RenewIslands meets optimization: Efficient synthesis of renewable energy systems

Conference Paper · September 2013

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RenewIslands meets optimization:
Efficient synthesis of renewable energy systems

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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. Concepts for renewable energy systems are generated that require up to 59 % less investment costs compared to solutions derived by a classical simulation approach. At the same time, solution times are less than 2 minutes. The hybrid approach thus provides 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, 2]. However, this is an intrinsically difficult task: A key challenge in the synthesis of renewable energy systems is to cope with the inherent complexity stemming from the temporal and spatial interdependencies associated with renewable resources. Additionally, the variety of available technologies and possible combinations adds to the complexity. Moreover, three hierarchically-dependant synthesis levels need to be taken into account [3] (Figure 1): The configuration level where equipment choices are made, the sizing level that determines (nominal) capacities and the operational level that specifies the actual load dispatch. Besides, the associated economic and ecological impacts have to be considered. Therefore, to find the best solution for a given synthesis problem, complex relationships and trade-offs between technical, economical and ecological consequences have to be balanced.

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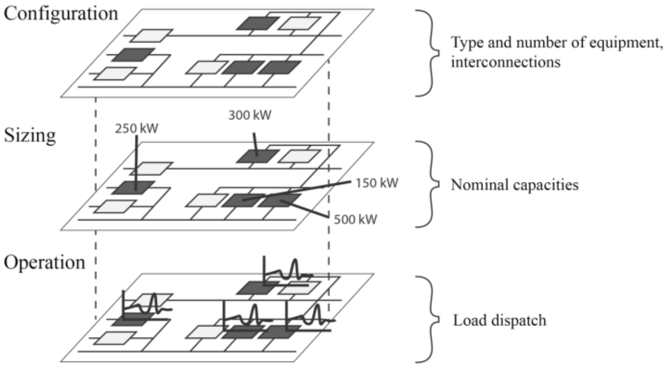

Figure 1. Hierarchically-dependant levels *configuration*, *sizing* and *operation* to be taken into account for the synthesis of energy supply systems.

For the solution of such synthesis problems, two types of approaches are widely followed. 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 [4–9]. On the one hand, this heuristic-based approach is usually robust and generates adequate solutions with manageable effort. On the other hand, only a limited number of alternatives can be studied in simulations and the risk to overlook superior solutions is high [3]. 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 [10–16]. However, for large problems modeling effort and solution times can become prohibitively large [17, 18].

To combine the advantages from both approaches, in other fields so called *hybrid approaches* have been successfully developed that combine heuristics and optimization techniques [19]. 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. [20] and the automated superstructure-based optimization approach developed by Voll et al. [21].

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 new method is applied to synthesize possible renewable energy systems with up to 100 % share of renewable resources. To evaluate and validate the method, the results are compared to findings from an earlier publication where the RenewIslands method has been applied to the same case but without optimization [22]. Finally, the paper is summarized (section 4).

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 [23] and has been implemented into the H2RES software [9, 24]**.** 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 used to derive a set of promising technologies. Based on this set of technologies, the synthesis alternatives to be considered are heuristically defined by the user and assessed in simulation studies (for details the reader is referred to [20]). 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 it requires the heuristic definition of synthesis alternatives by the user. In general, the optimal solution is not included within this limited set of alternatives and the RenewIslands method will thus lead to suboptimal solutions only.

The method developed by Voll et al. [21] has successfully been used for the automated synthesis of distributed energy supply systems. It is implemented as “eSynthesis” module into the TOP-Energy framework [25, 26]. 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 and optimizes a set of superstructure models until the optimal solution has been identified. For this purpose, the method includes an algorithm for the automated superstructure and model generation based on a set of specified technologies. Controlled by another algorithm, the (initially) generated superstructure model is successively optimized and expanded until it yields the optimal solution. However, the technologies considered in the superstructure should be limited to meaningful options since excessively large superstructures lead to increased computational effort.

To enable the efficient synthesis of renewable energy systems, the two discussed approaches have been integrated as follows (Figure 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 [9, 22], they are fed into the eSynthesis module of TOP-Energy to determine the optimal synthesis solution by superstructure-based optimization.

