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Energy 32 (2007) 948–954

ENERGY

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Two energy system analysis models: A comparison of methodologies and results

Henrik Lund[a,*], Neven Duić[b], Goran Krajačić[b], Maria da Graça Carvalho[c]

[a]Department of Development and Planning, Aalborg University, Denmark

[b]Power Engineering Department, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

[c]Research Group on Energy and Sustainable Development, Department of Mechanical Engineering, Instituto Superior Técnico, Lisbon, Portugal

Abstract

This paper presents a comparative study of two energy system analysis models both designed for the purpose of analysing electricity systems with a substantial share of fluctuating renewable energy. The first model (EnergyPLAN) has been designed for national and regional analyses. It has been used in the design of strategies for integration of wind power and other fluctuating renewable energy sources into the future energy supply. The model has been used for investigating new operation strategies and investments in flexibility in order to utilize wind power and avoid excess production. The other model (H_2RES) has been designed for simulating the integration of renewable sources and hydrogen into island energy systems. The H_2RES model can use wind, solar and hydro as renewable energy sources and diesel blocks as backup. The latest version of the H_2RES model has an integrated grid connection with the mainland. The H_2RES model was tested on the power system of Porto Santo Island, Madeira, Portugal, Corvo and Graciosa Islands, Azores Islands, Portugal and Sal Island, Cape Verde. This paper presents the results of using the two different models on the same case, the island of Mljet, Croatia. The paper compares methodologies and results with the purpose of identifying mutual benefits and improvements of both models.

Keywords: EnergyPLAN; H_2RES; Renewable energy; Energy storage; Islands; Hydrogen; Energy system analysis

1. Introduction

The utilization of renewable energy has become an important objective of many countries and governments around the world [1–10]. Renewable energy provides for a clean and sustainable approach to energy production, helps to ensure security of energy supply [11], and contributes to the meeting of the Kyoto Protocol objectives [12–16]. The integration of renewable energy in the power production, along with appropriate policies and regulations on the rational use of energy, is therefore very important for the achievement of a sustainable development [17–18]. The utilization of renewable energy is especially suitable for remote areas and islands [18–20]. Some countries have already increased the share of renewable energy in the energy supply [21], including strategies of 100% renewable islands.

However, when increasing the share of renewable energy, a number of problems arise in relation to the intermittent nature of renewable energy sources and the fluctuations in their intensity throughout the day. One problem is to generate enough renewable energy; another problem is to match a load that also has its own fluctuations. The outcome of fluctuations in renewable energy sources and load produces a situation in which substantial excess energy is sometimes generated, while at other moments there is a lack of generated energy. One solution to such balancing problems could be the integration of energy storages into the energy systems. The storage could vary from reversible hydro to hydrogen loops (electrolyser, fuel cell, and hydrogen storages), batteries and flywheels for medium and small systems. The storages are filled when excess energy is generated and used when there is a shortage of energy. Energy systems with heat demands also

*Corresponding author. Tel.: +45 9635 8309; fax: +45 9815 3788.
E-mail address: Lund@plan.aau.dk (H. Lund).

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doi:10.1016/j.energy.2006.10.014

have the possibility of implementing heat storage capacities in order to integrate fluctuations in renewable energy [22–24].

Such integrated approach to the utilization of renewable energy in the overall system calls for energy system analysis and optimization tools. Computer models have been developed and have become standard tools for energy planning and optimization of the energy systems that intends to increase the share of renewable energy. However, computer models are developed for different purposes, different technologies and different sizes of energy systems. HOMER is made particularly for small isolated power systems, although the model allows for grid connection. The optimization and sensitivity analysis algorithm of the model provides for the evaluation of the economic and technical feasibility of a large number of technologies and accounts for variations in costs and energy resource availability [25]. The model includes most of the relevant technologies, but not all of them. For example, the model does not support reversible hydro, which is often the cheapest way to store energy in systems of such potentials. Other models include precise physical data of specific technologies, like Hydrogems [26]. Such models are often too detailed for energy planning purposes and they often lack other relevant technologies. RETScreen software can be used for evaluating the energy production, life cycle costs and greenhouse gas emission reductions of various types of proposed energy-efficient and renewable energy technologies, but it does not provide tools for joint energy balancing with different renewable energy sources [27].

