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Techno-Economic Energy Models for Low Carbon Business Parks

Jonas Timmerman[a,]*, Christof Deckmyn[b], Lieven Vandevelde[b] ,
Greet Van Eetvelde[a]

[a]Environmental and Spatial Management, Faculty of Engineering and Architecture, Ghent University, Vrijdagmarkt 10-301, B-9000, Ghent, Belgium
[b]Electrical Energy Laboratory, Faculty of Engineering and Architecture, Ghent University, Sint-Pietersnieuwstraat 41, B-9000, Ghent, Belgium
jonas.timmerman@ugent.be

To mitigate climate change, global greenhouse gas emissions need to be reduced substantially. Industry and energy sector together are responsible for a major share of those emissions. Hence the development of low carbon business parks by maximising energy efficiency and changing to collective, renewable energy systems at local level holds a high reduction potential. Yet, there is no uniform approach to determine the optimal combination and operation of energy technologies composing such energy systems. However, techno-economic energy models, custom tailored for business parks, can offer a solution, as they identify the configuration and operation that provide an optimal trade-off between economic and environmental performances. However, models specifically developed for industrial park energy systems are not detected in literature, so identifying an existing model that can be adapted is an essential step. In this paper, energy model classifications are scanned for adequate model characteristics and accordingly, a confined number of models are selected and described. Subsequently, main model features are compared, a practical typology is proposed and applicability towards modelling industrial park energy systems is evaluated. Energy system evolution models offer the most perspective to compose a holistic, but simplified model, whereas advanced energy system integration models can adequately be employed to assess energy integration for business clusters up to entire industrial sites. Energy system simulation models, however, provide deeper insight in the system's operation.

1. Introduction

Energy consumption in the industry sector is responsible for a large share of greenhouse gas emissions, contributing to climate change. Therefore, a low carbon shift in the energy system of industrial parks must be initiated. Low carbon business parks envision a collective energy system that employs energy efficient technologies, maximises the integration of local renewable energy sources and enables heat exchange between companies (Maes et al., 2011). Techno-economic energy models provide a holistic approach towards the configuration and operation of such systems, and allow us to identify the optimal trade-off between energetic, economic and environmental performances. To our knowledge, there is no energy model available that has been custom tailored for industrial parks and therefore, it is necessary to adapt an existing model or to develop a new one. In this paper, several energy model classifications are studied and characteristics relevant for analysing business park energy systems are identified. Subsequently, a confined number of models corresponding to those characteristics is selected and described, followed by comparison of the main model features and the proposition of a practical typology. Finally, the suitability of these models towards modelling industrial park energy systems is assessed.

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2. Classification and selection of energy models

During the last decades a variety of techno-economic energy models has been developed, each serving particular purposes. Van Beeck proposed a classification scheme, in the process of identifying suitable models for local energy planning in developing countries, differentiating energy models according to characteristics in ten dimensions (van Beeck, 2003). Also Nakata adopted the same categorisation (Nakata et al., 2011). Connolly et al. (2010), however, established a more concise classification of energy tools by means of a survey sent out to tool developers, and presented it as a guide to identify a suitable tool for analysing the integration of renewable energy technologies. This classification distinguishes seven tool types, including simulation, scenario, equilibrium, top-down, bottom-up, operation optimisation and investment optimisation tools. Throughout literature, model, tool, modelling framework and model generator are used interchangeably. However, in a strict sense, an energy model is a simplified representation of a specific energy system, whereas a tool, modelling framework or model generator refers to the computer programme enabling the creation of various models.

From van Beeck's classification, appropriate features for modelling an industrial park's energy system are identified. Firstly, the search for an optimal future energy system, requires a scenario analysis or back casting perspective. Secondly, an integrated approach, focusing simultaneously on technical configuration, environmental impact and comparison of different options, is called for. As a local energy system does not influence overall economy, and due to the need for flexible manipulation of the model, exogenous parameter specification is required. Also, energy supply and demand should be disaggregated, with a high level of technological detail, in order to differentiate between technologies, requiring a bottom-up approach. Furthermore, partial equilibrium, simulation and optimisation, as well as spread sheet methods are applicable. Translated to Connolly's classification, the model needs to follow a bottom-up approach, that can be applied for either simulation or scenario analysis and optimises technology investment and/or operation. Taking into account these considerations, a preliminary selection of freely available models is made from Connolly's and Nakata's review, supplemented with additional models. Subsequently, a practical intuitive categorization of energy system (ES) models is proposed, distinguishing types according to primary focus, namely ES evolution, simulation and integration models. The following paragraph describes the studied models per type.