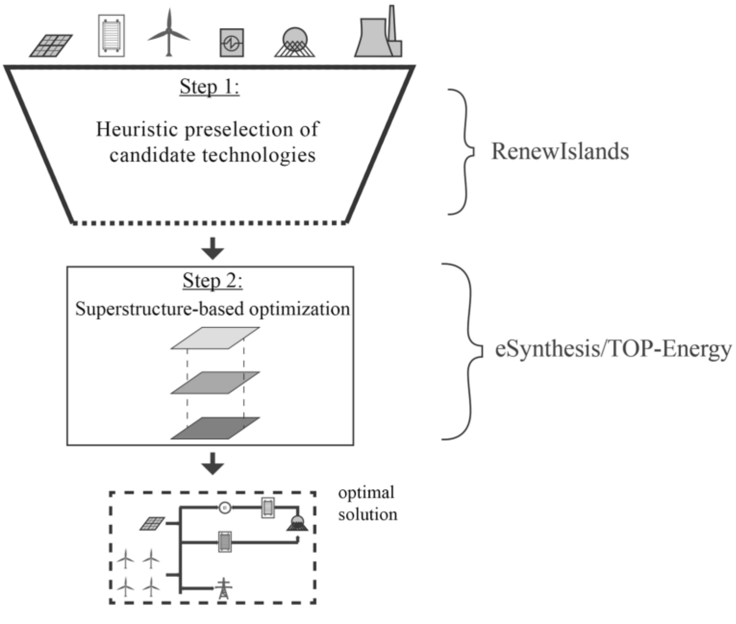

Figure 2. Proposed two-step hybrid approach for the synthesis of renewable energy systems. The candidate technologies identified by heuristic preselection (step 1) are employed in superstructure-based optimization (step 2) to determine the optimal renewable energy system.

In view of the authors, 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 selection of candidate technologies. This avoids the use of subjective assumptions as often required in current practice. Furthermore, the heuristic preselection of candidate technologies leads in two ways to a significant complexity reduction and facilitation of the optimization-based synthesis. On the one hand, the superstructure is kept small and contains only the essential equipment options. Correspondingly, the number of discrete degrees of freedom of the mathematical model (i.e. binary variables) is reduced. Since binary variables exponentially influence the solution time [27, 28], it is desirable to keep their number as small as possible. On the other hand, the mathematical modeling of the excluded technologies can also be omitted. Thus, further benefits in the solution process and a reduced modeling effort are expected. Most importantly in practice, for excluded technologies, the time-consuming effort for data collection and parameterization becomes obsolete.

3) CASE STUDY “MLJET ISLAND”

In the following, a real world case study – the Island of Mljet, Croatia – is considered. This case study has already been analyzed by Krajačić et al. [22] with the original form of the RenewIslands method, i.e., using simulation studies instead of rigorous optimization. The objective was set to identify energy supply systems for Mljet that maximize the use of locally available renewable resources and to investigate their economic viability. In the present work, the proposed hybrid approach is applied to the same objective. To evaluate and validate the method, all results are compared to the original study [22].

The island of Mljet is located on the Eastern part of the Adriatic Sea. Mljet measures 37 km in length by 3.2 km average width and an area of 100 km². General population of Mljet from the 2001 census was 1111 inhabitants. Local economy mainly relies on viticulture, olive growing and tourism.

Step 1: Preselection of candidate technologies

Following the proposed hybrid approach, in a first step, candidate technologies for a renewable-based energy system for Mljet Island are determined by heuristic preselection. According to the RenewIslands method, starting point for the preselection is a systematic mapping and assessment of the local needs and available resources (Table 1). Mljet is connected to the mainland with two undersea electricity grid connections. There is no electricity generation capacity on the island. Due to a lack of potable water in the summer, three desalination plants are installed on the island. Together with a 300-bed hotel, these desalination plants present the largest electricity consumers. The demand for heating and cooling is low because the climate of Mljet is Mediterranean with average yearly temperatures in the range of 9 °C in January to 24 °C in July. Thus, there is only a low demand for heating and cooling. Transport fuel is delivered via ship and there is only one fuel station for the entire island. The results of this mapping have been adopted from the original publication [22]. They are also described in more detail in [20].

Table 1. Needs and resources of Mljet Island, assessed according to the RenewIslands method.

Needs	Level	Geographic distribution
Electricity	Medium	Dispersed
Heat	Low	Dispersed
Cold	Low	Dispersed
Resources		
Wind	Medium	-
Solar	Medium	-
Hydro	Medium	-
Biomass	High	-
Geothermal	Low	-
Grid connection	Strong	-
Natural gas pipeline	No	-
LNG terminal	No	-
Oil terminal /refinery	No	-
Oil derivatives terminal	No	-

Based on this evaluation, the RenewIslands method (c.f. section 2) is applied for equipment preselection. Its application yields that 14 of 17 conversion technologies and 5 of 7 storage technologies can be eliminated from the general set of technologies defined in the RenewIslands method (Figure 3)**.** Hence, the preselection reduces the number of equipment considered from 24 to only 5. In particular, the provision of heat and cold can be excluded from further consideration due to the low demand for these needs and their dispersed geographic distribution. Hence, the synthesis task reduces to a renewable *electricity* supply system. Apart from the existing mainland grid connection, the remaining candidate technologies are wind turbines, photovoltaic cells and a hydrogen loop consisting of an electrolyser, a fuel cell and hydrogen storage. Further details on the preselection are provided in [20].

