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Østergaard, Poul Alberg; Andersen, Anders N.; Sorknæs, Peter

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The business-economic energy system modelling tool energyPRO

Poul Alberg Østergaard [a, *], Anders N. Andersen [a, b], Peter Sorknæs [a]

[a] Aalborg University, Department of Planning, Rendsburggade 14, 9000, Aalborg, Denmark
[b] EMD International, Niels Jernes Vej 10, 9220, Aalborg Ø, Denmark

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ABSTRACT

The transition towards carbon-neutral energy systems requires the identification of solutions that are optimal at a societal level, however, market actors operate under a different logic where each individual investment option is required to show business-economic feasibility. Thus, while there are energy system analysis modelling tools that can help identify optimal transition paths for a given society in general through the minimisation of national or regional energy system costs, there is also a need for modelling tools that take a closer focus on how energy system actors and their investment considerations perceive and are affected by the economic and technical environment. The modelling tool energyPRO is of the latter type developed and evolved over the last decades to assist in the assessment of the feasibility of different energy units in the energy systems, but which can also model larger complex systems. This article presents energyPRO with a focus on its system understanding and general model characteristics and a thorough view into its two optimisation approaches based on analytical programming or mixed integer linear programming. Finally, a comparison with other models as well as a review of its characterisation and application in the academic literature is supplied.

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1. Introduction

In line with the recommendations from the Intergovernmental Panel on Climate Change [1] and the stipulation of the widely adopted Paris Agreement [2], there is an eminent need to plan a transition towards sustainable energy systems [3].

Much research has gone into the identification of local, regional, national, or transnational scenarios that demonstrate socioeconomically feasible paths in such a transition process and the various technology constituents of such transition scenarios. From early studies focusing on expanding wind power, for instance, research has developed through increasing complex iterations focusing on sector integration through district heating (DH) [4] supplied by cogeneration of heat and power (CHP) or power-to-heat technologies such as heat pumps (HPs) and electric boilers to fully integrated smart energy-based systems [5] that may also include transportation [6] and, e.g., district cooling systems [7].

Barriers have also been investigated – ranging from ownership of wind power [8] and CHP systems [9] to neighbour [10] and public acceptance [11] - however, while significant focus has been put on overall energy system transition costs, less focus has been devoted to ensuring that proper incentives are given for investments in the transition.

Thus, for instance, several tools exist that consider holistic national or regional energy systems and the costs thereof such as the widely used EnergyPLAN [12], which is one of the models with a well-developed DH/CHP modelling ability or the LUT Energy System Transition Model [13]. EnergyPLAN has also been applied as the calculation engine in investment optimisation scenario modelling tools such as Prina's eplanOPT [14], Mahbub's model [15] and Bjelić's EPOPT [16], but still, these applications have been from a societal aspect. The EnergyPLAN model has also been applied to assess the integration of different planning levels which is a separate energy systems modelling target [17] in the transition to smart renewable energy systems.

Also, several tools focus on the design of specific DH grids and components including Termis [18], Hysopt [19] and Modelica [20]. TRNSYS-based modelling [21] is also applied by some, but typically from a more technical energy system perspective as in Ref. [22].

Fewer modelling tools enable the detailed modelling of how

Abbreviations: CHP, Cogeneration of heat and power; DH, District heating; DH, Domestic hot water; DHC, District heating and cooling; FIT, Feed-In Tariff; FRR, Frequency restoration reserves; HP, Heat pump; NZEB, Net zero energy building; PV, Photo voltaics; RES, Renewable energy sources; TES, Thermal energy storage; UC, Unit commitment.

* Corresponding author.
E-mail address: poul@plan.aau.dk (P.A. Østergaard).

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frameworks are perceived by potential investors - that being new market entrants competing against incumbent stakeholders or existing owners considering portfolio changes. Homer Pro [23] is a popular software package often used for investment optimisation of both off and on-grid hybrid systems (see e.g. Ref. [24]), and while it does have a CHP module, the more intricate system optimisation against markets is not prioritised.

Some development has been seen with models integrated into Modelica [25]. Python-based models are also gaining ground where PyLESA [26], for instance, offers some planning-level capability, however, there are limitations in its handling of power markets.

Other models that may include business-economic perspectives include e.g. models by Pablos [27], Gu [28] and Maribo [29], however, these do not seem to be in general use beyond the developers.

Unit commitment (UC) models are typically applied to electricity systems though nothing precludes the application in, e.g., DH systems or integrated electricity and heating systems – see, e.g., Boysen et al. [30]. UC models are designed for short term operation's planning with the identification of the optimal dispatch of various units – though as noted by Koltsaklis and Dagoumas [31], the transition of energy systems towards integrated smart energy systems has caused UC to be included into long-term expansion planning models also. Due to the operations' focus, UC models are typically of a business economic nature, thus expansion planning with an UC approach will also have this potential feature. Expansion planning in turn typically applies a time horizon of 20–30 years [32], but in contrast to most of the above-mentioned tools they typically solely address the electricity sector. Within this sector, on the other hand, they often have a more detailed representation which for instance includes transmission systems.

The label “expansion planning” may of course be questioned. Geiger (quoted in Ref. [33]) differentiates between corrective, prognostic and programmatic planning where in brief, corrective planning alleviates problems as they arrive, prognostic planning seeks to meet prognosticated infrastructure needs and programmatic planning seeks to address needs/provision more holistically. The term expansion planning suggests an approach that simply seeks to meet demands as they grow where, e.g., other models factor in potential demand side measures while also addressing transitions more explicitly. With the move of expansion planning models into smart energy systems, this gap is decreasing though.

A main tool in the field of business economic energy system investment models is energyPRO which in addition to offering full high-temporal resolution modelling also offers the possibility to optimise operation against different markets thereby allowing detailed business-economic feasibility studies of alternative energy systems investment options. This tool may be labelled a bottom-up simulation model using the definitions of Herbst et al. [34], where simulation models *“aim to replicate consecutive rules that describe the associations and interrelationships among various system elements”*.

Thus, there is an internal optimisation in energyPRO where the different units – according to rules and characteristics – optimise their operation, however, there is no endogenous system design optimisation as found in optimisation models or UC-based expansion planning models – nor any wider societal perspective as found in equilibrium models. Also, and drawing on [35], the modelling tool is more based on user engagement and conscious choices from the modellers' side. Thus, energyPRO is designed for the analysis of tangible user-defined alternatives.

In energyPRO, taxes on energy sources and emissions are integrated, and engagement with various electricity markets simulate how dispatch decisions should take place under actual operations. On the other hand, energyPRO may also be applied without this thorough market integration simulation to simply model the behaviour of a given energy system based on, e.g., technical priorities. These two qualities have given energyPRO a certain traction in the research community with a relatively high number of studies being published in the academic literature applying this modelling tool.

However, while energyPRO has been introduced and applied in several articles, there is lack of a thorough academic reference detailing the model for the research community as well as for the industry. This is one of the four primary novelties of this article which aims to provide such a reference for further energyPRO-based studies and in line with other formal model presentation articles on, e.g., H_2RES [36], EnergyPLAN [12] and Balmorel [37] which are preceded by several application papers.

A second novelty is the introduction of a fundamental new feature in energyPRO where an integrated Mixed Integer Linear Programming (MILP) solver expands its ability to simulate the optimal operation of energy systems that are not well-suited for the analytical programming approach that energyPRO hitherto has been based on.

Thirdly, the article reviews and synthesis a selection the existing body of journal literature based on energyPRO simulations to demonstrate how energyPRO has been instrumental in the analysis and design of energy system transition steps and analyses of economic impacts of potential investors.

Fourth, while it is beyond the scope of this article to present a comprehensive comparison between models, the article presents a targeted comparison between energy system simulation models aimed at business economic system evaluation.

The next section introduces the methodology applied in the paper followed by sections on model characteristics (Section 3), modelling approach (Section 4), model comparison (Section 5) and model application in the academic literature (Section 6). Finally, Section 7 synthesises the main findings.

2. Methodology

This section outlines the methodology of this paper with a focus on the model description used for Section 3 and the review procedure applied in Section 4.

2.1. Model description

The overall model description of this paper is inspired by similar papers on EnergyPLAN [12] and Balmorel [37], and is thus focused on a brief introduction into the main model characteristics and scope in terms of technical units, temporal and geographical granularity and a more thorough focus on energyPRO's simulation algorithms.

2.2. Model review

The literature review is based on the approach adapted in Ref. [38] where first relevant journals are identified and subsequently search engines with full-text capability are applied to search for the term “energyPRO”. Broad-fetching databases like Scopus [39] only enable searches in the fields harvested from different publishers, and this does not include full-text. Thus, in order to capture all relevant references – and not only references where the users have applied the term energyPRO in the fields captured by Scopus, publisher search facilities like ScienceDirect [40] have been used.

