAN results from the literature

This section reviews four categories of EnergyPLAN studies that may also be seen as a progression in terms of the level of complexity of the energy systems design and simulation. From the first studies, where focus was on the integration of CHP and RES into fossil-based systems with little sector integration, to some of the latest analyses, where EnergyPLAN is integrated with other modelling tools to form even more complex simulation environments. In this latest category, the aim is to address the integration between national energy systems or to form modelling environments that include both design optimisation and simulation approaches. The diversity and high application also support the notion of extreme input testing.

5.1. Early-stage sector integration studies

The early studies of sector integration using EnergyPLAN focused mainly on supplementing existing fossil-based energy systems and reducing the energy production of these technologies, as shown by the three phases listed in the Introduction. In these studies, the focus was only on a few energy sectors. More specifically, the review of the first stage shows how EnergyPLAN was instrumental in showing the feasibility of CHP combined with district heating and how this could help integrate RES into the energy systems. Many of the studies from the early 2000s used a scenario for the west Danish energy system in 2020 with 20% wind power integration as the basis for making different energy system analyses.

This scenario was modelled in an early version of EnergyPLAN that focused on the connection between the heating and electricity sectors, with the remaining energy sectors being included using simple representations.

Lund and Münster [54] used the scenario to evaluate different strategies for dealing with excess electricity production from wind power and later, Lund [65] used the scenario to identify an optimal mix of different types of variable RES in the electricity system.

Østergaard [62] used the scenario to analyse how wind power penetration could be increased in Western Denmark via sector integration, and Lund and Münster [63] used the scenario to analyse how to increase the flexibility in the Danish energy system, with a view to increasing the national utilisation of variable RES. The national flexibility options were compared with the potential to use the international transmission lines for balancing. Based on the total annual costs of the energy system, the study found that the share of wind power could be increased from 20% to 40% without significant imbalance issues in the electricity system.

Lund and Münster [64] used the scenario to analyse the energy system effects of changing a share of the passenger cars and vans in Denmark from oil-driven to battery electric vehicles and hydrogen fuel cell vehicles. The results were analysed using excess electricity production, socio-economic costs, and CO_2 emissions as criteria. Chen et al. [86] used the scenario to evaluate the energy system effect of using thermoelectric generators in CHP plants.

The 2020 scenario was not the only utilised scenario, as e.g. Münster and Lund [80] used a scenario for the Danish energy system in 2004 to analyse how different alternatives of utilising organic waste in the energy system could provide reductions in the fossil fuel consumption.

5.2. Full sector integration and smart energy systems

The progress from early stage studies to full sector integration was a process in which the research on different areas formed a new full system understanding as highlighted in Ref. [5]. Several studies have highlighted the importance of a variety of technologies to the large-scale integration of RES. In Ref. [81], seven different integration technologies were compared. Here, it became evident that it is not enough to conduct studies on how to reduce curtailment when analysing RES integration. Significant differences can be found among the technologies in terms of energy efficiency and thus the ability to reduce fossil fuel demands.

The first studies of fully 100% RES-based energy systems, however, revealed some challenges. Coherent analyses of full energy systems, such as in Refs. [75,95], formed a pathway together with the comparative assessments of different integration and technology studies presented in Ref. [81]. In fully renewable energy systems, bioenergy became a key parameter, especially in the transport sector [70]. A key solution to this challenge is electrofuels and power2X, due to a significantly more fuel-efficient conversion potential as well as a large potential to reduce the reliance on bioenergy in fully renewable energy systems [180].

EnergyPLAN has been used for the modelling of 100% RES-based energy systems for more than 15 years. As outlined in the previous section, it was initiated to address the large-scale penetration of RES -based electricity in the Danish context. This has meant that the tool already from this stage included sector integration on the thermal side, considering CHP as well as district heating. Already at an early stage, the tool also included large-scale heat pumps and thermal storage.

A significant challenge in the context of further integration of RES going beyond the heat and electricity sector is the transport sector. While EnergyPLAN included industry, transport as well as biogas from early stages, further developments took place to also include electrofuels for transport and industry as well as in relation to the dynamic modelling of these components. The transport sector can now be modelled with a variety of options from gaseous to liquid fuels, biofuels and power2X to electrofuels, as well as smart charge and V2G of electric vehicles [71]. Rather advanced modelling of electrofuels, transport solutions and power2X for transport and industry is now possible with fully dynamic abilities, such as presented in Korberg et al. [649].

The smart energy systems approach represents a level of systems integration that ensures balance between energy savings and energy efficiency on the one side and the integration of RES on the other, using several different energy vectors, infrastructures and storages [5] that are now better integrated in EnergyPLAN.

Several studies now use the smart energy systems approach, not only from a national level but also from a local, city, regional or island level, e.g. for Aalborg [545], Zagreb [372] as well as Madeira [557].