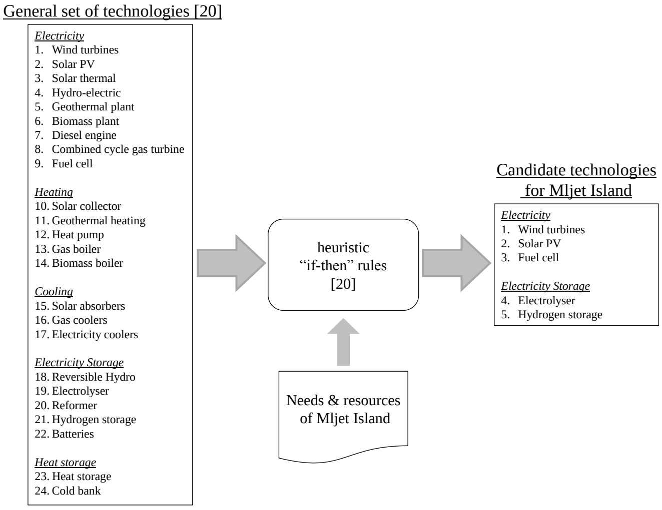

Figure 3. Preselection of candidate technologies for the synthesis of a renewable electricity supply system for Mljet Island. Based on the assessment of local needs and resources, heuristic “if-then” rules of the RenewIslands method are used to eliminate unsuitable options from the general set of technologies.

Step 2: Superstructure-based optimization

Setup of the optimization model. The preselection step has lead to five candidate technologies for a renewable electricity supply system for Mljet Island. Now, in the second step of the proposed hybrid method, the optimal synthesis of a system considering only these candidate technologies is determined by superstructure-based optimization.

The method developed by Voll et al. [21] provides an algorithm for automated superstructure and model generation. This algorithm makes use of the P-Graph based *maximal structure generation* method [29]. Its application to the candidate technologies yields the initial superstructure illustrated in Figure 4. The renewable electricity produced by wind turbines and photovoltaic cells can be used to satisfy the local demand, to operate the electrolyser loading the hydrogen storage or it can be exported to the mainland. Demand satisfaction is also possible by operating the fuel cell unloading the hydrogen storage or by importing electricity from the mainland.

The underlying technology models are kept consistent to the original models [22], i.e., exactly the same data for demand, operating behavior, costs, etc. is used. This implies the following assumptions:

- all calculations are based on known annual time series with discrete time steps of 1 hour for demand and generation data (wind speeds, solar irradiation, etc.);
- for the power output of the wind turbines, part-load behavior is modeled with the help of performance curves;
- for all other technologies, constant efficiencies are assumed and neither part-load behavior, minimum part-load restrictions or minimum technology sizes are considered;
- the specific investment costs of the equipment are kept constant, i.e., no economy of scale effects are modeled;
- the share of renewable electricity in the grid is not limited, i.e., 100 % demand satisfaction by renewable resources is allowed; however, the export of excess electricity is limited to 30 % of the annual renewable production;
- the hydrogen loop can only be operated by renewable resources.

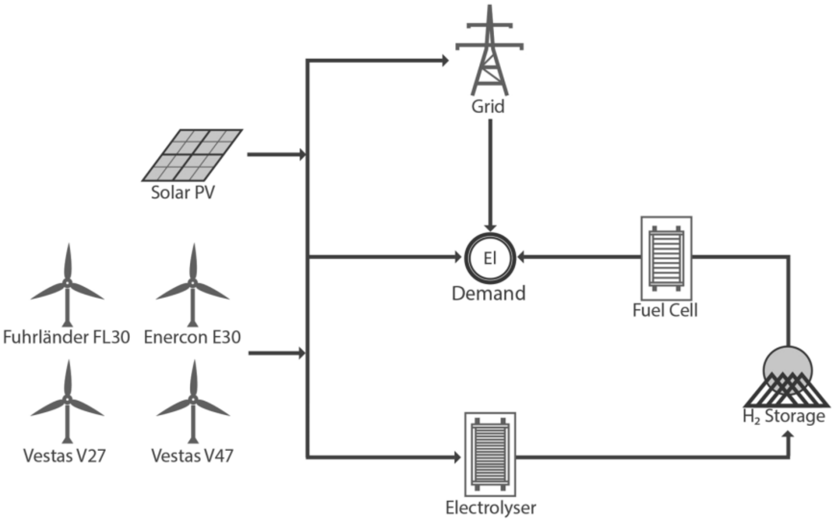

Figure 4. General superstructure of a renewable electricity supply system for Mljet Island based on the preselected technologies.

With these assumptions, the optimization model is formulated as MILP with integer-type variables only for the sizing of the wind turbines. All other technologies can be sized continuously. Hence, the application of the successive superstructure expansion algorithm of the method by Voll et al. [21] is not required in this example. Thus, the problem can be solved to the global optimal solution in a single run using CPLEX® 12.5 as solver on a 3.3 GHz Intel® Core™ i-5-2500 CPU with 3.23 GB RAM.

Scenarios. The superstructure for the electricity supply system presented above (Figure 4) is the most general superstructure considered. In [22], additional scenarios are studied involving other subsets of the candidate technologies, cf. Table 2. In the present work, several of these scenarios are studied as well. This comparison of the results enables the evaluation of the hybrid method. To model the additional scenarios, constraints to fix decisions on the structural level are added to the general mathematical problem description. The scenarios are numbered as in [22][1]. The general superstructure is represented by scenario 12. In the following, the superstructure optimization model set up above is solved for each scenario and the results are presented and discussed.