Secondly, once identified, articles are evaluated for inclusion. Here the article relevance is assessed in five categories:

1. articles where the term energyPRO is in entirely unrelated contexts - e.g., due to the very similar name EnergyPro being used for a software package from the United States with a building focus
2. duplicates
3. articles that refer to energyPRO results end mentions energyPRO in the context
4. articles that refer to energyPRO model characteristics or considers energyPRO for use in a given analysis
5. articles that present analyses conducted using energyPRO
All articles in Category 5 are reviewed in Section 5 and some of the findings from some of the main model review articles from Category 4 are also included there. In addition, quantitative data for Categories 3, 4 and 5 are presented.

3. Model characteristics

This section describes the main characteristics of energyPRO with a focus on its system understanding.

3.1. Purpose and development of energyPRO

The purpose of energyPRO is to provide a tool for the business-economic assessment of investment alternatives in the energy sector factoring in both a detailed simulation of the alternatives' technical behaviour in the energy system and the business economic implications based on market, taxes, subsidies and more.

The development of energyPRO started around 1990, when it was politically decided to develop small-scale CHP in connection to DH systems in Denmark (see e.g. Ref. [41]). Until then, both the research community and consultancy companies had been able to model CHP/DH systems sufficiently detailed in spreadsheets. However, the legislation creating the framework for the development of small-scale CHP also included an interesting feed-in tariff that included an allowance for saved new capacity in electricity grid and central coal-fired power plants as well as an allowance for saved operating costs of these.

The detailed legislation split the tariff into a time-differentiated triple tariff [42]. This incentivised investments in more CHP capacity, larger thermal energy storage (TES), and, e.g., larger biogas storages. The identification of optimal investment in combined production and storage capacity became too complex for spreadsheet analyses, which created the demand which energyPRO eventually fulfilled.

The development of energyPRO in the coming years followed closely the development of small-scale CHP, but in parallel, a major expansion of wind power took place. When the time came where it occurred that wind had to be curtailed to make room for, e.g., natural gas-fired CHPs, the time had come to discontinue the triple tariff. Instead, the prices for produced electricity were settled hourly in the wholesale markets – Day-ahead and the Intraday markets. This also introduced the need to have prognosis-based scheduling of production in the wholesale markets in energyPRO.

In recent years, new features have also been added allowing to model participation in delivering balancing and ancillary services. Thus, besides the two wholesale markets, energyPRO also enables the user to simulate participation in balancing and ancillary services.

Furthermore, due to the expected increasing interaction between different energy sectors, recently, features have been added to energyPRO allowing the modelling of Power2X - e.g., production of methanol from combining electrolysis-produced H_2 with CO_2 from biogas plants, where waste heat is delivered to nearby DH systems.

3.2. Availability of energyPRO

Being a commercial product, commercial companies are paying for energyPRO licenses, and around 400 companies have bought the software worldwide (See also Fig. 1).

Academic licenses are available for universities, and typically, groups of students, using it for project work, acquire the license free of charge.

In addition, a demo version is available free of charge. This version has limited capability as it will not enable users to create or save new models. It will permit users to load and calculate existing models, e.g., own models or any of the many models available from EMD.dk. As such, energyPRO allows for analysing energyPRO models even without a license.

A large selection of tutorials enable users to access information ranging from “getting started” to insights on more advanced features [43]. EMD International also offers courses in energyPRO.

3.3. Geographical scope and level of aggregation

The geographical focus of energyPRO is on being able to model and simulate specific plants and their energy conversion and storage technologies. The geographical basis for energyPRO is sites, being geographical points where energy conversion technologies, storage technologies and/or energy demands are located. These sites can then be connected via different energy vectors, allowing for representation of, e.g., grid constraints. Though the focus is on specific plants, in principle entire countries could be modelled and simulation in energyPRO – possibly with an aggregation of units.

3.4. Time resolution and simulation horizon

The time resolution of the simulations has to a high degree been determined by the electricity markets energyPRO is dealing with. The two wholesale markets have required hourly and half hourly resolutions, whereas, e.g., the European automatic Frequency restoration reserves (FRR) market requires a 5-min resolution and the manual FRR market requires a 15-min resolution.

The simulation horizon extends from calculating a few days when energyPRO deals with the daily operation where energy storages allow storing energy across more days, to calculating across many years to find a net present value in an investment analysis. The maximum number of years is set endogenously to 100.

3.5. Structure of models in energyPRO

The overall structure of a model in energyPRO is divided into inputs for:

- Project identification
- External conditions, where, e.g., weather and price time series and time series functions of these can be entered
- Sites (See Section 3.3)
- Transmission capacity between sites
- Fuels
- Demands
- Energy conversion and storage units
- Operation strategy (See Section 4)
- Environmental impacts
- Revenues based on the sale of energy products
- Operation expenditures including energy, fixed and variable costs
- Investments
- Financing, where long-term and short-term loans can be modelled

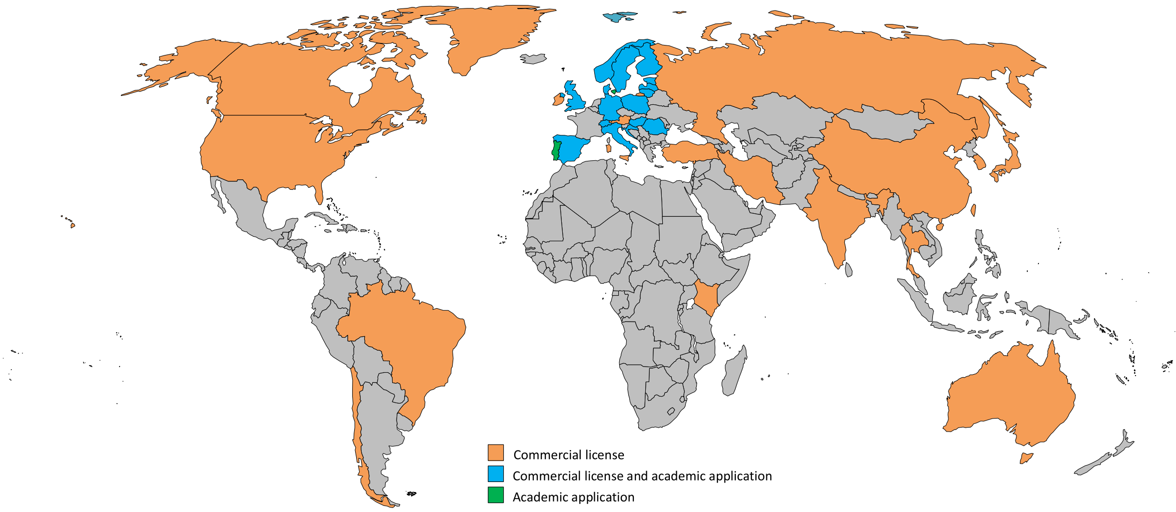

Fig. 1. Geographical outreach of energyPRO in the journal literature as well as commercial use. (Data as of July 1st 2022). The blue and green colouring indicates that energyPRO has been applied academically to a case within that country; not that it has been applied to the entire country. Orange and blue indicate nationality of licence holders, not necessarily their application.

- Taxation, where company taxes are modelled

Depending on the simulation horizon chosen, some of these will be hidden. If, e.g., calculating a few days is chosen, investments, financing and taxation will not be accessible.

Within each item in the overall structure, users can add as many components as required, e.g., add as many energy conversion units as desired. Users may also choose between endogenously predefined components of, e.g., a HP, or instead make it as a user-defined unit, where the user through formula expressions establish their own model of the HP, being dependent on, e.g., the weather time series entered in External conditions or dependent on a specific demand entered in Demands.

Environmental impacts can be of any user-defined type and can relate to, e.g., the use of given fuels or the operation of specific conversion units – e.g., CO_2 from the use of specific fossil fuels or NO_x from specific processes.

Likewise, users can include as many payments – both revenues and expenditures – as required linking to, e.g., emissions or operational parameters.

3.6. Coding and execution

energyPRO is coded in Delphi Pascal and can be used as a standalone application. It also allows for interfacing with other application through XML-files. Users can instruct energyPRO to read an XML file, in which users may specify changes in the specific energyPRO project file, perform a calculation and save specific reports as files. Typically, Excel or Python have been used to generate the XML file [44].

As an example, if a user has a heating system with natural gas-fired boilers and wishes to install a solar collector, one may wish to investigate the impact of two different collector types, three different collector areas and two different storage capacities. Including a reference scenario this altogether amounts to 13 separate calculations. Typically, it would require 13 different energyPRO project files to simulate this but by using XML it performs the 13 calculations and have the results presented in report files.

In other applications, this feature has been used to run several 100s of separate calculations to generate 3D meshes showing the impact of two factors, for instance in Ref. [45].