3. Energy system evolution models

Energy system evolution models analyse the long term evolution of an energy system, at global to regional level, driven by techno-economic optimisation. Numerous modelling frameworks carry this label, such as MARKAL (Loulou et al., 2004), TIMES (Loulou et al., 2005), ETEM (Drouet and Thénié, 2009), and OSeMOSYS (Howells et al., 2011). The time horizon consists of a number of periods, containing an equal or varying number of years, each subdivided into time slices. Starting from the base year, the model endogenously develops the configuration and regulates the operation of the energy system over the entire time horizon, in order to satisfy energy service demands at minimum costs, while complying with technologic, economic and environmental limits. Therefore, an optimisation algorithm is employed, that in every time slice computes the values of the decision variables for which an objective function is minimised, subject to a number of constraints. Decision variables are technology investments, operation levels and trade of commodities. The objective function represents total discounted costs to be minimised or, equivalently, net total surplus to be maximised. Indeed, for models that take into account demand price-elasticity and assume competitive markets for all commodities, supply-demand equilibrium corresponds to maximisation of net total surplus. When demands are inelastic, however, equilibrium translates into minimisation of total discounted costs (Loulou et al., 2005). Constraints are given by mathematical formulations that model technologies, describe commodity balances and impose bounds to variables. In case objective function and equations are linear, linear programming techniques can be used. However, when discrete technology sizes matter, mixed integer linear programming is employed.

4. Energy system simulation models

Energy system simulation models allow optimising an energy system's operation within a configuration that is fixed over time. Operation is simulated over a one year timespan, divided into chronologic time steps of one hour or less. Accordingly, yearly distributions of renewable resources and demand are modelled by either measured or artificially created hourly time series, featuring stochastic character. Furthermore; operation costs are minimised in every time step, taking into account dispatch strategies for regulating operation of energy production units. The models EnergyPLAN and Homer correspond to this label.

4.1 EnergyPLAN

EnergyPLAN has been developed since 1999 at Aalborg University, Denmark, to assist in techno-economic analysis of regional and national energy systems. Meanwhile, it has been widely applied in Europe to analyse the integration of renewable energy technologies. It calculates energy and fuel balances, annual costs and emissions associated with a user-defined system layout. A detailed technical model description can be found in (Lund, 2012), while a guide for the practical use of EnergyPLAN, including the collection of relevant data can be found in (Connolly, 2010). EnergyPLAN is a deterministic input/output model that uses analytical programming to calculate hourly energy balances for district heating and cooling, electricity, hydrogen and natural gas, subject to a user-selected dispatch strategy. In the technical optimisation strategy, technologies are dispatched to satisfy demand, disregarding cost data. Within this strategy, the user can choose to operate heat producing units solely according to heat demand, or to balance both electricity and heat demands. Secondly, in the market optimisation strategy, the operation costs of the system are minimised under the assumption that each production unit operates to maximise its profits.

4.2 HOMER

HOMER is developed by the U.S. National Renewable Energy Laboratory (NREL) and is commercially available since 2009 (Homer Energy LLC, 2013). The model facilitates the design of grid-connected and off-grid small scale energy systems by ranking all possible configurations, according to increasing discounted costs. HOMER simulates a one-year sequence of time steps of user-defined length, ranging from several hours to one minute. Within a user-specified search space, consisting of technology-specific capacity or quantity ranges, the model assembles all possible configurations. Then, for each configuration, energy balances are calculated in every simulation time step, subject to a dispatch strategy. Subsequently, infeasible configurations are omitted and feasible options are ranked by total discounted system costs. When renewable technologies are insufficient to satisfy electric and thermal loads or operating reserve, controllable power sources are operated according to the ‘load following’ or the ‘cycle charging’ strategy. Homer calculates the system for both strategies as the least-cost option is not known a priori. Moreover, user-defined operation schedules allow to specify generator availability (Lambert et al., 2006).

