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A hybrid approach for the efficient synthesis of renewable energy systems

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HIGHLIGHTS

- A hybrid synthesis method for renewable energy systems is presented.
- Heuristic equipment preselection is combined with superstructure-based optimization.
- A real world case study is analyzed (Mljet Island, Croatia).
- Investment cost savings of up to 59% compared to classical simulation are achieved.
- The computational effort required for optimization is low.

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ABSTRACT

An efficient synthesis method for renewable energy systems is presented that exploits synergies between heuristic- and optimization-based approaches. For this purpose, the RenewIslands method has been integrated into a superstructure-based optimization approach. The resulting hybrid approach consists of two steps: First, heuristic-based equipment preselection identifies a set of promising candidate technologies. Next, the preselected technologies are employed in superstructure-based optimization to determine the optimal renewable energy system. The heuristic preselection systematically avoids excessively large superstructures, while the subsequent optimization ensures that the optimal solution is selected. The proposed method is applied to the case of Mljet Island, Croatia. A renewable energy system is synthesized that requires 59% less investment costs compared to the solution derived by classical simulation. At the same time, the optimization problem is solved in less than 2 min. The proposed hybrid method is shown to provide an efficient route to the synthesis of renewable energy systems.

1. Introduction

The synthesis of energy supply systems with renewable resources is a key lever for facing the challenges of sustainable development and climate protection [1–3]. However, the synthesis problem is an inherently difficult task for which three hierarchically-dependent levels need to be taken into account [4] (Fig. 1): The *configuration* level where equipment choices are made, the *sizing* level where equipment's capacities are determined and the *operational* level where the actual load dispatch is specified. While these levels need to be considered for any energy system, a key challenge in the synthesis of renewable energy systems is to cope with the complexity stemming from the temporal and spatial interdependencies associated with renewable resources, usually requiring the installation of storage systems [5]. Additionally, the variety of available technologies and possible combinations adds significantly to the complexity. Besides, both the associated economic and ecological impacts have to be considered since the use of renewables is still usually motivated by environmental arguments. Thus, to find the best solution for a given synthesis problem, complex relationships and trade-offs between technical, economic and ecological consequences have to be balanced.

For the solution of such synthesis problems, two types of approaches are widely followed [4]: Traditionally, *heuristic-based* approaches are used, but also *optimization-based* approaches have been developed. Heuristic-based approaches typically rely on specific expert knowledge or physical insights to define possible energy systems and analyze them in simulation studies [6–12]. On the one hand, the heuristic-based approach is usually robust and generates solutions with manageable effort. On the other hand, only a limited number of alternatives can be studied in

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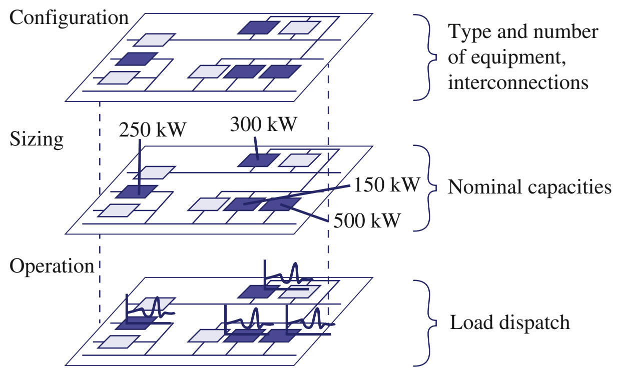

Fig. 1. Hierarchically-dependent levels *configuration*, *sizing* and *operation* to be taken into account for the synthesis of energy supply systems.

simulation studies and the risk to overlook superior solutions is high [4]. In contrast, optimization-based synthesis approaches allow for the investigation of a virtually unlimited number of alternatives and thus generally enable to find the optimal solution among all possible alternatives [13–20]. However, for large problems the modeling effort and solution times can become prohibitively large [21,22].

To combine the advantages from heuristic and optimization-based approaches, so called *hybrid approaches* have been successfully developed in other fields [23]. In this work, a hybrid approach is developed for the efficient synthesis of renewable energy systems. The proposed method builds upon the RenewIslands method by Duić et al. [24] and the automated superstructure-based optimization approach developed by Voll et al. [25].