3.7. Climate time series downloaded from an online server

energyPRO is dependent on high temporal resolution data for demand, supply, and costs. Temporal data may be inputted by the user, however, instead of importing climate time series from files and spreadsheets energyPRO also offers the opportunity to download such data from an online server provided by EMD International.

The data from the energyPRO online server originates from three different climate models:

- The National Center for Atmospheric Research (NCAR) reanalysis project,
- the Climate Forecast System Reanalysis (CFSR) and
- the Climate Forecast System Reanalysis 2 (CFSR2).

The three models offer modelled weather data in a high-resolution grid covering the whole world, based on weather measurements. The data cannot be downloaded using the demo version of energyPRO.

3.8. Reports in energyPRO

All inputs and results from energyPRO can be exported for further analyses or illustration elsewhere, or they can be shown graphically in energyPRO. In addition, energyPRO can create several pre-defined reports with specific foci as detailed below:

- Production, graphics – where users can scroll through the planning period day by day to inspect the production and storage contents as well as applied time series
- Production, carpets - where all time series are shown with values as colours in matrixes with vertical axis as days and horizontal axis as hours
- Energy conversion tables
- Duration curves
- Environment - where all user-defined emissions are shown
- Cash flow, where all payments are calculated monthly and shown both in tables and graphically

- Key financial figures - with figures such as net present values and internal rate of return
- Income statements - where the income from the sale of energy is detailed
- Balance sheets - where, amongst others, values of assets and remaining debt of loans are shown
- Catalogue of technical assumptions - documenting all entered technical data
- Catalogue of economic assumptions - documenting all entered economic factors
- Operation strategy calculation - where possible net production costs are shown

Depending on the chosen simulation horizon, some of these will be hidden.

3.9. Sector integration in energyPRO

In energyPRO it is possible to include electricity, heating, cooling, and different types of fuels, both in relation to the production, storage, and demands of these. It is possible to setup energy conversion units for connecting either or potentially several of these.

Fuels can be set to be imported into the specific sites modelled in energyPRO, where they are simply modelled as amounts and associated costs. Electricity can both be imported and exported to/from the model sites. Here, the surrounding electricity system is modelled as an electricity market with prices on different electricity markets, and potential grid tariffs and connection constraints to the external electricity system.

4. Modelling approach

There are two main modelling approaches — or simulation strategies — in energyPRO. The analytic dispatch mode and a MILP dispatch. These two are detailed in this section.

4.1. The analytic dispatch mode in energyPRO

In energyPRO, a priority number is attached to each energy conversion technology in each time step. The analytic dispatch mode then considers the entire optimisation period and activates the lowest priority numbers first, disregarding the chronological order of the time step except for priority numbers that are the same.

Units are then activated until all energy demands are met within the optimisation period using energy storages to move energy between time steps, considering user-defined technical limitations of, e.g., storages and energy conversion units.

Two options for optimisation period exists in energyPRO - monthly and yearly. The monthly optimisation period allows for a more realistic operational forecast as it cannot predict the entire year, and the yearly being able to simulate the operation of seasonal energy storages. The two options also reflect that the calculation time grows significantly when the optimisation period grows. It will normally be sufficient to split the planning period into monthly optimisation periods, however, when seasonal energy storage is considered a yearly optimisation period is needed.

The priority numbers can either be calculated by energyPRO or be defined by the user. If calculated by energyPRO then the aim is to get the lowest total heat production costs of the modelled energy system, where the short-term marginal heat production cost for each unit in each hour is used as the priority number. Here energyPRO also considers, e.g., the heat input for absorption chillers a heat demand, when calculating the priority numbers, but the cost of supplying all other energy demands is not directly considered in the priority numbers. The focus on the production cost of heat is due to the mentioned historic development of energyPRO, first being a modelling tool for DH companies.

The analytic dispatch method's starting point in net heat production costs provides useful information for operators of District Energy plants regarding daily operational strategies; operators who often have a clear opinion on these costs.

If the user defines own priority numbers, then it is possible to setup equations that define the priority numbers on more aspects than reducing the heat production cost of the system, including priority numbers that change from calculation step to calculation step, depending on, e.g., electricity prices or energy demands. Priority numbers may also simply be set as fixed numbers to mimic a set dispatch order.

4.2. MILP-based dispatch model in energyPRO

Besides the analytic dispatch method, energyPRO offers a MILP-based dispatch method. Where the analytic approach is based on the calculation of priorities for given units and thus priorities with an actual techno-economic meaning, the MILP-based approach treats dispatch optimisation as a purely mathematical problem. In the MILP-based approach, the objective function to be optimised is the operation income, as given by the all the revenues and operation expenditures. Included in energyPRO is the open CBC solver but energyPRO can also use commercial solvers such as Gurobi.

The MILP-approach includes constraints as, e.g., minimum loads. These constraints are experienced daily by the plant operators, who have extensive experience in the complexity, non-linearities and constraints of the daily operation of the energy plants.

In the literature, it is made probable that no single dispatch method can solve all dispatch problems [46], therefore, an option is to make use of and combine the best of, e.g., analytical and solver-based dispatch methods. Andersen [46], for instance, compared energyPRO's analytical approach and a solver-based method for optimal UC of a complex district energy plant. The comparison showed that the analytical method of energyPRO delivers operation income within 1% of the optimal operation income as determined via the solver approach. This is fully adequate for daily operation planning, yearly budgeting, and long-term investment analysis. In general, the analytic method is faster, however, if the optimisation problem deals with small energy storages and more production units with minimum loads, or more different types of loads (e.g., heating, cooling, electricity) then the analytic method may fail to find an optimal load of the production units. In contrast, the solver approach handles such systems well.

Examples of where MILP performs well and even better than the analytic dispatch mode is in energy systems, where it is difficult to attach priority numbers to each energy conversion technology. To revisit the example from Section 4.1, when it comes to, e.g., an absorption chiller, the cost of producing cooling depends on the costs of the consumed heat, which may be retrieved from a TES and depends on which production unit has produced the heat. Another example is a plant producing methanol and consuming CO_2 and hydrogen, where the cost of producing methanol depends on the costs of CO_2 and hydrogen, which may both be stored before producing the methanol.

The MILP approach in energyPRO is further detailed in Ref. [47].

5. Techno-economic model comparison

This section presents a targeted comparison between energyPRO and a selected range of other models that share the common trait that they target business economic assessments of energy systems. Many or possibly most energy systems models applied in the analysis of the transition towards renewable energy systems address some variety of societal cost where total system costs are aggregated and possible combined with a monetised externality. Fewer models focus on the business-economic reality of investors. See Table 1 for the full model comparison.

Compared to other business economic models, energyPRO stands out through its higher temporal resolution, its ability to model large and comprehensive energy systems, its ability to model relevant markets while offering the possibility for detailed inclusion of taxes and subsidies. TOP-Energy shares some of these traits though with a lower granularity in temporal resolution.

6. energyPRO in the academic literature

This section provides an overview of how energyPRO has been characterised in the literature followed by an overview of its application in the literature separated into main categories of field of application.

6.1. Characterisation of energyPRO

The energyPRO modelling tool has been mentioned in 168 journal articles as of July 1st· 2022. This ranges from passing remarks where results found in other work is referenced or where the model has been considered but discarded as a potential candidate for use for analyses to in-depth review articles where energyPRO is characterised and compared to other models in the field.

One of the newer review articles by Chang et al. [54] gathered information on 54 simulation models – among them energyPRO – and used the information to extract aggregated quantitative findings on the trends in energy system modelling. Among the findings are a *"Growing coverage of cross-sectoral synergies, open access, and improved temporal detail"*, where at least cross-sectoral synergy and high temporal resolution applies to energyPRO.

In the model review by Olsthoorn and co-authors, energyPRO is briefly listed as a *"Modelling package for cogeneration and trigeneration plants of fossil fuels, biomass and other complex energy systems"* [55], while the model review by Ringkjøb [56] categorises it as a bottom-up investment and operation decision support model based on analytical optimisation.

Ferrari et al. [57] surveyed 17 models for urban or district scales, shortlisting energyPRO (along with e.g. HOMER and EnergyPLAN) as a model which *"can provide hourly energy calculations and can be considered as viable for widespread use"*

Lyden et al. [58] probe deeper into the simulation processes of various models and describe energyPRO's non-sequential simulation process where units are dispatched in order of increasing cost. Sharma et al. [59], on the other hand investigate models and compare them with respect to their handling of environmental assessment – thus including up and downstream energy used, finding however, that energyPRO does not cover these and only includes CO_2, SO_2 and NO_x emissions. While this observation may typically be correct, it should be noted that users may define other externalities without any restrictions and even apply costs to these if required.

Klemm and Vennemann [60] categorise a number of simulation models according to various characteristics. Here, energyPRO is characterised as being based on dynamic programming defined as *"an algorithmic approach to solving problems by splitting them into sub-problems and systematically storing intermediate results."*

Connolly et al. [61] in their comparison of 37 models note

Table 1
Overview of techno-economic model comparison.