5. Energy system integration models

Energy system integration models facilitate the optimal design of complex thermal energy systems, such as industrial processes, industrial plants and heat networks. They employ Pinch analysis (Linhoff 1998) to minimise energy requirements by heat exchange between process streams, and optimise the integration of energy conversion technologies. The methodology followed by energy system integration models comprises different steps, though elaboration differs between the studied models. In a first step, after assembling the process flow sheet model, thermodynamic calculations is performed and for each process stream the required heating or cooling load in function of temperature is calculated. Secondly, from the composite curves of the cold and hot streams, the maximum heat recoveries, and consequently the minimum external energy requirements, are determined, taking into account a minimum temperature difference for heat transfer. Moreover, starting from the grand composite curve, energy saving process modifications can be identified. In a third step, appropriate energy conversion technologies are selected and integrated into the heat cascade to satisfy minimum energy requirements in such a way that annual costs are minimised. This can be done manually by the analyst or by means of an optimisation algorithm, selecting utility units from a technology database and optimizing their operation levels. When at the same time annual costs and emissions have to be minimised, a multi-objective optimisation algorithm must be used (Fazlollahi and Maréchal, 2013). Furthermore, when using multiple inter-annual time steps, utility units have to be integrated in every time step, in such a way that annual costs are minimised (Marechal and Kalitventzeff, 2003). In a final step, the heat exchanger network, that physically enables the exchange of heat between hot and cold streams of both process and utilities, is designed and optimised. In case some process streams are excluded from direct heat exchange, intermediate heat transfer units can be introduced. The methodology described above can be applied for the optimisation of one or more processes in an industrial plant or for the preliminary design of thermal energy networks between industrial processes at industrial sites or clusters (Becker and Maréchal, 2012, Nemet et al., 2012). Other applications are the optimisation of the layout and the energy supply system of district energy systems (Weber et al., 2007), and the design of energy conversion systems in urban areas (Gerber et al., 2012).

5.1 EINSTEIN

Einstein combines an energy system integration model with a guide for thermal energy audits (Schweiger, 2011). It has been developed in the European IEE project Einstein II, to optimise thermal energy supply in companies, tertiary buildings and district heating or cooling networks. Therefore, the existing system is compared with a proposed alternative, which includes a heat exchanger network, in terms of energetic, economic and environmental performance. The model is organized in different modules that correspond to the steps described above. However, the selection of utility units has to be done manually instead of by a cost optimisation algorithm. Simulation is carried out in hourly time steps over a one-year time horizon. Furthermore, the mathematical equations describing the energy system are solved iteratively, to cope with feedback loops and dispatch strategies are approximated by a priority sequence.

5.2 OSMOSE

OSMOSE is a software program, developed by the Industrial Energy Systems Laboratory at the Swiss Federal Institute of Technology Lausanne (EPFL), for analysis and design of complex energy systems (Palazzi, 2010). It interconnects several sub-models and steers computation sequence and data exchange. A first model assists in assembling the process and performs thermodynamic calculation, a second model applies Pinch analysis and optimally integrates utility units and a third model evaluates system performance. In case multiple performance indicators have to be optimised, a multi-objective optimisation algorithm is activated. Up to this moment, OSMOSE does not include the design and optimisation of a heat exchanger network.

6. Comparison model features

Based on the description of the studied energy models, important features are highlighted and compared.

6.1 Focus

ES evolution models analyse the least cost pathway towards a desired long term future, taking into account several time dependent constraints, whereas ES simulation models are used to compare different configurations or to analyse different operation strategies. ES integration models, however, focus on optimal integration of energy conversion technologies, starting from thermal energy demands that have been minimised by heat exchange.

6.2 Time horizon

Within the multiple-period time horizon of ES evolution models, each period is conceived as a repetition of its representative year and data have to be specified accordingly. Annual and periodic costs are then discounted and accumulated over the time horizon. The other model types however, analyse technologic aspects in a single representative year and as a result, evolution of parameters and variables over subsequent years cannot be modelled. Nevertheless, a simplified financial analysis can be performed over the project lifetime.

6.3 Temporal detail

Seasonal, weekly or daily variations in energy supply and demand patterns can be captured by subdividing the year into time segments. Parameters and variables are disaggregated and specified accordingly, keeping constant values at segment level. Consequently, this inter-annual subdivision should be sufficiently detailed to capture key characteristics in time profiles (Kannan and Turton, 2012). Time slices aggregate time intervals with similar conditions and thus have no inherent chronology, whereas time steps are sequential. For modelling the level of storage, chronologic time steps are required, although time sequence can also be extracted from time slice definition (Welsch et al., 2012). ES evolution models use time slice division, that may be hierarchically organised in seasonal, weekly and diurnal levels. ES simulation models on the other hand, exhibit a higher temporal detail and apply hourly time steps, allowing us to capture the stochastic character of renewable energy and unpredictable deviations in demand by importing either measured or artificially created time series. In the case of ES integration models, EINSTEIN simulates hourly time steps, while time steps with OSMOSE are user-defined.