The EnergyPLAN model has been designed for national and regional analyses and is described in more detail in the following chapter. The H_2RES computer model, which is designed for simulating the integration of renewable sources and hydrogen into island energy systems, is described in detail in the third chapter. Both models use hour-by-hour calculations of energy generations and loads. This approach is necessary because of the fluctuations of renewable energy generation and energy system load. It is presumed that there are no big fluctuations in an hourly period, but if fluctuations are significant the period used for balancing should be further shortened.

2. The EnergyPLAN model

The EnergyPLAN model is a deterministic input/output simulation model. General inputs are demands, capacities and a number of optional regulation strategies, placing emphasis on import/export and excess electricity production. Outputs are energy balances and resulting annual production, fuel consumption and import/export. For a detailed description of the model, please consult [22,28].

The EnergyPLAN model is designed for the analysis of different regulation strategies of complex energy systems including district heating and electricity supply. The model is able to calculate different strategies for the optimisation of closed systems with no exchange of electricity and the optimisation of open market systems. In the latter case, the model is able to optimise import/export strategies in relation to external electricity markets with fluctuating prices.

The model has been used for analysing a number of scenarios of the integration of substantial inputs of renewable energy into the Danish electricity supply, both from a technical and a market exchange point of view [29–32].

The energy system in the EnergyPLAN model includes heat production from solar thermal, industrial CHP, CHP units, heat pumps and heat storage and boilers. Additional heat production from electric heating and heat from electrolysers/hydrolysers can be utilised. District heating supply is divided into three groups of boiler systems and decentralised and centralised CHP systems.

Additional to the CHP units, the systems include electricity production from renewable energy, i.e. photo–voltaics (PV) and wind power inputs divided into onshore and offshore, and traditional power plants (condensation plants). Meanwhile, the model can be used for calculating other renewable energy sources than wind and PV, such as, for example, wave power. Furthermore, the model can store electricity by using pumps for hydro storage or batteries and converting electricity into fuel by electrolysers.

The model requires four sets of input for the technical analysis. The first set is the annual district heating consumption and the annual electricity consumption, including flexible demand and electricity consumption from the transport sector, if any. The second set is the capacity of PV and wind power, including a moderation factor that is used in order to adjust the relationship between the wind capacity and the correlating electricity production. This part also defines solar thermal and industrial CHP heat production inputs to district heating. The third set comprises capacities and operation efficiencies of CHP units, power stations, boilers, and heat pumps. The last set specifies some technical limitations; namely the minimum CHP and power plant percentage needed by the load in order to retain grid stability. Furthermore, it includes the maximum heat pump percentage of the heat production, in order to achieve the specified efficiency of the heat pumps.

The model emphasises the consequences of different regulation strategies. Basically, the technical analyses distinguish between the two following strategies:

Regulation strategy I: meeting heat demand: In this strategy, all units are producing solely according to the heat demands. In district heating systems without CHP, the boiler simply supplies the difference between the district heating demand and the production from solar thermal and industrial CHP. For district heating with CHP, the units are given priority according to the following sequence: Solar thermal, industrial CHP, CHP units, heat pumps and peak load boilers.

Regulation strategy II: meeting both heat and electricity demands: When choosing strategy II, the export of electricity is minimised mainly by replacing CHP heat production by boilers or by the use of heat pumps. This strategy increases electricity consumption and decreases electricity production simultaneously, as the CHP units must decrease their heat production. With the use of extra capacity at the CHP plants combined with heat storage capacity, the production at the condensation plants is minimised through CHP production.

In the economic analysis, the two strategies mentioned above are moderated by a market trade strategy based on the principle of exporting when the market prices are higher than the marginal production costs and importing when the market prices are lower. In both types of strategies, the model takes a number of restrictions and limitations into consideration, such as

- degree of grid-stabilising capacity needed by the system,
- bottlenecks in transmission capacity,
- strategies for avoiding critical surplus production,
- maximum percentage of heat production from heat pump.

Here, the model has been used only for making technical calculations and not for making strategies for optimising exchange of electricity on an external market. Moreover, only calculations on electricity supply and not district heating have been included in the analysis.