	Technical characteristics				Economic characteristics				
	Temporal resolution	System aggregation level of production units and demands	Energy sectors included	Storages included	Taxes & Subsidies	Electricity markets	Money streams	Optimisation approach	Profitability assessment
energyPRO [48]	User defined; minimum 5 min	Demand of each building or total. Production units modelled with functional expressions	All sectors	Thermal, cold, electricity and fuel storages	Can be applied to any activity in a model	Day-ahead markets Feed-in-tariffs	Detailed to and from the modelled system	Nonchronological analytic optimisation and Solver optimisation	Net present value and income statement
TOP-Energy [49]	1 h	Demand of each building or total. Production units modelled technically detailed	All sectors	Thermal, steam, cold, electricity, compressed air and fuel storages	Can be applied to any activity in a model	Day-ahead markets Feed-in-tariffs	Detailed to and from the modelled system	Solver optimisation	Net present value
Solvergy [50]	1 day	Building level	Heat	None	Applied to export and import	Day-ahead markets	Aggregated to and from the modelled system	Chronological analytic optimisation	Net present value and payback
Energy Optima 3 [51]	1 h	Aggregated heat demands	Heat and electricity	Thermal storage	Applied to export and import	Day-ahead markets	Aggregated to and from the modelled system	Solver optimisation	Detailed operation income
RET Screen [52]	1 h	Aggregated heat demands	Heat and electricity	Thermal storage	Applied to export and import	Feed-in-tariffs	Private wire/ behind own meter economy	Chronological analytic optimisation	Net present value and payback
Homer PRO [23]	1 h	Aggregated heat demands	Heat and electricity	Thermal and electricity storage	Applied to export and import	Microgrid, without market participation	Microgrid economy, without market payments	Chronological analytic optimisation	Comparing mix of components at micrograms with payback
Polysun [53]	1 h	Building level	Heat	Thermal storage	Applied to export and import	Feed-in-tariffs	Aggregated to and from the modelled system	Chronological analytic optimisation	Net present value and payback time

energyPRO as being a model for *"Single power-plant analysis"*. While this may be true for many applications, it is, however, not a restriction within energyPRO as also demonstrated by some of the applications in the academic literature review in Section 7 where also regional and country studies are found.

Hinojosa et al. [62] not only reviews energyPRO and compares it to three other models with a CHP focus; the group also applies all four (SEA/RENUE model, CHP Sizer 2, Ready Reckoner 3.1 and energyPRO v3.2) to the same case study. In their findings, they write that energyPRO *"is a powerful and flexible application. Many different scenarios can be modelled, but a good understanding of the system and the program is fundamental."* For comparison, CHP Sizer is characterised as a simple tool *"only intended to give a first feasibility indication"*, SEA/RENUE is listed as being in an early stage of development and lastly Ready Reckoner *"requests a great number of inputs"* and *"only allows a maximum of 12 entries for each load profile, which it is not satisfactory with highly variable profiles"*.

6.2. Geographic reach in the journal literature

The model energyPRO has been applied in the journal literature to analyse cases in Northern, Central, Eastern and Southern Europe with a certain prevalence for Northern Europe as shown in Fig. 1. While 17 articles have been about or have included Danish cases, 34 have addressed cases in other countries. Three articles include cases in multiple countries [63–65] to enable comparison between conditions in different places – and two are undefined. See also Fig. 1. As of July 1st, 2022, 52 journal articles employing energyPRO have been published, and applying the same argumentation as done in Ref. [66], this application rate can be seen as *"an inferred internal validation"*.

Most studies address single sites – district energy plants – but a few transcend this and address towns of entire countries – e.g. [67,68] while a few go below the urban level to address groups of buildings or neighbourhoods e.g. [69–71].

6.3. CHP and boiler system analyses

With a history of playing a role in the development of CHP in Denmark and elsewhere, this feature of energyPRO has also played a role in the academic application of the model, and indeed, the first published articles applying energyPRO were based on the analysis of CHP systems.

Lepiksaar at al. [72], for instance, apply energyPRO to analyse natural gas savings potentials in Tallin, Estonia, through a combination of CHP, TES and an electric boiler in a 4th Generation DH [73] context.

Andersen and Østergaard [46] take a more fundamental approach to their modelling of district energy plants operation against an electricity market; they compare the outcome of energyPRO simulations with two alternative UC approaches. Grouped under the headers Solver-based UC and Analytical UC, a simple and an advanced analytical UC method and a solver-based (i.e., MILP) method are established. Of these three, the advanced analytical UC method corresponds to energyPRO's approach, and the MILP-based approach is used as the point of reference for the other approaches as the designated optimal operation strategy. One difference between the approaches is that in the analytical approaches, intermediate results have actual physical or operational meanings where the MILP-based approach is a purely mathematical optimisation process.

Kazagic et al. [74] use energyPRO to model and analyse renewable DH system in Visoko, Bosnia and Herzegovina. They combine energyPRO with an environmental module to assess CO_2, SO_2, NO_x and particulate matter emissions to form a modelling environment they use to identify optimal RES-based system.

6.4. Storage system analyses

Future high-RES energy systems require flexibility and or storage to ensure a continuous balance between supply and demand. In an analysis of the Danish city Aalborg, Østergaard [75] investigate the impacts of different types of energy storage – TES, biogas and electric storage – on the system's ability to integrate wind power into the energy system. TES and biogas storage are the cheapest options – however the largest potential impact comes from direct electricity storage.

In a study of Järvenpää, Finland, Hast et al. [76] investigate the potential future role of TES and HPs under different electricity price developments. They find, for instance, that in future energy systems where RES integration is an important role of DH systems, TES of about 1% of the annual DH demand is economically feasible. For comparison, this around 10 times as much as what Danish DH plants are generally supplied with.

In Ref [77], the authors investigate the optimal design and operation of compressed air energy storage systems using energyPRO, EnergyPLAN and a dynamic programming model written in Python. The three different approaches find similar optimal operation strategies, but the authors argue, that in practise due to less-than-optimal foresight, earnings can only be expected to reach 80–90% of the earnings found using the models.

6.5. Solar systems and waste heat sources

Valančius & Mikučionienė [70] apply energyPRO to investigate the renovation of Soviet-era buildings of flats in Lithuania. Specifically, they investigate the potential role of PV and solar collectors in a renovation process, finding that, e.g., for a five-storey building, 61% of the domestic hot water (DHW) demand could be supplied by solar thermal collectors. The share naturally depends on the relative roof-top area per dwelling, so for higher buildings, the solar coverage is less.

Solar heating and HPs share some of the same characteristics in the energy system. Both prosper from low DH forward temperatures and draw on RES - or in case of HPs, heat sources of a use-it-or-lose-it nature irrespective of their origin. Also, both perform better in the warmer part of the year than the in the colder, depending on the heat reservoir exploited by HPs. Rämä and Wahlroos [78] use energyPRO to analyse the prospects of solar thermal and HPs in Helsinki, Finland. Specific HP heat sources are not assessed, but tentatively include both waste heat from industry and service-sector sources and from wastewater and natural sources such as ground water and other bodies of water. Under Helsinki conditions, the authors find that HPs outperform solar thermal both in economic and emission reduction terms.

6.6. Heat pump analyses

While space heating demand can be met using DH at relatively low temperatures [73], DHW preparation typically requires higher temperatures for legionella and cleaning purposes. With DH grid losses proportional to the difference between water and surrounding soil and HP efficiencies also related to temperature levels, lowering the DH temperatures improves overall efficiency. With booster HPs installed to boost DHW temperatures, DH water temperatures may be lowered to below the level normally required to produce DHW. In Ref. [79], Østergaard & Andersen analyse the energy system value of introducing booster HPs into HP-based DH systems, finding that energy use and cost are lower in such a system than in DH systems where temperatures are maintained at a sufficiently high level to produce DHW without boosting.

In a study of the Danish island Samsø, Østergaard et al. [80] investigate the potential for switching existing DH systems from being based on biomass boilers to being based on HPs. While overall analyses are conducted using EnergyPLAN, more detailed analysed of the business-economic feasibility of the HPs are conducted using energyPRO. The analyses demonstrate an all-too-common situation – that HPs are appropriate from a general energy systems' perspective but that they are not competitive with biomass boilers from a business economic perspective.

6.7. Holistic systems

Kiss [67] investigated the feasibility of a municipal energy strategy developed by the municipality of Pécs, Hungary based on biomass, biogas, geothermal energy, PV, solar heating, HPs and fossil fuel-based conversion systems. Compared to an alternative business-*as*-usual scenario, the energy strategy scenario is both technically feasible, reduces emissions and employs a greater share of locally available RES – but from an economic perspective not all elements are favourable.