This paper is organized as follows: In Section 2, the proposed hybrid approach is presented. In Section 3, a real world case study is considered - the island of Mljet, Croatia. The proposed method is applied to synthesize a 100% renewable energy system. The solution is compared to findings from an earlier publication where the RenewIslands method has been applied to the identical case but without rigorous optimization [26]. In Section 4, the benefits of the optimization-based synthesis are further elaborated and the required solution effort is analyzed. Finally, the paper is summarized (Section 5).

2. A hybrid approach for the synthesis of renewable energy systems

The proposed hybrid approach combines two well-founded synthesis methods. The RenewIslands method has been developed for energy planning of isolated islands [27] and has been implemented into the H2RES software [11,28]. Its core concept is to use heuristic rules to evaluate and structure information on local resources and demands, select promising renewable technologies and devise possible energy systems. The inputs are qualitative statements about the energy demand levels and the available resources which are classified as "low", "medium" or "high". A range of *if–then*-relations is then provided to derive a set of promising technologies. Based on this set of technologies, synthesis alternatives to be considered are heuristically defined by the user and assessed in scenario-type simulation studies (for details the reader is referred to [24]). The major strength of the RenewIslands method is that it significantly narrows down the complexity of the synthesis problem by systematically eliminating unsuitable technologies from consideration. The major shortcoming of the RenewIslands method is that the user is required to define the synthesis alternatives using heuristics, i.e. all decisions on structure, sizing and operation need to be specified manually. In general, the optimal solution is not included within this limited number of alternatives and the RenewIslands method will thus lead to suboptimal solutions only.

Voll et al. [25] successfully developed a method for the automated synthesis of distributed energy supply systems. It is implemented as "eSynthesis" module into the TOP-Energy framework [29,30]. The key concept is to apply rigorous, superstructure-based optimization to the configuration, sizing and operation of energy systems. To circumvent the manual definition of a superstructure containing all possible synthesis alternatives, a successive optimization approach is realized that automatically generates, optimizes and expands a set of superstructure models until the optimal solution is found. For this purpose, the method includes an algorithm for automated superstructure and model generation which only needs a set of specified technologies as input. This algorithm makes use of the P-Graph based *maximal structure generation* method [31]. The (initially) generated superstructure model is successively optimized and expanded until it yields the optimal solution. While the method has been shown to allow for efficient synthesis of decentralized energy supply systems [25], the technologies considered in the superstructure should be limited to meaningful options. Otherwise, excessively large superstructures lead to increased computational effort which may even become prohibitive.

To enable the efficient synthesis of renewable energy systems, the two discussed approaches have been integrated as follows (Fig. 2): In a first step, the RenewIslands method is used to reduce the complexity of the considered synthesis problem by preselecting promising candidate technologies. Next, instead of assessing the identified technologies in scenario-type simulation studies [11,26], they are fed into the superstructure-based optimization framework to determine the optimal renewable energy system.

In the authors' opinion, the proposed hybrid approach has the potential to combine the benefits of heuristic- and optimization-based synthesis. First of all, RenewIslands provides a transparent method with clearly defined rules for the preselection of candidate technologies. This avoids the use of subjective assumptions as often required in current practice. Furthermore, the heuristic preselection of candidate technologies leads to a significant complexity reduction and facilitates optimization-based synthesis: Most importantly, the superstructure is limited to contain only the essential equipment options. Consequently, the modeling of excluded equipment options can be omitted which is often the most time-consuming step in practice. Algorithmically, all equations and

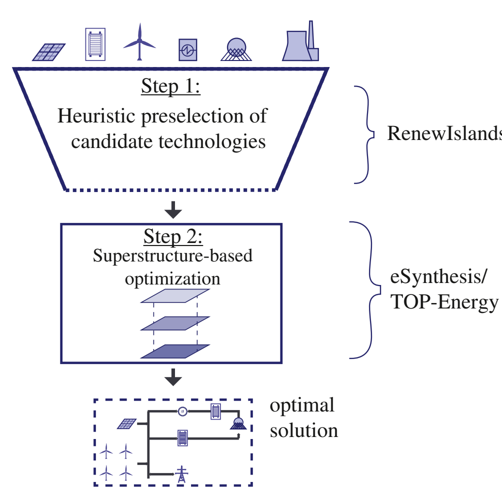

Fig. 2. Proposed two-step hybrid approach for the synthesis of renewable energy systems. The candidate technologies identified by heuristic preselection (step 1) are employed in superstructure-based optimization (step 2) to determine the optimal renewable energy system.