Other studies see technologies in the perspective of fully integrated renewable energy systems, e.g. for the effects of system design on infrastructures [379], the impact of electrification of ferries [566] and the use of biogas in smart energy systems [549].

In two works, Bačeković and Østergaard investigated the value of sector integration [372] and the value of integration between separate systems [373] finding a strong value of sector integration – and a lesser value of integration between systems. The former article finds that RES-based systems not based on sector integration results in biomass demands higher than the sustainably available quantity while integrated smart energy systems are much better at integrating fluctuating RES. Costs are similar in the two instances.

A coherent understanding of the roles and the design of energy systems based on RES is dependent on a system understanding. In fully integrated energy systems in EnergyPLAN, several different future contexts can be used in the analysis of different sides of the transition from more traditional energy systems.

5.3. Multi-tool analyses

EnergyPLAN has been and still is mostly used as a stand-alone energy system analyses tool. However, with a general increase in both modelling and computer power, a recent development is the increasing number of analyses that have been made which either combine EnergyPLAN with other energy system analysis tools or utilise EnergyPLAN as the computational engine in optimisation algorithms or other multi-run analyses. These multi-tool approaches form an even more complex modelling approach with, in general, two different approaches.

The first approach is to combine inputs and outputs from two different energy system modelling tools, for instance by linking outputs from one tool into EnergyPLAN, or vice versa. This approach typically has the aim to utilise the strengths of different energy system analysis tools to provide a greater insight into the energy systems, and maybe overcome any potential weaknesses that certain modelling tools might have.

De Luca and co-authors use this approach to link Trnsys and EnergyPLAN to evaluate the implementation of RES in Altavilla Silentina in Southern Italy [371]. With Trnsys, they are able to model PV in detail, then using EnergyPLAN to simulate the entire energy system using the PV outputs from Trnsys.

EnergyPLAN has also been combined with LEAP [840], utilising the benefit of LEAP's long-term projection of energy system development combined with EnergyPLAN's capabilities of investigating the annual operation of the energy system on an hourly basis. Bhuvanesh and co-authors [383] use this combination to investigate the case of Tamil Nadu in India. Kiwan and Al-Gharibeh [574] use the approach for Jordan, also combining it with another tool, SAM, to capture meteorological data and designing the power plants. Also Cantarero [381] utilises the same approach to investigate Nicaragua, by combining the long investment paths of LEAP with the hourly simulations from EnergyPLAN.

A similar approach is used by Thellufsen and co-authors to investigate the potential for district heating in Ireland. Here, the long-term investment paths are determined by Markal/TIMES [841], and combined with an hourly investigation of the potential for district heating in Ireland, using the features of EnergyPLAN [16].

Østergaard and co-authors [464] conduct a multi-tool analysis by comparing results from EnergyPLAN on the overall system level to more local analyses conducted in EnergyPRO, thus comparing the outputs to gain more insight into the consequences of implementing heat pumps in district heating systems.

EnergyPLAN has the distinct feature of including the entire energy system, whereas other modelling tools focus mostly on the electricity system. Thus, researchers have combined outputs from an electricity model and simulated this in EnergyPLAN to capture the whole energy system. This is the case for Groppi et al. [460] that use HOMER to optimise the electricity system of Favignana Island, Italy, and then use these outputs as inputs for EnergyPLAN to simulate the entire system. From HOMER, they calculate, for instance, RES capacity and electricity load.

EnergyPLAN uses demands as inputs, which has led researchers to link demand response modelling tools with EnergyPLAN. Olkkonen and co-authors model demand side response in the electricity sector, using their own demand response model, and generate an optimal use of flexible electricity demand on an hourly basis. The total system effect of this demand response is then investigated using EnergyPLAN [320]. Olkkonen and co-authors expand on this approach in a later study, also including a wind power simulation tool. Both examples are analyses of a

Finnish energy system [387].

The second overall approach concerns using EnergyPLAN as the computational solver in optimisation algorithms, agent-based models and other multi-run algorithms written in different tools, such as MATLAB, Python and other tools and languages. Here, EnergyPLAN, in most cases, is used to calculate a large number of scenarios for the same case, to assist researchers in identifying one or more optimal solutions to the posed research questions.

Several different applications have been developed to use EnergyPLAN as an energy system simulation core in an optimisation algorithm. One set of modelling tools focuses on single objective decision tools; as seen in the GenOpt and EnergyPLAN linking described by Bjelic and Rajakovic [214]. This has been applied to the case of Serbia and used for investigating how to combine different solutions in the energy system to the flexibility gap coming from implementing wind and solar energy [257]. Another developed tool which is useable for these single objective optimisations is the EnergyPLAN toolbox for MATLAB, developed by Cabrera et al. [613] This has been used for the case of Lanzarote [659]. These tools run EnergyPLAN with the objective of minimising or maximising one parameter, for instance CO_2 emissions or RES share.