In a similar analysis with the same lead author [68], overall national transition scenarios are developed and analysed for Hungary. Generated scenarios are again favourable from an emission perspective – but more expensive than the fossil-based alternative, though the authors argue that the extra cost is outweighed by better performance with respect to environment and security of supply.

DH is widely applied in Northern Europe, and much effort has also been on analysing such cases as well as the transition of such cases. Popovski et al. [81] takes a Southern European view, analysing the prospects of district heating and cooling (DHC) in Matosinhos, Portugal. With waste resources that may be exploited, DHC shows promise, being the socioeconomically most feasible options. PV and HP systems equally so – however, only if investment costs of the present systems are considered, i.e., a PV HP combination with a new investment cannot compete against the short-term marginal costs of the present system.

6.8. Economic conditions

District energy plants have a pivotal role to play in future energy systems; this is the starting point for the analyses of Andersen & Østergaard in Ref. [82]. Such district energy plants can help in the integration of fluctuating RES, however, without proper incentives, such units will not be installed – nor will they - if installed - possess the required capability in terms of flexibility providers unless incentives promote this. The authors take an analytical starting point in the prudent allocation of public funding to ensure that support incentivises the installation of adequate capacity at plants while not overcompensating this. Using energyPRO as the simulation engine, they develop a methodological framework for analysing support systems.

One of their findings is that a Premium scheme requires a little less total support compared to a Feed-In Tariff (FIT) paid in all hours for promoting a certain amount of CHP capacity but promotes a five times larger TES to be installed. The Premium scheme thus promotes increased flexibility for integrating intermittent RES power production.

In a follow-up analysis [42], the same authors analyse the FIT against a market-based system showing that the former is shown to be particularly well adapted towards incentivising the construction of district energy plants with TES capacity and some excess CHP capacity to make use of the TES, which is beneficial for district energy CHP to fulfil its subsequent tasks in a RES-based energy system.

6.9. Overview of tool application

Fig. 2 presents an overview of the application of energyPRO in the journal literature with a focus on system scale, focus, type of economic assessment, sectors covered, and technologies included. The full list of the identified journal articles including categorisations can be found in the appendix.

Regarding scale, the categories plant, local and national are applied. Plant is a system typically connected by a thermal network. Local is a system not confined to such a network while national are more such networks. In most applications, energyPRO is applied to a single plant with a single – typically DH – grid.

Focus is separated into technical, economic, and techno-

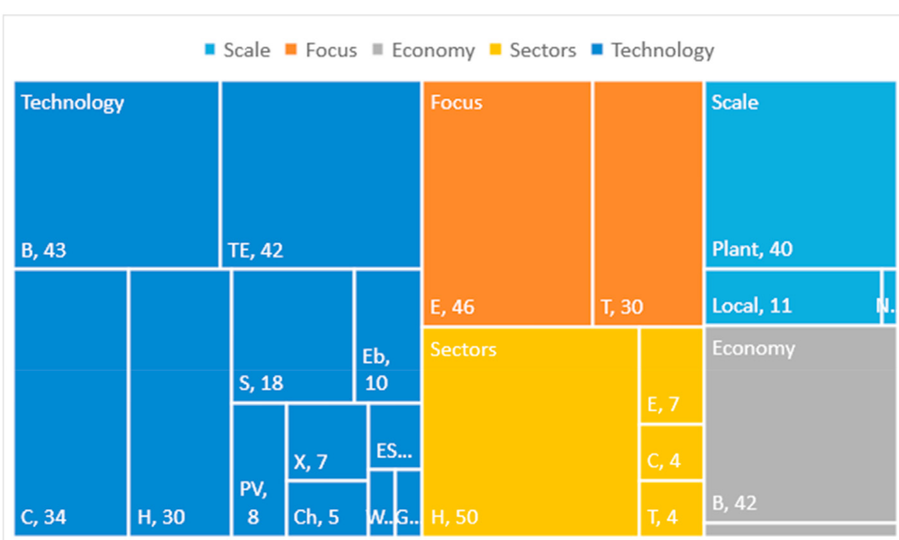

Fig. 2. Treemap of energyPRO application in the academic literature based on Table 2 in the appendix. The number shows the number of academic papers with the category. Data as of July 1st, 2022.

economic, where a few examples are purely technical analyses and equally few have a very strong economic angle. Most are classified as being techno-economic assessment though.

Regarding economic perspective, most work is based on business-economic assessment where a specific plant's feasibility is assessed including factors such as electricity markets, taxes, grid tariffs, subsidies, and even insurance costs. Less work takes a more holistic total energy system or societal costs.

Almost all articles include a heat demand that needs to be covered, while a minority include cooling, electricity, and transport demands. In the categorisation, the modelling of a CHP plant is not inferred as indicating that the electricity sector is included. Sectors are only included where there is a demand that energyPRO needs to cover in the respective sector.

True to energyPRO's starting point, most articles include CHP and TES, but in later years, there is also a strong predominance of HPs or even electric boilers.

Key to Figure 2:

- Scale: **P**lant, **L**ocal, **N**ational.
- Focus: **T**echnical performance, **E**conomic assessment.
- Economy: **B**usiness, **T**otal system costs.
- Sectors: **H**eating, **C**ooling, **T**ransport, **E**lectricity.
- Technology: **C**HP, Fuel **B**oiler, **E**lectric **b**oiler, **H**P, E**x**cess heat, **S**olar Collector, **Ch**illers, **W**ind, **P**V, **TE**S, **E**lectricity **S**torage, **G**as storage.

7. Conclusions

The energyPRO software package is developed for the techno-economic analysis and design of district energy plants, and it has played an important role in many of the investment decisions in such plants. Compared to other models, it is based on a business-economic optimisation of plant operation and design, and where, e.g., models based on a purely mathematical heuristics not necessarily reflect actual physical parameters in the optimisation process, energyPRO is based on priority numbers with actual physical meanings. It is thus based on marginal production costs of the different units in the given time steps, and thus offers users a more intuitively comprehendible understanding compared to solver-based approaches.

Acknowledging that solver-based approaches may outperform the analytical approach of energyPRO, energyPRO is also fitted with a MILP-based optimisation procedure.

Apart from being operated in stand-alone mode, energyPRO may also be operated in batch mode using XML data for interfacing, thus enabling it being run from environments that can optimise scenarios iteratively.

The review part of the article demonstrates how energyPRO – in addition to being used for actual project planning – has been instrumental in the systematic analysis of district heating in Denmark. The same applies outside Denmark, but with a stronger focus on assessing the options and appropriateness from a more theoretical perspective.

A smaller category of work consists of models and analyses of larger areas – urban and country level – for the comprehensive modelling and analysis of more holistic energy systems.

As demonstrated by some of the energyPRO work published, energyPRO has also been used for the design of economic conditions to further specific energy system technologies.

Credit author statement

Poul Alberg Østergaard: Conceptualization, Methodology, Writing – original draft preparation, Funding acquisition, Visualization. **Anders N Andersen:** Software, Writing- Reviewing and Editing. **Peter Sorknæs:** Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anders N Andersen is working for the company developing the energyPRO model and as such has an interest in the model, however, this article is targeting the academic community where energyPRO is mostly provided pro bono.

Data availability

No data was used for the research described in the article.

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Appendix

Table 2
Overview of energyPRO application in the academic literature. Articles are sorted by year and by first author within the year. The table is updated with information up to and including July 1st 2022.

Article	Scale			Focus		Econ		Sectors				Technologies											
	P	L	N	T	E	B	T	H	C	E	T	C	B	Eb	H	X	S	Ch	W	PV	TE	ES	G
[83]	✓				✓	✓		✓				✓	✓								✓		
[62]	✓			✓	✓	✓		✓		✓		✓	✓										
[84]	✓				✓	✓		✓				✓	✓								✓		
[77]	✓				✓	✓																✓	
[85]	✓				✓	✓		✓				✓	✓								✓		
[86]	✓				✓	✓		✓				✓	✓								✓		
[87]		✓		✓				✓				✓	✓				✓				✓		
[75]		✓		✓			✓	✓				✓	✓		✓				✓		✓	✓	✓
[67]	✓			✓				✓		✓	✓	✓	✓		✓		✓			✓	✓		✓
[88]	✓				✓	✓		✓				✓	✓	✓			✓				✓		
[89]	✓			✓				✓				✓	✓				✓				✓		
[90]	✓			✓				✓									✓						
[68]			✓	✓	✓		✓			✓		✓							✓	✓		✓	

(continued on next page)

Table 2 (*continued*)