As part of the work, two new possibilities of storing/converting electricity have been added to the EnergyPLAN model. The one is a hydro storage consisting of a pump, a hydro storage and a turbine. The other is an electrolyser capable of producing fuel (for example hydrogen) and heat for district heating. The hydrogen can then be used in a CHP unit (for example a fuel cell). Fuel storage can also be specified. The principle of the EnergyPLAN energy system including the two new possibilities as shown in Fig. 1.

The electricity storage is described in the model as a hydro storage consisting of the following components:

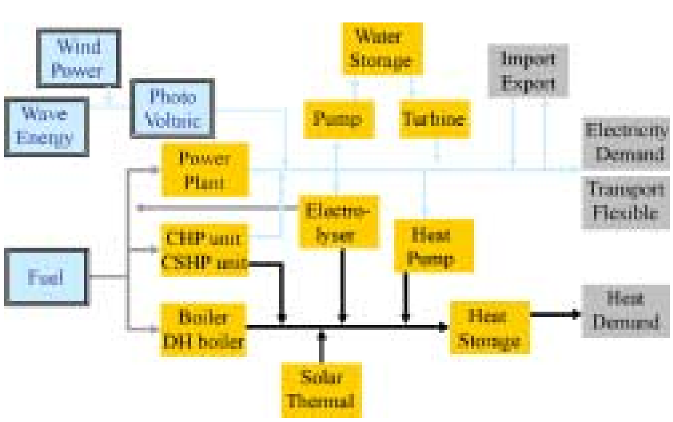

Fig. 1. EnergyPLAN scheme.

pump (converting electricity into potential energy) defined by a capacity and an efficiency; turbine (converting potential energy into electricity) defined by a capacity and an efficiency; and storage (storing energy) defined by a capacity. Meanwhile, the hydro storage can be used for modelling any kind of electricity storage, such as for example batteries.

The storage facility is regulated in the following way: the pump is used for filling the storage in the case of excess production. In such case, the space available in the storage is calculated and the electricity demand of the pump is found as the minimum value of the following three figures: the excess production, the available storage capacity divided by the pump efficiency, or the maximum capacity of the pump.

The turbine is used for emptying the storage by replacing the power plant. If the power plant is producing, the content of the storage is identified and the electricity production of the turbine is found as the minimum value of the following three figures: the electricity production of the power plant, the storage content multiplied by the turbine efficiency, or the maximum capacity of the turbine.

To correct errors created by differences in the storage content between the beginning and the end of the calculation period, the above calculation is repeated until the storage content in the end is the same as in the beginning. Initially, the storage content is defined as 50% of the storage capacity. After the first calculation, a new initial content is defined as the resulting content in the end of the former calculation. Such procedure is repeated until the difference is insignificant.

Here, the pump/turbine hydro storage has been used for modelling the electrolyser/FC H_2 storage in the case described below.

3. The H_2RES model

The H_2RES model (see Fig. 2) is designed for balancing between hourly time series of water, electricity and hydrogen demand, appropriate storages, and supply (wind, solar, hydro, diesel or mainland grid). The main purpose of the model is energy planning of islands and isolated regions which operate as stand alone systems, but it may also serve as a planning tool for single wind, hydro or solar power producers connected to bigger power systems.

Wind velocity, solar radiation, and precipitation data obtained from the nearest meteorological station are used in the H_2RES model. The wind module uses the wind velocity data at 10 m height, adjusts them to the wind turbine's hub level, and, for a given choice of wind turbines, converts the velocities into the output. The solar module converts the total radiation on the horizontal surface into the inclined surface, and then into the output. The hydro module takes into account precipitation data, typically from the nearest meteorological station, and water collection area and evaporation data based on the reservoir free surface to predict the water net inflow into

