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Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design

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HIGHLIGHTS

- Proposing a framework for designing future energy scenarios.
- Multi-objective evolutionary algorithm is combined with an hourly simulation model.
- We tested the framework on real-world data.
- A significant number of optimized scenarios can be identified.

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ABSTRACT

Environmental and security concerns urge energy planners to design more sustainable energy systems, reducing fossil fuel consumptions in favour of renewable solutions. The proposed scenarios typically rely on a mixing of different energy sources, thereby mitigating the availability and intermittency problems typically related to renewable technologies. Optimizing this combination is of crucial importance to cope with economic, technical, and environmental issues, which typically give rise to multiple contradictory objectives. To this purpose, this article presents a generalized framework coupling EnergyPLAN – a descriptive analytical model for medium/large-scale energy systems – with a multi-objective evolutionary algorithm – a type of optimizer widely used in the context of complex problems. By using this framework, it is possible to automatically identify a set of Pareto-optimal configurations with respect to different competing objectives. As an example, the method is applied to the case of Aalborg municipality, Denmark, by choosing cost and carbon emission minimization as contrasting goals. Results are compared with a manually identified scenario, taken from previous literature. The automatic approach, while confirming that the available manual solution is very close to optimality, yields an entire set of additional optimal solutions, showing its effectiveness in the simultaneous analysis of a wide range of combinations.

1. Introduction

Energy is one of the key components for the development of modern society. Energy supply is however predominantly based on fossil fuels, which have several negative consequences on the environment [1]. This harmful impact, combined with the fact that fossil fuels are frequently found in politically volatile regions, encourages the use of renewable energy resources (RES) within the energy system. The design of future energy scenarios with a correct balance between fossil fuels and RES is hence a very important topic to energy planners worldwide. This implies to consider changes in the present energy technology portfolio, typically on a long term basis. While an optimization of the operation of the current energy system can indeed be helpful, a strong impact is expected only by increasing the RES generation capacities with respect to the current energy scenario.[1]

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[1] In this paper, we use the terms energy scenario and energy system interchangeably, referring to the complete set of parameters (e.g., generation capacities for given technologies) describing an energy system configuration.

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In fact, though RES are desirable for the reasons mentioned above, their exploitation on large scale involves other issues, like fluctuating behaviour, limited availability, and economic or financial obstacles. These difficulties can be addressed – introducing, e.g., proper control strategies, efficient couplings between different resources, and supporting policies – but they increase the complexity of the resulting energy systems, requiring the analysis of many decision variables. Identifying viable configurations – parametrized for example in terms of type and capacity of energy generation technologies, for given demand conditions – can hence be a hard task for energy planners [2,3].

To face this challenge, different approaches are possible. From a quantitative viewpoint, in order to provide a reliable background for the design of future energy systems, two ingredients appear to be crucial: the *simulation model* used to analyse the behaviour of the considered configurations and the *optimization method* used to identify the most convenient parameters.

While several solutions are available in the literature in terms of these two ingredients, their coupling in the context of energy scenario design is still far from being fully satisfactory. In practice, either advanced optimization algorithms are applied to sectorial models, or more comprehensive models are optimized with simplified methods. Several examples of the first case are reviewed in [4], where distributed energy resources (DER) are considered, and in [5] where hybrid renewable energy Systems (HRES) models are considered: while detailed models and optimization algorithms are used, these works typically analyse small systems or limited energy sectors (typically focusing on electricity only). Concerning the second case, much less literature is available. Some notable examples are found in [6–8]: here the used models allow to include electric energy, thermal energy, and transportation, but only single-objective optimization is considered. Koroneos et al. [9] performed a case study on the Greek island Lesvos, investigating the penetration of renewables by applying multi-objective optimization (in terms of costs and CO_2 emissions). However, the energy system (including electric and thermal energy, but no transportation) is represented with a simplified and specifically developed model, not immediately generalizable to other cases, and no details about the optimization method are provided. In Table 1, a simple classification of the screened papers is reported.

Table 1
Positioning of papers cited in the text with respect to comprehensive energy system modelling and multi-objective optimization.