Article	Scale		Focus		Econ		Sectors				Technologies										
[79]	✓		✓	✓	✓		✓					✓		✓						✓	
[91]		✓	✓	✓	✓		✓				✓	✓		✓		✓				✓	
[69]		✓	✓	✓			✓	✓	✓	✓		✓		✓		✓	✓			✓	
[76]		✓		✓	✓		✓				✓	✓		✓		✓				✓	
[92]	✓		✓	✓	✓		✓				✓	✓		✓		✓				✓	
[93]	✓		✓	✓	✓		✓					✓	✓	✓						✓	
[94]	✓		✓	✓	✓		✓				✓	✓		✓	✓						
[82]	✓			✓	✓		✓				✓	✓								✓	
[63]		✓		✓	✓		✓				✓	✓		✓	✓					✓	
[64]	✓			✓	✓		✓				✓	✓	✓							✓	
[81]		✓		✓	✓		✓	✓				✓		✓	✓		✓		✓		
[95]	✓			✓	✓		✓				✓	✓		✓		✓				✓	
[65]	✓			✓	✓		✓				✓	✓	✓							✓	
[96]	✓		✓	✓	✓		✓					✓		✓						✓	
[46]	✓			✓	✓		✓				✓	✓		✓						✓	
[97]		✓	✓	✓	✓		✓				✓	✓		✓	✓	✓				✓	
[98]	✓		✓	✓	✓		✓		✓		✓									✓	
[74]	✓		✓	✓	✓		✓				✓	✓		✓		✓			✓	✓	
[99]	✓			✓	✓		✓				✓	✓		✓							
[100]		✓		✓		✓	✓					✓		✓							
[101]	✓		✓	✓	✓		✓					✓		✓		✓				✓	
[102]	✓		✓	✓	✓		✓				✓	✓									
[80]	✓			✓	✓		✓					✓		✓						✓	
[42]	✓			✓	✓		✓				✓	✓								✓	
[103]	✓			✓	✓		✓				✓	✓		✓	✓	✓				✓	
[71]	✓		✓	✓	✓		✓	✓			✓	✓		✓		✓	✓		✓	✓	
[104]		✓		✓	✓		✓	✓	✓	✓		✓		✓			✓		✓	✓	✓
[105]	✓		✓	✓	✓		✓				✓	✓								✓	
[70]	✓		✓				✓									✓				✓	
[106]	✓			✓	✓		✓					✓	✓	✓		✓				✓	
[72]	✓		✓	✓	✓		✓				✓	✓	✓							✓	
[107]	✓		✓	✓	✓		✓				✓	✓			✓						
[108]	✓		✓	✓	✓		✓							✓						✓	
[45]	✓		✓	✓	✓		✓					✓	✓	✓						✓	
[109]	✓		✓	✓	✓		✓						✓	✓						✓	
[110]	✓		✓	✓	✓		✓				✓	✓		✓						✓	
[111]	✓		✓	✓	✓		✓							✓	✓		✓		✓	✓	
[112]	✓		✓	✓	✓		✓				✓	✓	✓			✓				✓	
[113]		L		✓			✓		✓	✓			✓	✓					✓	✓	

Key to table:

- Scale: **P**lant, **L**ocal, **N**ational
- Focus: **T**echnical performance, **H**olistic energy system, **E**conomic assessment
- Economy: **B**usiness, **T**otal system costs
- Sectors: **H**eating, **C**ooling, **T**ransport, **E**lectricity
- Technology: **C**HP, Fuel **B**oiler, **E**lectrical **b**oiler, **H**P, E**x**cess heat, **S**olar Collector, **Ch**illers, **W**ind, **PV**, **TE**S, **E**lectricity **S**torage, Gas storage

References

[1] Technical Summary. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental Panel on climate change. IPCC; 2014.

[2] United Nations. Framework convention on climate change [UNFCCC]. Paris agreement. Paris, France: United Nations; 2015. FCCC/CP/2015/L.9.

[3] Østergaard PA, Sperling K. Towards sustainable energy planning and management. Int J Sustain Energy Plan Manag 2014;1:1–5. https://doi.org/10.5278/ijsepm.2014.1.1.

[4] Connolly D, Lund H, Mathiesen BVV, Werner S, Möller B, Persson U, et al. Heat roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system. Energy Pol 2014;65:475–89. https://doi.org/10.1016/j.enpol.2013.10.035.

[5] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025.

[6] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.

[7] Østergaard PA, Werner S, Dyrelund A, Lund H, Arabkoohsar A, Sorknæs P, et al. The four generations of district cooling - a categorization of the development in district cooling from origin to future prospect. Energy 2022;253. https://doi.org/10.1016/j.energy.2022.124098.

[8] Hvelplund F, Østergaard PA, Meyer NI. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Pol 2017;107. https://doi.org/10.1016/j.enpol.2017.05.009.

[9] Hvelplund F, Djørup S. Consumer ownership, natural monopolies and transition to 100% renewable energy systems. Energy 2019;181:440–9. https://doi.org/10.1016/j.energy.2019.05.058.

[10] Rudolph D, Kirkegaard J, Lyhne I, Clausen N-E, Kørnøv L. Spoiled darkness? Sense of place and annoyance over obstruction lights from the world's largest wind turbine test centre in Denmark. Energy Res Social Sci 2017;25:80–90. https://doi.org/10.1016/j.erss.2016.12.024.

[11] Aaen SB, Kerndrup S, Lyhne I. Beyond public acceptance of energy infrastructure: how citizens make sense and form reactions by enacting networks of entities in infrastructure development. Energy Pol 2016;96:576–86. https://doi.org/10.1016/j.enpol.2016.06.031.

[12] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN – advanced analysis of smart energy systems. Smart Energy 2021:100007. https://doi.org/10.1016/j.segy.2021.100007.

[13] Child M, Kemfert C, Bogdanov D, Breyer C. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew Energy 2019;139:80–101. https://doi.org/10.1016/j.renene.2019.02.077.

[14] Prina MG, Cozzini M, Garegnani G, Manzolini G, Moser D, Filippi Oberegger U, et al. Multi-objective optimization algorithm coupled to EnergyPLAN software: the EPLANopt model. Energy 2018;149:213–21. https://doi.org/10.1016/J.ENERGY.2018.02.050.

[15] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140–51. https://doi.org/10.1016/