Table 2. Definition of scenarios for the case study.

Original Scenario Number	Wind	PV	Electrolyser	Fuel Cell	H2 Storage
2	✓				
4		✓			
6	✓	✓			
8	✓		✓	✓	✓
10		✓	✓	✓	✓
12	✓	✓	✓	✓	✓

The optimal renewable energy system. In accordance to the original study [22], the scenarios are optimized aiming at a maximum share of renewable energies. Hence, minimization of electricity import is used as objective function. Each scenario is solved to its optimal solution in less than a minute. The solution comprises all information on the structure of the energy system, the sizing of the technologies and a schedule for the operation in every hour of the year. The results are shown in Figure 5 a). As should be expected, optimization-based results are always equal or better than the results from the previous simulation study [22]. In particular, optimization-based synthesis increases the share of renewable resources for scenarios 2 and 6 by 8 % and 3 %, respectively. Furthermore, optimization confirms that a share of 35 % is the maximum value to be reached when only photovoltaic panels are installed (scenario 4). Naturally, no improvements can be found for scenarios 8, 10 and 12 with a share of renewable resources already at its maximum level of 100 %.

For the sole minimization of electricity import, costs are not taken into account. Hence, at a share of 100 % renewable resources, solutions are found with highly oversized storage capacities (variables are set to their upper bounds by optimization). These solutions lead to immense investment costs. To avoid the economically undesirable oversizing of equipment, the optimization runs are repeated using the minimization of investment costs as objective function (Figure 5b).

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[1] In [22], also scenarios with a grid limit of 30 % renewable penetration and / or hydrogen use for mobility needs are studied. These scenarios have uneven and / or higher numbers and are not considered in the present work.

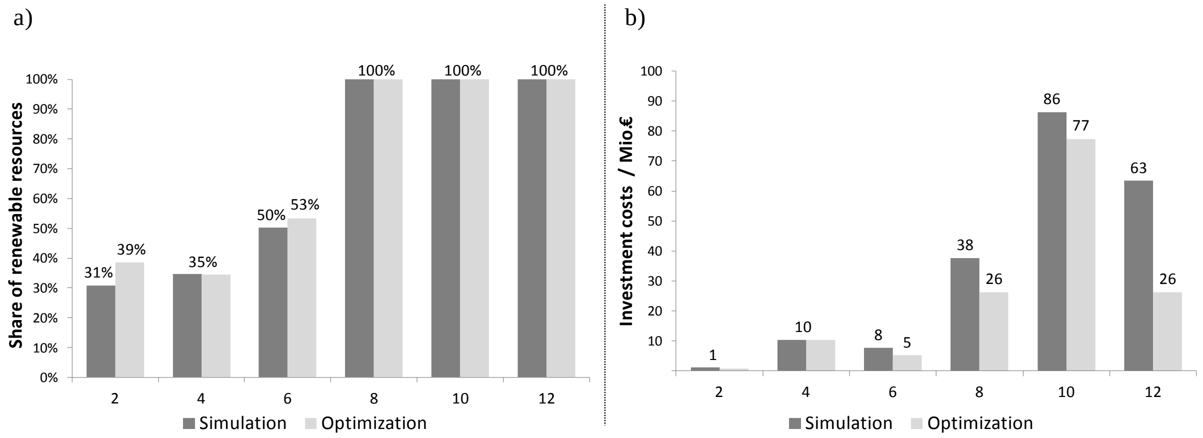

Figure 5. Comparison of simulation and optimization results for all scenarios: a) Maximum share of renewable resources as objective for optimization. b) Minimum investment costs as objective for optimization, where the share of renewable resources from the simulation results is set as constraint.

In this case, a constraint is added assuring that for each scenario the share of renewable resources must still be equal or greater than in the original simulation study [22]. Again, for each scenario, the optimal solution can be found within solution times smaller than 2 minutes. All solutions require less investment costs at equal or higher shares of renewable resources. The cost reductions range between 11 % (scenario 10) and 59 % (scenario 12). The largest reduction of 59 % is achieved in scenario 12 which represents the general superstructure and thus possesses the highest degree of freedom for optimization. However, even when the structure is fixed and only sizing and operation decisions are taken into account (scenarios 2-10), the optimization still yields large savings. Note that scenarios 8 and 12 have an identical optimal solution. This solution represents the cheapest concept to supply Mljet Island with 100 % electricity from locally available renewable resources with the technologies considered (Figure 6). For a complete overview, the detailed results for all scenarios are summarized in Table 3.