6.4 Methodology

ES evolution models employ an optimisation algorithm to calculate the values of the decision variables that minimise or maximise an objective function, expressing economic performance, subject to a number of constraints. When demands are inelastic, total discounted costs are minimised, whereas with elastic demands, total surplus is maximised. Decision variables are technology investments and operation levels and trade of commodities. Constraints are given by the equations governing the system’s operation and bounds to decision and output variables, in every time slice and/or every period. The ES integration model OSMOSE first analytically calculates minimum energy requirements and subsequently employs an optimisation algorithm to optimise selection and operation levels of energy conversion units, so that annualised costs are minimised, subject to heat and power balances and equations modelling process and utility units. When multiple objectives are involved, a multi-objective optimisation algorithm is required. In contrast, the other model types use analytical methods and regulate technology operation by a user-selected dispatch strategy. EINSTEIN however, employs an iterative method to calculate feedback loops.

6.5 Analysis of alternatives

ES evolution models allow us to compare alternative scenarios to a reference scenario, in terms of energetic, economic and environmental performance. Each scenario corresponds to a separate model set-up, represented by a coherent set of input parameters over the time horizon, defining energy service demands, resource potentials, technology characteristics and regulatory or policy constraints. Other model types evaluate the performance of alternative cases or configurations that correspond to different conditions in a representative future year.

6.6 Reference energy system

The reference energy system describes the techno-economic behaviour of all possible components and the interactions between them. A particular configuration is set up by selecting the components to be included and specifying their characteristics. In case of ES evolution models, the configuration endogenously evolves over the subsequent time periods, starting from the initial configuration. Within other models, however, the configuration is completely specified by the user. Yet, Homer endogenously creates a finite number of technology combinations within user-defined ranges with discrete steps. ES evolution models use a highly simplified representation of technologies, whereas the other types describe them in more complexity.

6.7 Demand

Energy service demands in ES evolution models are user-defined, but are in most applications allocated to residential, public, service, transport and industry sectors. ES simulation models have a predefined organization of demand that includes electricity, heat or fuel, which may be allocated to energy services. ES integration models focus on the thermal demand of process streams in function of temperature. Some ES evolution models can only handle price-inelastic demands, necessarily specified for each scenario. For price-elastic models of this type however, the demand in the reference scenario has to be fully specified, while in alternate scenarios, it is calculated endogenously, based on user-defined elasticities. The other model types do not incorporate elasticity, except for EnergyPLAN, that includes price elasticity for electricity demand.

7. Applicability energy models towards industrial parks

When making abstraction of an industrial park’s energy system, different components are distinguished. Energy sources are transformed by conversion technologies into heat and electricity that are subsequently transformed by end-use equipment into energy services. Conversion technologies can directly supply individual companies or first feed into a local energy network, connecting multiple companies. Additionally, technologies can be considered that directly provide energy services for a specific company. Local networks, as well as individual companies, are able to exchange energy with a regional electric or heat network. Furthermore, energy demands can be specified in terms of energy services or energy carriers (heat, electricity, fuel) and be allocated to individual companies or be aggregated over the entire industrial park.

The applicability of energy models for representing the energy system of a business park is related to the level of detail in demand side representation. OSMOSE and ES-evolution models enable detailed energy system analysis onto company level, as well as onto cluster and industrial park level, provided that energy demand data are specified accordingly. Homer and EnergyPLAN, however, do not allow such level of detail, as demands can only be specified at overall system and not at company level. Furthermore, models can be chosen according to the aim of the analysis to be performed. Assessment of energy policies and investment planning calls for ES evolution models, while ES simulation models such as EnergyPLAN enable quick evaluation of energetic, economic and environmental performance. Moreover, EnergyPLAN offers insight into hourly operation, whereas Homer does not provide inter-annual results. When focusing on energy efficiency and heat recovery within and between industrial processes of an individual company, EINSTEIN is an effective model. In addition to that, OSMOSE enables energy integration analysis between different companies, connected by a thermal network. Finally, due to their generic description, both ES evolution models and OSMOSE offer great flexibility in modelling the energy system of an industrial park.

8. Conclusions

In order to identify energy models suited for modelling an industrial park's energy system, a confined review has been carried out, while detecting and comparing relevant model features. Based on common properties, a practical typology has been proposed, existing of ES evolution, simulation and integration models. In conclusion, the applicability of models depends on the level of detail in demand side representation and the envisaged objective. Overall, ES evolution models offer the most perspective for a simplified, holistic approach, whereas OSMOSE is adequate for detailed total site energy integration.

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