j.apenergy.2015.11.042.
[16] Batas Bjelić I, Rajaković N, Krajačić G, Duić N. Two methods for decreasing the flexibility gap in national energy systems. Energy 2016;115:1701–9. https://doi.org/10.1016/j.energy.2016.07.151.
[17] Thellufsen JZ, Lund H, Sorknæs P, Østergaard PA, Chang M, Drysdale D, et al. Smart energy cities in a 100% renewable energy context. Renew Sustain Energy Rev 2020;129. https://doi.org/10.1016/j.rser.2020.109922.
[18] Tol HI, Svendsen S. Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: a case study in Roskilde, Denmark. Energy 2012;38: 276–90. https://doi.org/10.1016/j.energy.2011.12.002.
[19] Hysopt. District Heating - Hysopt n.d. https://www.hysopt.com/district-heating/.
[20] Sommer T, Sulzer M, Wetter M, Sotnikov A, Mennel S, Stettler C. The reservoir network: a new network topology for district heating and cooling. Energy 2020;199:117418. https://doi.org/10.1016/j.energy.2020.117418.
[21] Welcome | Trnsys : Transient System Simulation Tool n.d.
[22] Jung Y, Kim J, Lee H. Multi-criteria evaluation of medium-sized residential building with micro-CHP system in South Korea. Energy Build 2019;193:201. https://doi.org/10.1016/j.enbuild.2019.03.051. 15.
[23] UL. Homer Pro - Microgrid Software for Designing Optimized Hybrid Microgrids n.d. https://www.homerenergy.com/products/pro/index.html (accessed March 9, 2022).
[24] Johannsen RM, Østergaard PA, Hanlin R. Hybrid photovoltaic and wind mini-grids in Kenya: techno-economic assessment and barriers to diffusion. Energy Sustain Dev 2020;54:111–26. https://doi.org/10.1016/j.esd.2019.11.002.
[25] Gopisetty S, Treffinger P, Reindl LM. Open-source energy planning tool with easy-to-parameterize components for the conception of polygeneration systems. Energy 2017;126:756–65. https://doi.org/10.1016/j.energy.2017.03.013.
[26] Lyden A, Flett G, Tuohy PG. PyLESA: a Python modelling tool for planning-level Local, integrated, and smart Energy Systems Analysis. SoftwareX 2021;14:100699. https://doi.org/10.1016/j.softx.2021.100699.
[27] Pablos C, Merino A, Acebes LF. Modeling on-site combined heat and power systems coupled to main process operation. Processes 2019;7. https://doi.org/10.3390/pr7040218.
[28] Gu C, Xie D, Sun J, Wang X, Ai Q. Optimal operation of combined heat and power system based on forecasted energy prices in real-time markets. Energies 2015;8:14330–45. https://doi.org/10.3390/en81212427.
[29] Maribu KM, Fleten S-E. Combined heat and power in commercial buildings: investment and risk analysis. Energy J 2008;29:123–50.
[30] Boysen C, Kaldemeyer C, Hilpert S, Tuschy I. Integration of flow temperatures in unit commitment models of future district heating systems. Energies 2019;12. https://doi.org/10.3390/en12061061.
[31] Koltsaklis NE, Dagoumas AS. State-of-the-art generation expansion planning: a review. Appl Energy 2018;230:563–89. https://doi.org/10.1016/j.apenergy.2018.08.087.
[32] Gacitua L, Gallegos P, Henriquez-Auba R, Lorca Á, Negrete-Pincetic M, Olivares D, et al. A comprehensive review on expansion planning: models and tools for energy policy analysis. Renew Sustain Energy Rev 2018;98: 346–60. https://doi.org/10.1016/j.rser.2018.08.043.
[33] Gaardmand A. Plan og politik : Om fysisk planlægnig og dens muligheder for at være med til afklaringen af nye samfundsmaal. København: Hans Reitzel; 1980.
[34] Herbst A, Toro F, Reitze F, Jochem E. Introduction to energy systems modelling. Swiss J Econ Stat 2012;148:111–35. https://doi.org/10.1007/BF03399363.
[35] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, et al. Simulation versus optimisation: theoretical positions in energy system modelling. Energies 2017;10:1–17. https://doi.org/10.3390/en10070840.
[36] Gašparović G, Krajačić G, Duić N, Baotić M. New energy planning software for analysis of island energy systems and microgrid operations – H2RES software as a tool to 100% renewable energy system. Comput Aid Chem Eng 2014;33:1855–60. https://doi.org/10.1016/B978-0-444-63455-9.50144-6.
[37] Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, et al. Balmorel open source energy system model. Energy Strategy Rev 2018;20:26–34. https://doi.org/10.1016/j.esr.2018.01.003.
[38] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154: 921–33. https://doi.org/10.1016/j.apenergy.2015.05.086.
[39] Elsevier B.V. Scopus n.d. www.scopus.com.
[40] Elsevier. Sciencedirect n.d. sciencedirect.com.
[41] Chittum A, Østergaard PA. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Pol 2014;74: 465–74. https://doi.org/10.1016/j.enpol.2014.08.001.
[42] Andersen AN, Østergaard PA. Support schemes adapting district energy combined heat and power for the role as a flexibility provider in renewable energy systems. Energy 2020;192:116639. https://doi.org/10.1016/j.energy.2019.116639.
[43] EMD International A/S. Tutorials & Guides n.d. https://www.emd.dk/energypro/support/tutorials-guides/.
[44] EMD International A/S. How To Guide - The INTERFACE-module in energyPRO - XML-call of energyPRO 2020. https://www.emd.dk/files/energypro/HowToGuides/The INTERFACE-module in energyPRO.pdf.
[45] Østergaard PA, Andersen AN. Variable taxes promoting district heating heat pump flexibility. Energy 2021;221. https://doi.org/10.1016/j.energy.2021.119839.
[46] Andersen AN, Østergaard PA. Analytic versus solver-based calculated daily operations of district energy plants. Energy 2019;175:333–44. https://doi.org/10.1016/j.energy.2019.03.096.
[47] EMD International A/S. How To Guide - The MILP Solver optimization method in energyPRO n.d. https://www.emd.dk/files/energypro/HowToGuides/HowToGuide_MILP solver.pdf.
[48] EMD International A/S. enerrgyPRO n.d. https://www.emd.dk/energypro/ (accessed March 9, 2022).
[49] Society for the Advancement of Applied Computer Science e. V. (GFaI). Top Energy n.d. www.top-energy.de (accessed March 9, 2022).
[50] Solvergy n.d. https://solvergy.org/(accessed March 9, 2022).
[51] Energy Opticon AB. Energy Optima 3 n.d. http://www.energyopticon.com (accessed March 9, 2022).
[52] Government of Canada. RETScreen n.d. http://www.retscreen.net/(accessed March 9, 2022).
[53] Vela Solaris. Polysun n.d. www.velasolaris.com (accessed March 9, 2022).
[54] Chang M, Thellufsen JZ, Zakeri B, Pickering B, Pfenninger S, Lund H, et al. Trends in tools and approaches for modelling the energy transition. Appl Energy 2021;290:116731. https://doi.org/10.1016/j.apenergy.2021.116731.
[55] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: a review of modelling and optimization. Sol Energy 2016;136:49–64. https://doi.org/10.1016/j.solener.2016.06.054.
[56] Ringkjøb HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 2018;96:440–59. https://doi.org/10.1016/j.rser.2018.08.002.
[57] Ferrari S, Zagarella F, Caputo P, Bonomolo M. Assessment of tools for urban energy planning. Energy 2019;176:544–51. https://doi.org/10.1016/j.energy.2019.04.054.
[58] Lyden A, Pepper R, Tuohy PG. A modelling tool selection process for planning of community scale energy systems including storage and demand side management. Sustain Cities Soc 2018. https://doi.org/10.1016/J.SCS.2018.02.003.
[59] Sharma H, É Monnier, Mandil G, Zwolinski P, Colasson S. Comparison of environmental assessment methodology in hybrid energy system simulation software. Procedia CIRP 2019;80:221–7. https://doi.org/10.1016/j.procir.2019.01.007.
[60] Klemm C, Vennemann P. Modeling and optimization of multi-energy systems in mixed-use districts: a review of existing methods and approaches. Renew Sustain Energy Rev 2021;135:110206. https://doi.org/10.1016/j.rser.2020.110206.
[61] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.
[62] Hinojosa LR, Day AR, Maidment GG, Dunham C, Kirk P. A comparison of combined heat and power feasibility models. Appl Therm Eng 2007;27: 2166–72. https://doi.org/10.1016/j.applthermaleng.2005.07.028.
[63] Hast A, Syri S, Lekavičius V, Galinis A. District heating in cities as a part of low-carbon energy system. Energy 2018;152:627–39. https://doi.org/10.1016/j.energy.2018.03.156.
[64] Sneum DM, Sandberg E, Koduvere H, Olsen OJ, Blumberga D. Policy incentives for flexible district heating in the Baltic countries. Util Pol 2018;51: 61–72. https://doi.org/10.1016/j.jup.2018.02.001.
[65] Sneum DM, Sandberg E. Economic incentives for flexible district heating in the Nordic countries. Int J Sustain Energy Plan Manag 2018;16. https://doi.org/10.5278/ijsepm.2018.16.3.
[66] Østergaard PA, Lund H, Thellufsen JZ, Sorknæs P, Mathiesen BV. Review and validation of EnergyPLAN. Renew Sustain Energy Rev 2022. https://doi.org/10.1016/j.rser.2022.112724. In press.
[67] Kiss VM. Modelling the energy system of Pécs – the first step towards a sustainable city. Energy 2015;80:373–87. https://doi.org/10.1016/j.energy.2014.11.079.
[68] Kiss VM, Hetesi Z, Kiss T. Issues and solutions relating to Hungary's electricity system. Energy 2016;116:329–40. https://doi.org/10.1016/j.energy.2016.09.121.
[69] Fonseca JA, Estévez-Mauriz L, Forgaci C, Björling N. Spatial heterogeneity for environmental performance and resilient behavior in energy and transportation systems. Comput Environ Urban Syst 2017;62:136–45. https://doi.org/10.1016/j.compenvurbsys.2016.11.001.
[70] Valančius K, Mikučionienė R. Solar energy as a tool of renovating soviet-type multi apartment buildings. Sol Energy 2020;198:93–100. https://doi.org/10.1016/j.solener.2020.01.046.
[71] Asim M, Saleem S, Imran M, Leung MKH, Hussain SA, Miró LS, et al. Thermo-economic and environmental analysis of integrating renewable energy sources in a district heating and cooling network. Energy Effic 2020;13: 79–100. https://doi.org/10.1007/s12053-019-09832-9.
[72] Lepiksaar K, Mašatin V, Latõšov E, Siirde A, Volkova A. Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system. Smart Energy 2021:100022. https://doi.org/10.1016/j.segy.2021.100022.
[73] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The