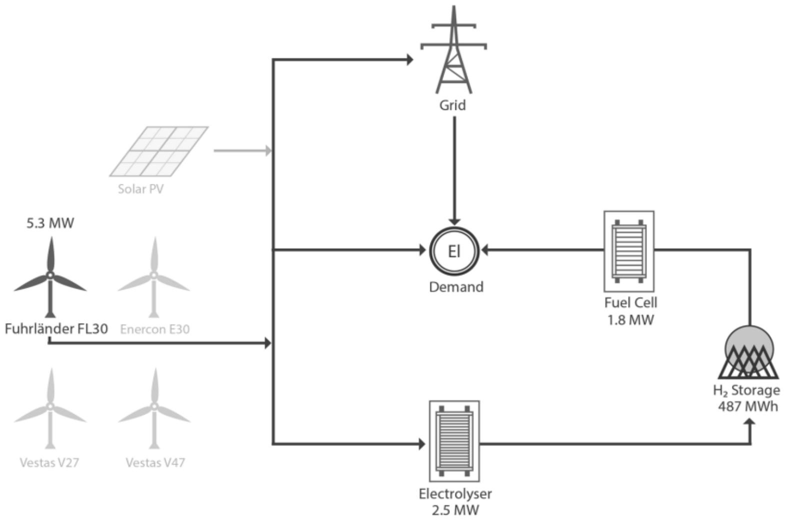

Figure 6. Minimum investment cost solution of a 100 % renewable electricity supply system for Mljet Island, identified by optimization of the general superstructure. Units not selected are shown in light grey.

Table 3. Comparison of simulation and optimization results for all scenarios. “sim” = simulation results, “RES” = optimization results for maximum share of renewables, “INVEST” = optimization results for minimum investment. Variables at their upper bound are marked with an asterisk (*).

Scenario		Wind /MW	PV /MW	Electrolyser /MW	Fuel cell /MW	H_2 storage /MWh	Renewable resources	Investment /Mio. €
2	sim	0.8					31 %	1.2
	RES	0.8					39 %	1.2
	INVEST	0.6					31 %	0.8
4	sim		1.9				35 %	10.4
	RES		1.9				35 %	10.4
	INVEST		1.9				35 %	10.4
6	sim	0.7	1.2				50 %	7.7
	RES	0.6	1.3				53 %	8.2
	INVEST	0.8	0.7				50 %	5.2
8	sim	6		4.5	1.8	873	100 %	37.7
	RES	6		6	1.8	5000*	100 %	95.8
	INVEST	5.3		2.5	1.8	487	100 %	26.3
10	sim		12.1	4.4	1.8	210	100 %	86.3
	RES		14.3	10.7	1.8	5000*	100 %	177.5
	INVEST		10.4	4.6	1.8	217	100 %	77.4
12	sim	1.2	7.8	4	1.8	188	100 %	63.4
	RES	2.1	8.5	7.9	1.8	5000*	100 %	141.2
	INVEST	5.3		2.5	1.8	487	100 %	26.3

The results show large benefits of the optimization-based synthesis in terms of investment costs. Now, it is analyzed where these benefits come from. For this purpose, a detailed comparison of the simulation and optimization results for scenario 8 is presented.

The major difference in the optimization and simulation results is the sizing of the electrolyser and the hydrogen storage. While the original simulation study proposes the installation of an electrolyser with about 4.5 MW nominal capacity, the optimization-based synthesis yields an optimal size of 2.5 MW (Table 3). Likewise, the simulation study recommends a size of 873 MWh for the H_2 storage whereas the optimal size lies at 487 MWh. In both cases, the capacities determined in the simulation study are almost twice the size required in the optimal solution. Accordingly, the investment costs for these oversized components are almost twice as high (23 Mio. € vs. 13 Mio. €). Regarding the installed capacity of wind power, the differences are not as significant. In the simulation study 6 MW are installed; the optimal solution provides 5.3 MW. However, the types of installed wind turbines differ between the approaches. In the simulation study, wind turbines of the type “Enercon”, “Vestas” and “Fuhrländer” are installed. The optimal solution in contrast chooses only wind turbines of the type “Fuhrländer”. Thus, among all available wind turbines the “Fuhrländer” type possesses the best trade-offs between (locally dependant) performance characteristics and costs. In total, the savings achieved by installing less capacity and better suited types of wind turbines accumulate to about 1 Mio. € in the optimal solution. In summary, the significant reduction of investment costs found by the superstructure-based optimization is the result of both a better equipment sizing and a better configuration (i.e. equipment choice) of the renewable electricity supply system compared to the solution suggested in the original simulation study.

However, equipment configuration and sizing are not independent from its operation. Correspondingly, also the operation strategy for the presented optimal solution differs from the original simulation result (Figure 7): A higher share of wind energy is stored via the hydrogen loop (59 % instead of 53 %) and less wind energy is used for direct demand supply. The controllable components of the hydrogen loop (electrolyser and fuel cell) can be better utilized in this strategy. This offers more flexibility for demand satisfaction.