Furthermore, a branch has developed looking at multi-objective/multi-criteria optimisation algorithms utilising EnergyPLAN. The early development of this application was initiated by Mahbub et al. [267], using Java to combine multi-objective evolutionary algorithms (MOEA) with EnergyPLAN and applying it to the case of Aalborg, Denmark. Viesi et al. continued the work utilising this application on Trento in Italy [572].

Another application is the ePLANopt protocol, which uses MOEA implemented in python programming, essentially running several EnergyPLAN analyses with the objective of identifying the optimal solutions for more optimisation criteria.

Typical for ePLANopt models is to investigate CO_2 emissions and total annual costs calculated by EnergyPLAN. If convergence is reached, the ePLANopt stops; if there is no convergence, it will generate new parameters and execute the tool again, thus being evolutionary. EPLANOpt has been used on cases in Italy [397] and South Tyrol [374], and has been developed to be able to calculate marginal abatement cost curves. Other multi-objective approaches have been developed such as by Bellochi et al. [565] and Menapace et al. [547].

By combining EnergyPLAN with single and multi-objective optimisation algorithms, EnergyPLAN has entered a much more comprehensive modelling scope, where computer algorithms are able to identify solutions much faster than the individual user. This both provides more details to an analysis, but also requires a sufficient overview from the researcher grasping the wide number of results and outcomes from such optimisation procedures.

A final EnergyPLAN development worth mentioning here is the development of help add-on tools to EnergyPLAN, which expands the capabilities of EnergyPLAN beyond the initial scope of the tool. The MultiNode add-on expands the capabilities of EnergyPLAN analyses, by allowing the user to investigate the consequences of linking two or more EnergyPLAN models through electricity transmission. It has been applied to investigate whether local system integration or electricity transmission benefits the energy system technically [322]; how a number of islands in Croatia can potentially link [398], and the linking between local and national energy systems in Croatia [373] and Denmark [253]. In a parallel development, Huang et al. have developed a multi-node approach to EnergyPLAN between the two cities Beijing and Zhangjiakou in China [563].

6. Conclusions

This paper has discussed the issue of how to validate complex energy systems modelling tools such as EnergyPLAN. There are different scientific views on how to do so, but consensus seems to be that it is difficult tantamount to impossible to do so in a traditional sense. This leads to statements as "A model code may be verified within given ranges of applicability and ranges of accuracy, but it can never be universally verified" [834] and the consequence that models and modelling tool developers are left with the choice of arguing for credibility "beyond reasonable doubt", as phrased by Kleindorfer et al. [695].

In this paper, we have operated from a point of departure of *inferred internal validation* – i.e., that the internal coding may be validated or corroborated simply through a large-scale application. We have thus synthesised EnergyPLAN's application both from a quantitative and qualitative perspective. Indeed, EnergyPLAN is one of the leading energy systems analyses modelling tools in use with 315 case studies in the journal literature as of July 1st, 2022. It is considered, mentioned, or reviewed in further 494 articles in the journal literature, and it may thus be stated that it has had and has a strong fingerprint on the modelling and energy systems analyses field.

The large-scale application of EnergyPLAN may serve as an inferred internal validation, i.e., the combined efforts of the researchers involved have tested EnergyPLAN and found it appropriate not only for modelling given systems but also for producing credible results.

The application across multiple countries and energy system development stages confirms the ability of EnergyPLAN to replicate different systems through calibration thus serving as an element in its validation. This is labelled validation through distributed stepwise replication.

Several authors have compared EnergyPLAN to other modelling tools and have in general found good agreement in obtained results, thus also serving as an element in its validation.

The review of EnergyPLAN applications demonstrates how EnergyPLAN has been instrumental in early analyses of CHP systems with varying degrees of RES penetration to later analyses of fully integrated smart energy systems, where the flexibility across all sectors is drawn upon to analyse and design RES-based energy systems with proper load-following capabilities.

An important early-phase finding reached using EnergyPLAN is the value of district heating in energy systems – as well as the value of district heating in assisting in the integration of fluctuating RES.

The review of EnergyPLAN applications for smart energy systems analyses has clearly shown the value of this possibility in EnergyPLAN and that there is a need to further understand the local or national roles or specific technologies' roles in future fully integrated systems. The problems addressed are typically related to e.g., balances between energy sources or bioenergy, the most feasible uses of these fuels, and the role of flexibility. A smart energy system approach highlights the need to understand that conclusions within energy systems are completely system dependent. Thus, the development of EnergyPLAN has followed or preceded the developments in the energy systems analysis community.

An important finding from this phase is the importance of aiming for integrated smart energy systems when transitioning to fully RES-based energy systems. Other options are possible, but they will result in poorer performance and a higher drain of non-fluctuating energy sources.

The specific review of the role of EnergyPLAN in simulation setups with other models also show how these multi-tool approaches only increase the role and potential of EnergyPLAN in future energy system analyses and the use of EnergyPLAN to validate new models supports its credibility and serves as a further inferred internal validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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