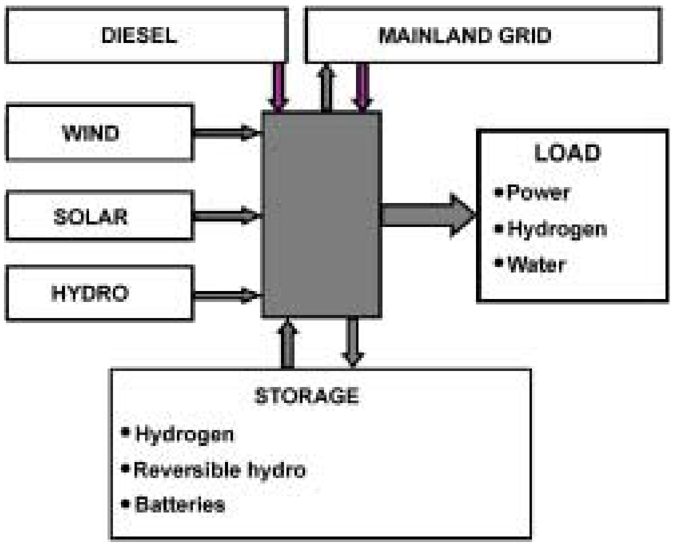

Fig. 2. H_2RES scheme.

the reservoir. The load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, integrates a part or all of the wind and solar output into the system and discards the rest of the renewable output. The excess renewable electricity is then stored either as hydrogen, pumped water or electricity in batteries, or for some non-time critical use. The energy that is stored can be retrieved later and supplied to the system as electricity or hydrogen for transport purpose. If there is still an unsatisfied electricity load, it is covered by diesel blocks or by the mainland grid where such connection exists. The model can also optimise the supply of water and hydrogen demand.

The wind module of the H_2RES system is designed for accepting up to four types of wind turbines which may be located in two different wind parks. The conversion from wind velocities to electrical output is done using wind turbine characteristics obtained from the producer. The solar module can use either data for solar radiation on a horizontal surface which then has to be adjusted for the inclination of PV array or it can use directly radiation on a tilted surface. The adjustment of solar radiation to the inclination angle is done by monthly conversion factors that are calculated by the RETScreen or the PV–GIS programme. Efficiency data for PV modules and other components (inverter, line losses, etc.) can be obtained from the producer and they serve for calculation of the hourly PV output. The hourly precipitation data of the hydro module can either be obtained from the nearest meteorological station, or can be estimated by using daily, weekly or monthly averages. Generally, the necessary resolution of the precipitation data should be depending on the storage size. Similarly, the evaporation per unit of the surface free of the reservoir should be estimated. The difference will then produce net water inflow into the storage system. The load module of the H_2RES model, based on a given hourly renewable and intermittent limit, accounts for the renewable electricity taken by the grid, and the excess production is available for storage, desalination or some other kind of dump load. The excess electricity can be exported if the island has a connection with the mainland grid. The storage module can either be based on an electrolysing unit, a hydrogen storage unit, and a fuel cell, or a hydro pumping storage, a reversible fuel cell or batteries. The input into the storage system is limited by the chosen power of the electrolyser, the pumps or the charging capacity of the batteries, so the renewable excess power which is superfluous to the storing facility or cannot be taken to the storage system because the storage is full has to be dumped or rejected. On islands, there is often also a need for the desalination of seawater, which might be a good destination of dumped load, water pumps, or refrigeration units.

4. The Island of Mljet

The Island of Mljet is situated in the southern Dalmatian archipelago, 30 km to the west of Dubrovnik and south of the Peljesac Peninsula, separated from it by the Mljet channel. Mljet is an elongated island, with an average width of 3 km, and 37 km long. The total area of the island is 1004 km^2 and the highest peak is Veli Grad (514 m). The climate is Mediterranean; the average air temperature in January is 8.7 °C and in July 24 °C. The large part of the island (72%) is covered by thick green forests of Aleppo pine, especially around the two salty lakes in the north-western part of the island which was declared a "national park" in 1960. National Park Mljet with its lakes, Malo Jezero (Small Lake) and Veliko Jezero (Big Lake) which are connected by canals to the sea, is a masterpiece of nature (see Fig. 3). The small forested island of Saint Mary in the Big Lake, within the National Park, is the setting for a Benedictine monastery of the 12th Century.

Fig. 3. National park Mljet.

In the year 2001, the Island of Mljet had a population of 1111 people. The economy is based on farming, viticulture, the cultivation of olives and medicinal herbs, fishing and tourism. The regional road (52 km) runs through the island. Mljet has ferry links with Peljesac and Dubrovnik.