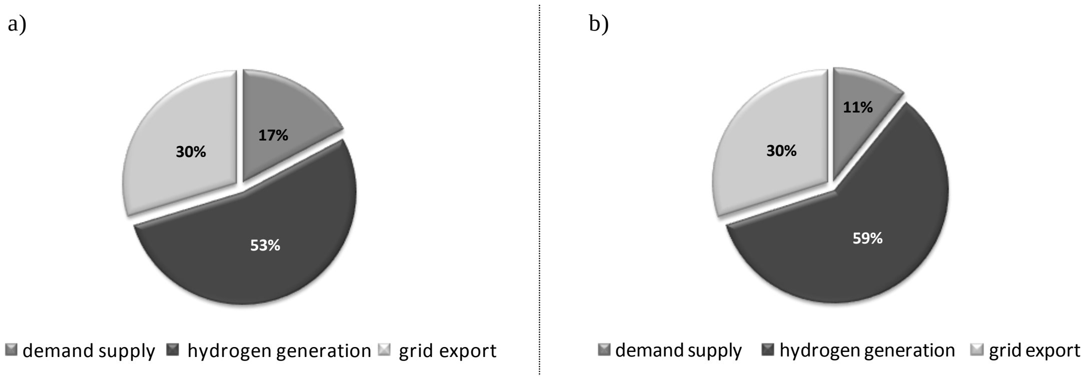

Figure 7. Comparison of wind power utilization in scenario 8: a) Results of the original simulation study. b) Optimal operation strategy.

Multi-objective analysis. Finally, due to the reduced computational effort of the hybrid approach, multi-objective optimization [30–32] is possible to provide additional insights. A Pareto frontier (Figure 8, top) is generated using the ε-constraint method [31] to investigate how much investment is at least necessary for a certain share of renewable resources. The generation of the Pareto frontier requires nine additional optimization runs and is completed in 24 minutes.

The slope of the Pareto frontier (Figure 8, top) shows that it becomes progressively expensive to increase the share of renewable resources towards 100 %, as progressively more equipment needs to be installed (Figure 8, bottom). Roughly three ranges can be identified: Renewable resources supplying less than 40 %, 40-90 % or up to 100 % of the demand. If renewable resources supply less than 40 % of the demand, moderate costs of less than 1.5 Mio. € occur and it is sufficient to install wind turbines. The wind power can be used for synchronous demand supply and no energy storage is needed. However, if a share of more than 40 % of renewable resources is desired, it becomes unavoidable to compensate the temporal offset between generation and demand and to provide energy storage by installing the hydrogen loop. From that point on, the costs for the electrolyser, the hydrogen storage and the fuel cell add to the total investment costs and the slope of the Pareto frontier becomes steeper. At a share of 60 % of renewable resources, investment costs have reached already 5 Mio. € and further increase up to 15 Mio. € at 90 %. Due to the conversion losses that occur in the hydrogen loop, considerably more wind energy than required for demand supply needs to be harvested. Accordingly, the installed equipment size of wind turbines rises from 0.9 MW to 4.3 MW between 40 % and 90 % share of renewable resources. Likewise, the electrolyser size rises from less than 100 kW to almost 2 MW to convert the harvested (surplus) wind power into hydrogen. Between 40-90 %, both the installed fuel cell size and the storage size can be kept relatively low. For a share of renewable resources between 90-100 %, the slope of the Pareto frontier rises again. In fact, the last 10 % are almost equally expensive as the first 90 % with investment costs increasing from 15 Mio. € up to 26 Mio. €. This is mostly due to fact that the fuel cell and storage capacities now need to be expanded massively (by the factors three and four, respectively) to cover the lack of wind in summer when the electricity demand is at its peak.