Papers	Simultaneously including electricity, thermal, and transportation sectors	Multi-objective
Alarcon-Rodriguez et al. [4] (review including about 80 papers)	No	Yes
Fadaee and Radzi [5] (review including about 50 papers)	No	Yes
Koroneos et al. [9]	No	Yes
Pina et al. [8]	Yes	No
Dong et al. [7]	Yes	No
Cormio et al. [6]	Yes	No

We therefore propose a step forward in this direction by coupling advanced optimization techniques (multi-objective evolutionary algorithms) to a fairly detailed and comprehensive energy system simulation model (EnergyPLAN). Our choices concerning the model and optimization algorithms are motivated as follows.

A wide literature about energy simulation models exists. They can be classified in different ways, depending on their nature (descriptive, analytical, etc.) or on technical aspects. An extended review is contained in [10], which differentiates models mainly in terms of time step, time extent, and modelled energy sectors. From these points of view, two requisites seem to be needed for a complete analysis. First, the intermittency typical of renewable sources requires a fine time step in order to properly evaluate the issues related to this aspect (possible need for energy storages, effects on grid stability, transmission line capacity, etc.). At least an hourly simulation model appears to be necessary to this purpose. Second, issues related to intermittency and supply-demand matching have shown the importance of considering peak shaving strategies exploiting all the possible synergies between different energy sub-systems, for example between electric energy and thermal energy (through, e.g., heat pumps and thermal storages), and between electric energy and transportation (through, e.g., electric vehicles). Hence, a comprehensive model is needed, including all the three energy sectors mentioned above. Within the large number of available models – HOMER [11,12], RETScreen [13,14], H_2RES [15,16], LEAP [17,18], and TIMES [19,20], to cite a few – it is typically difficult to find tools satisfying both of these requisites. Either they are not fully comprehensive (e.g., focused on the electric system only) or difficult to extend to large scale. Our choice fell hence on EnergyPLAN, which satisfies both requisites, is a freely available model, and is already used in several papers [21,22], as further described in Section 2.3. A model such as EnergyPLAN can simulate an energy system yielding its yearly performance (e.g., in terms of aggregate energy consumptions, costs, and emissions) after proper inputs have been provided (e.g., power capacities for different energy production, conversion, and consumption units). On the other hand, as capacities are an input of the tool, their choice is left to the user, so that their optimization against specific objectives is typically performed manually.

Concerning optimization of system configurations, again several methods are available in the literature. In this case, the requisites are determined by the following aspects. First, the high number of decision variables which can enter the optimization process gives rise to a very large search space, where advanced optimization techniques are required in order to yield a feasible computational demand. Second, optimization of energy systems needs to deal with multiple criteria, often in mutual contrast. For instance, the ability of an electricity system to balance demand and supply may be in opposition to its efficiency, as higher flexibility typically requires higher consumptions. Consequently, the optimization problem of a large energy system is in general a multi-objective optimization (MOO) problem with features reminiscent of complexity (e.g., the strong interaction among its many components). Combining these needs, we decided to resort to meta-heuristic optimization algorithms in a multi-objective framework [23] to tackle this task. This goes well beyond the optimization tools embedded in some energy models (e.g., HOMER), which are single-objective and tailored for small systems, where a brute-force search on a discretized design space is possible.

Meta-heuristic algorithms are indeed especially suitable for large and complex search spaces. Among these algorithms, we choose the class of evolutionary algorithms (EAs). Inspired from biological evolution, EA is a population-based, fitness-oriented algorithm to solve optimization problems [24]. Until the 1990s, EAs were mostly applied to solve single-objective optimization problems. However, in the last two decades, researchers have come up with a number of algorithms based on EAs to solve multi-objective optimization problems [23]. These algorithms are generally called multi-objective evolutionary algorithms (MOEAs). EAs (with single or multi-objective optimization) have been applied for solving different energy related problems such as: photovoltaic related problems [25]; wind farm layout (turbine selection and positioning) problems [26–29]; design and optimization of hybrid stand-alone energy systems [30,31]; HVAC (heating, ventilation,