status of 4th generation district heating: research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.
[74] Kazagic A, Merzic A, Redzic E, Tresnjo D. Optimization of modular district heating solution based on CHP and RES - demonstration case of the Municipality of Visoko. Energy 2019;181:56–65. https://doi.org/10.1016/j.energy.2019.05.132.
[75] Østergaard PA. Comparing electricity, heat and biogas storages' impacts on renewable energy integration. Energy 2012;37:255–62. https://doi.org/10.1016/j.energy.2011.11.039.
[76] Hast A, Rinne S, Syri S, Kiviluoma J. The role of heat storages in facilitating the adaptation of district heating systems to large amount of variable renewable electricity. Energy 2017;137:775–88. https://doi.org/10.1016/j.energy.2017.05.113.
[77] Lund H, Salgi G, Elmegaard B, Andersen AN. Optimal operation strategies of compressed air energy storage (CAES) on electricity spot markets with fluctuating prices. Appl Therm Eng 2009;29:799–806. https://doi.org/10.1016/j.applthermaleng.2008.05.020.
[78] Leurent M, Da Costa P, Rämä M, Persson U, Jasserand F. Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries. Energy 2018;149:454–72. https://doi.org/10.1016/J.ENERGY.2018.01.149.
[79] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2016;184:1374–88. https://doi.org/10.1016/j.apenergy.2016.02.144.
[80] Østergaard PA, Jantzen J, Marczinkowski HM, Kristensen M. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renew Energy 2019;139:904–14. https://doi.org/10.1016/J.RENENE.2019.02.140.
[81] Popovski E, Fleiter T, Santos H, Leal V, Fernandes EO. Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos, Portugal. Energy 2018;153:311–23. https://doi.org/10.1016/J.ENERGY.2018.04.036.
[82] Andersen AN, Østergaard PA. A method for assessing support schemes promoting flexibility at district energy plants. Appl Energy 2018;225. https://doi.org/10.1016/j.apenergy.2018.05.053.
[83] Lund H, Andersen AN. Optimal designs of small CHP plants in a market with fluctuating electricity prices. Energy Convers Manag 2005;46:893–904. https://doi.org/10.1016/j.enconman.2004.06.007.
[84] Fragaki A, Andersen AN, Toke D. Exploration of economical sizing of gas engine and thermal store for combined heat and power plants in the UK. Energy 2008;33:1659–70. https://doi.org/10.1016/j.energy.2008.05.011.
[85] Streckienė G, Martinaitis V, Andersen AN, Katz J. Feasibility of CHP-plants with thermal stores in the German spot market. Appl Energy 2009;86:2308–16. https://doi.org/10.1016/j.apenergy.2009.03.023.
[86] Fragaki A, Andersen AN. Conditions for aggregation of CHP plants in the UK electricity market and exploration of plant size. Appl Energy 2011;88:3930–40. https://doi.org/10.1016/j.apenergy.2011.04.004.
[87] Nielsen S, Möller B. Excess heat production of future net zero energy buildings within district heating areas in Denmark. Energy 2012;48:23–31. https://doi.org/10.1016/j.energy.2012.04.012.
[88] Sorknæs P, Lund H, Andersen AN. Future power market and sustainable energy solutions – the treatment of uncertainties in the daily operation of combined heat and power plants. Appl Energy 2015;144:129–38. https://doi.org/10.1016/j.apenergy.2015.02.041.
[89] Wang H, Abdollahi E, Lahdelma R, Jiao W, Zhou Z. Modelling and optimization of the smart hybrid renewable energy for communities (SHREC). Renew Energy 2015;84:114–23. https://doi.org/10.1016/j.renene.2015.05.036.
[90] Wang H, Yin W, Abdollahi E, Lahdelma R, Jiao W. Modelling and optimization of CHP based district heating system with renewable energy production and energy storage. Appl Energy 2015;159:401–21. https://doi.org/10.1016/j.apenergy.2015.09.020.
[91] Ben Amer-Allam S, Münster M, Petrović S. Scenarios for sustainable heat supply and heat savings in municipalities - the case of Helsingør, Denmark. Energy 2017;137:1252–63. https://doi.org/10.1016/j.energy.2017.06.091.
[92] Rudra S, Rossendahl L, From N. Optimization of a local district heating plant under fuel flexibility and performance. In: ASME 2011 5th Int. Conf. Energy Sustain. Parts A, B, C, ASME; 2011. p. 1159–65. https://doi.org/10.1115/ES2011-54600.
[93] Trømborg E, Havskjold M, Bolkesjø TF, Kirkerud JG, Tveten ÅG. Flexible use of electricity in heat-only district heating plants. Int J Sustain Energy Plan Manag 2017;12:29–46. https://doi.org/10.5278/ijsepm.2017.12.4.
[94] Wahlroos M, Syri S, Pärssinen M, Manner J. Utilizing data center waste heat in district heating – impacts on energy efficiency and prospects for low-temperature district heating networks. Energy 2017. https://doi.org/10.1016/j.energy.2017.08.078.
[95] Rämä M, Wahlroos M. Introduction of new decentralised renewable heat supply in an existing district heating system. Energy 2018;154:68–79. https://doi.org/10.1016/j.energy.2018.03.105.
[96] Østergaard PA, Andersen AN. Economic feasibility of booster heat pumps in heat pump-based district heating systems. Energy 2018;155:921–9. https://doi.org/10.1016/J.ENERGY.2018.05.076.
[97] Büchele R, Kranzl L, Hummel M. Integrated strategic heating and cooling planning on regional level for the case of Brasov. Energy 2019;171:475–84. https://doi.org/10.1016/j.energy.2019.01.030.
[98] Gliński M, Bojesen C, Rybiński W, Bykuć S. Modelling of the biomass MCHP unit for power peak shaving in the local electrical grid. Energies 2019;12. https://doi.org/10.3390/en12030458.
[99] Kontu K, Rinne S, Junnila S. Introducing modern heat pumps to existing district heating systems – global lessons from viable decarbonizing of district heating in Finland. Energy 2019;166:862–70. https://doi.org/10.1016/j.energy.2018.10.077.
[100] Popovski E, Aydemir A, Fleiter T, Bellstädt D, Büchele R, Steinbach J. The role and costs of large-scale heat pumps in decarbonising existing district heating networks – a case study for the city of Herten in Germany. Energy 2019;180:918–33. https://doi.org/10.1016/j.energy.2019.05.122.
[101] Thomson A, Claudio G. The technical and economic feasibility of utilising phase change materials for thermal storage in district heating networks. Energy Proc 2019;159:442–7. https://doi.org/10.1016/j.egypro.2018.12.042. Elsevier Ltd.
[102] Widzinski M. Simulation of an alternative energy system for district heating company in the light of changes in regulations of the emission of harmful substances into the atmosphere. Int J Sustain Energy Plan Manag 2019;24. https://doi.org/10.5278/ijsepm.3354.
[103] Doračić B, Pukšec T, Schneider DR, Duić N. The effect of different parameters of the excess heat source on the levelized cost of excess heat. Energy 2020;201:117686. https://doi.org/10.1016/j.energy.2020.117686.
[104] Revesz A, Jones P, Dunham C, Davies G, Marques C, Matabuena R, et al. Developing novel 5th generation district energy networks. Energy 2020;201:117389. https://doi.org/10.1016/j.energy.2020.117389.
[105] Teräsvirta A, Syri S, Hiltunen P. Small nuclear reactor—nordic district heating case study. Energies 2020;13. https://doi.org/10.3390/en13153782.
[106] Johannsen RM, Arberg E, Sorknæs P. Incentivising flexible power-to-heat operation in district heating by redesigning electricity grid tariffs. Smart Energy 2021;2:100013. https://doi.org/10.1016/j.segy.2021.100013.
[107] Hiltunen P, Syri S. Low-temperature waste heat enabling abandoning coal in Espoo district heating system. Energy 2021;231:120916. https://doi.org/10.1016/j.energy.2021.120916.
[108] Trabert U, Mateo J, Bergstraesser W, Best I, Kusyy O, Orozaliev J, et al. Techno-economic evaluation of electricity price-driven heat production of a river water heat pump in a German district heating system. Int J Sustain Energy Plan Manag 2021:31. https://doi.org/10.5278/ijsepm.6291.
[109] Javanshir N, Syri S, Teräsvirta A, Olkkonen V. Abandoning peat in a city district heat system with wind power, heat pumps, and heat storage. Energy Rep 2022;8:3051–62. https://doi.org/10.1016/j.egyr.2022.02.064.
[110] Su Y, Hiltunen P, Syri S, Khatiwada D. Decarbonization strategies of Helsinki metropolitan area district heat companies. Renew Sustain Energy Rev 2022;160:112274. https://doi.org/10.1016/j.rser.2022.112274.
[111] Revesz A, Dunham C, Jones P, Bond C, Fenner R, Mody S, et al. A holistic design approach for 5th generation smart local energy systems: project GreenSCIES. Energy 2022;242:122885. https://doi.org/10.1016/j.energy.2021.122885.
[112] Aliana A, Chang M, Østergaard PA, Victoria M, Andersen AN. Performance assessment of using various solar radiation data in modelling large-scale solar thermal systems integrated in district heating networks. Renew Energy 2022;190:699–712. https://doi.org/10.1016/j.renene.2022.03.163.
[113] Han M-E, Alston M, Gillott M. A multi-vector community energy system integrating a heating network, electricity grid and PV production to manage an electrified community. Energy Build 2022;266:112105. https://doi.org/10.1016/j.enbuild.2022.112105.