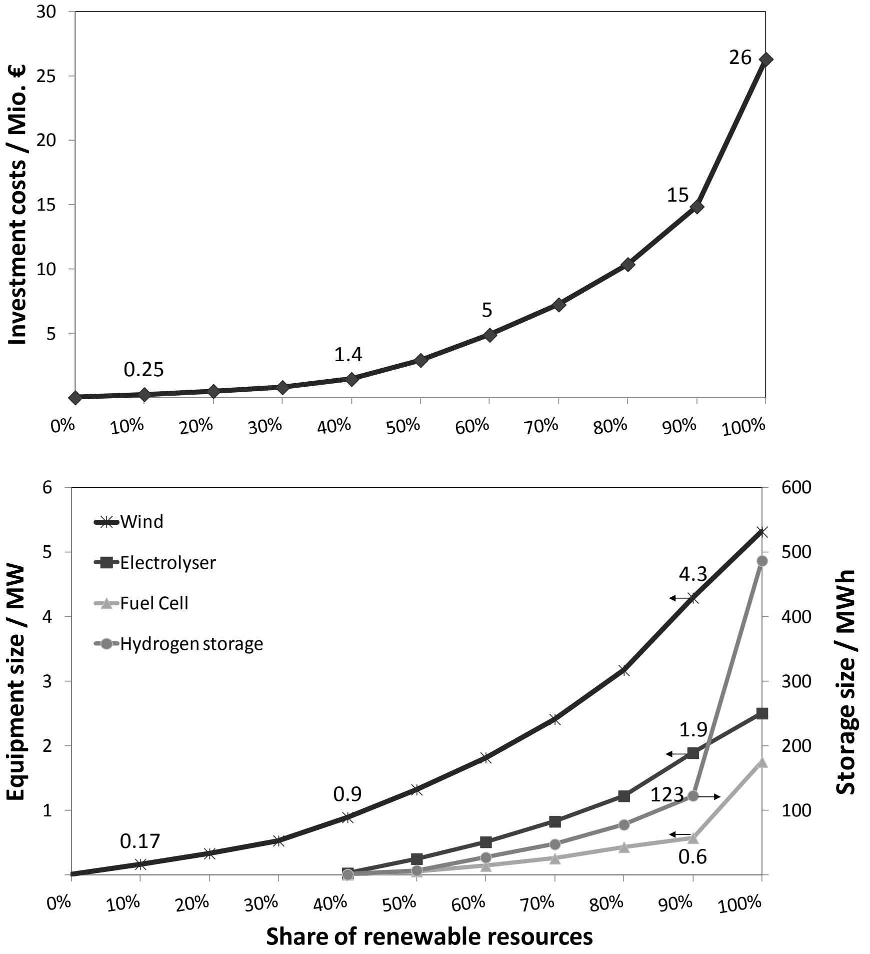

Figure 8. Results of the multi-criteria optimization for the case study. Top graph: Pareto frontier showing minimum invest costs for a given share of renewable resources. Bottom graph: Corresponding equipment sizes.

4) SUMMARY

This paper presents a hybrid approach for the synthesis of renewable energy systems. The hybrid approach consists of an initial heuristic-based preselection of candidate technologies followed by a rigorous optimization and is based on the RenewIslands method [20] and superstructure-based optimization as developed by Voll et al. [21]. The preselection effects an important complexity reduction of the synthesis problem facilitating the optimal synthesis by avoiding large superstructures and reducing the modeling effort.

The application of the hybrid approach to the case study of Mljet Island shows that the complexity of the synthesis problem can successfully be narrowed down by preselecting five promising candidate technologies from a comprehensive set of more than 20 options. The implemented MILP optimization model is solved in less than two minutes to the global optimal solution using a standard solver. A comparison of the optimization results to the results originally derived by simulation [22] demonstrates a clear benefit of the hybrid approach. For the most general scenario, the optimal solution requires only 41 % of the investment costs determined by simulation at an equal share of 100 % renewable resources in the energy system.

The low computational effort achieved by the hybrid approach also enables to provide additional insights for the case study by performing multi-criteria optimization. The calculated Pareto frontier reveals that it becomes progressively expensive to reach a share of 100 % renewable resources. The last 10 % require equal investments to the first 90 % since equipment capacities need to be extended immensely.

In light of the short solution times and the excellent optimization results, the proposed hybrid approach represents an efficient and comprehensive method for the synthesis of renewable energy systems.

Acknowledgment

It is gratefully acknowledged that this work has been supported by the Croatian Science Foundation through the “Optimization of Renewable Electricity Generation Systems Connected in a Microgrid” collaborative research project, grant No. HRZZ 08/40.

REFERENCES

1. Lund, H., Renewable energy strategies for sustainable development, *Energy*, Vol. 32, No. 6, pp. 912–919, 2007.
2. Edenhofer, O., Madruga, R. P., Sokona, Y., Seyboth, K., et al., *Renewable energy sources and climate change mitigation*, Cambridge Univ. Press, Cambridge, 2012.
3. Frangopoulos, C. A., A Brief Review of Methods for the Design and Synthesis Optimization of Energy Systems, *Int. J. Applied Thermodynamics*, Vol. 5, No. 4, pp. 151–160, 2002.
4. Ramakumar, R., Abouzahr, I., Ashenayi, K., A knowledge-based approach to the design of integrated renewable energy systems, *IEEE Trans. Energ. Conv.*, Vol. 7, No. 4, pp. 648–659, 1992.
5. Elliston, B., Diesendorf, M., MacGill, I., Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market, *Energy Policy*, Vol. 45, pp. 606–613, 2012.
6. Wang, Y., Ronilaya, F., Chen, X., Roskilly, A. P., Modelling and simulation of a distributed power generation system with energy storage to meet dynamic household electricity demand, *Appl. Therm. Eng.*, Vol. 50, No. 1, pp. 523–535, 2013.
7. Bakic, V., Pezo, M., Stevanovic, Ž., Živkovic, M., et al., Dynamical simulation of PV/Wind hybrid energy conversion system, *Energy*, Vol. 45, No. 1, pp. 324–328, 2012.
8. Beccali, M., Brunone, S., Cellura, M., Franzitta, V., Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings, *Renew. Energ.*, Vol. 33, pp. 366–382, 2008.
9. Segurado, R., Krajačić, G., Duić, N., Alves, L., Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde, *Appl. Energ.*, Vol. 88, No. 2, pp. 466–472, 2011.
10. Baños, R., Manzano-Agugliaro, F., Montoya, F. G., Gil, C., et al., Optimization methods applied to renewable and sustainable energy: A review, *Renew. Sust. Energ. Rev.*, Vol. 15, No. 4, pp. 1753–1766, 2011.
11. Papoulias, S. A., Grossmann, I. E., A structural optimization approach in process synthesis - I, *Comput. Chem. Eng.*, Vol. 7, No. 6, pp. 695–706, 1983.
12. Bazmi, A. A., Zahedi, G., Sustainable energy systems: Role of optimization modeling techniques in power generation and supply - A review, *Renew. Sust. Energ. Rev.*, Vol. 15, No. 8, pp. 3480–3500, 2011.
13. Söderman, J., Pettersson, F., Structural and operational optimisation of distributed energy systems, *Appl. Therm. Eng.*, Vol. 26, No. 13, pp. 1400–1408, 2006.

14. Liu, P., Gerogiorgis, D. I., Pistikopoulos, E. N., Modeling and optimization of polygeneration energy systems, *Catalysis Today*, Vol. 127, No. 1–4, pp. 347–359, 2007.
15. Ren, H., Gao, W., A MILP model for integrated plan and evaluation of distributed energy systems, *Appl. Energ.*, Vol. 87, No. 3, pp. 1001–1014, 2010.
16. Mehleri, E. D., Sarimveis, H., Markatos, N. C., Papageorgiou, L. G., Optimal design and operation of distributed energy systems: Application to Greek residential sector, *Renew. Energ.*, Vol. 51, No. 0, pp. 331–342, 2013.
17. Bixby, R. E., Fenelon, M., Gu, Z., MIP: Theory And Practice - Closing The Gap, In: M. J. D. Powell & S. Scholtes (Eds.), *System modelling and optimization*: *Methods, theory, and applications,* Cambridge, UK, 2000.
18. Koch, T., Achterberg, T., Andersen, E., Bastert, O., et al., MIPLIB 2010, *Math. Prog. Comp.*, Vol. 3, No. 2, pp. 103-163, 2011.
19. Yuan, Z., Chen, B., Gani, R., Applications of process synthesis: Moving from conventional chemical processes towards biorefinery processes, *Comput. Chem. Eng.*, Vol. 49, pp. 217–229, 2013.
20. Duić, N., Krajačić, G., da Graça Carvalho, M., RenewIslands methodology for sustainable energy and resource planning for islands, *Renew. Sust. Energ. Rev.*, Vol. 12, No. 4, pp. 1032–1062, 2008.
21. Voll, P., Klaffke, C., Hennen, M., Bardow, A., Automated superstructure-based synthesis and optimization of distributed energy supply systems, *Energy,* Vol. 50, pp. 374–388, 2013.
22. Krajačić, G., Duić, N., da Graça Carvalho, M., H2RES, Energy planning tool for island energy systems – The case of the Island of Mljet, *Int. J. Hydrogen Energy,* Vol. 34, No. 16, pp. 7015–7026, 2009.
23. Chen, F., Duic, N., Alves, L. M., da Graça Carvalho, M., Renewislands—Renewable energy solutions for islands, *Renew. Sust. Energ. Rev.,* Vol. 11, No. 8, pp. 1888–1902, 2007.
24. Lund, H., Duić, N., Krajačić, G., da Graça Carvalho, M., Two energy system analysis models: A comparison of methodologies and results, *Energy*, Vol. 32, No. 6, pp. 948–954, 2007.
25. Augenstein, E., Wrobel, G., Kuperjans, I., Plessow, M., TOP-ENERGY – Computational support for energy system engineering processes, *1st International Conference From Scientific Computing to Computational Engineering (1st IC-SCCE)*, Athens, September 8-10, 2004.
26. Voll, P., Kirschbaum, S., Bardow, A., Evaluation of quasi-stationary simulation for the analysis of industrial energy systems, In: D. Favrat & F. Maréchal (Eds.), *ECOS 2010*: *Proceedings of the 23rd International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems,* Lausanne, June 14-17, 2010, pp. 219–231.
27. Nemhauser, G. L., Wolsey, L. A., *Integer And Combinatorial Optimization,* Wiley, New York, 1988.
28. Wolsey, L. A., *Integer programming,* Wiley, New York, 1998.
29. Friedler, F., Tarjan, K., Huang, Y. W., Fan, L. T., Graph-theoretic approach to process synthesis: Polynomial algorithm for maximal structure generation, *Comput. Chem. Eng.,* Vol. 17, No. 9, pp. 929–942, 1993.
30. Miettinen, K., *Nonlinear multiobjective optimization,* Kluwer Academic Publishers, Dordrecht, 1999.
31. Haimes, Y. Y., Lasdon, L. S., Wismer, D. A., On a Bicriterion Formulation of the Problems of Integrated System Identification and System Optimization, *IEEE Trans. Syst. Man. Cybern.*, Vol. 1, No. 3, pp. 296–297, 1971.

32. Ehrgott, M., Figueira, J., Greco, S., *Trends in Multiple Criteria Decision Analysis,* Springer, New York, 2010.