The power system of the Island of Mljet is connected to the mainland grid with two undersea cables. In 2002, the peak load was 1018 kW and the annual electricity consumption was 2696 MWh. The annual increase of consumption in all calculations was set to 7%. Fig. 4 represents the load curve for the year 2002.

A wind (Fig. 5) and solar radiation (Fig. 6) represent the most promising renewable energy sources on the Island of Mljet. On the Island, there is a small meteorological station, but it does not have the necessary equipment for measuring the hourly average wind speed and solar radiation. Therefore, the data used in the energy models have been obtained from the meteorological station in Dubrovnik and they have been adjusted for the Island of Mljet.

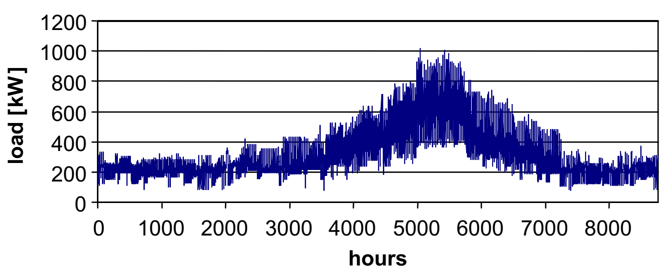

Fig. 4. Hourly average electricity system load, 2002.

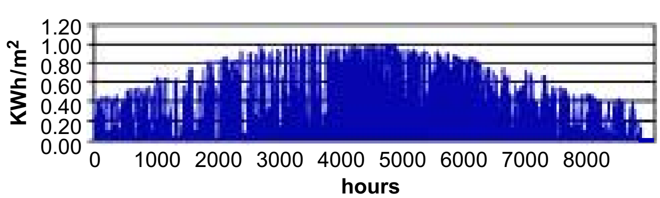

Fig. 5. Hourly average solar radiation intensities on horizontal surface, Dubrovnik.

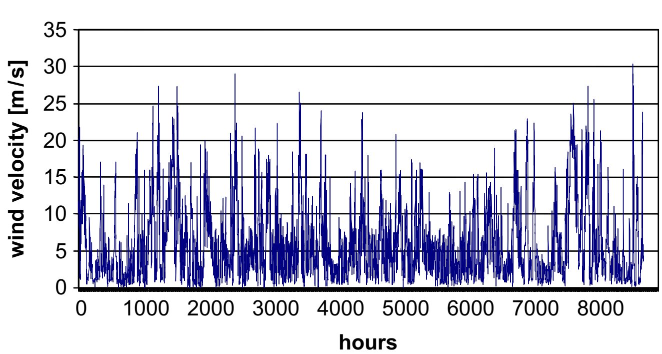

Fig. 6. Hourly average wind velocities at 10 m height, Mljet.

5. Results

Eighteen different scenarios of Mljet have previously been calculated by use of the H_2RES model for the years 2005, 2010 and 2015 [33]. The same scenarios have been calculated by use of the EnergyPLAN model for the year 2010. The results are very much alike. For practical reasons, three scenarios have been chosen for more detailed analyses. The three scenarios are shown in Table 1. All three scenarios represent systems in which 100 per cent of the electricity demand comes from renewable energy sources. The system optimization (number and size of wind turbines and installed power of PV, size of hydrogen storage, fuel cell and electrolyser) has been done by the H_2RES model. The excess of electricity, could not be stored because of the limited capacity of the electrolyser or the hydrogen storage, could be exported to the mainland grid. In all the presented scenarios, the amount of exported electricity was kept close to 30% of the annual renewable energy source (RES) potential.

Scenario 6 has not integrated any energy storage, so for given optimization conditions, 50 per cent of the consumption is covered by RES and the rest is covered by the mainland grid. Scenario 12 has integrated a hydrogen loop and represents a 100 per cent renewable scenario concerning the electricity demand. Scenario 18 represents the same situation. It only differs by adding hydrogen load for transport, so it is a 100 per cent renewable scenario concerning both electricity and transport. The annual electricity generation of the three scenarios calculated on both models is presented in Fig. 7.

6. Conclusion

The EnergyPLAN and the H_2RES models both focus on the integration of fluctuating renewable energy sources into the energy supply. Both models calculate each hour during a period of 1 year. However, the models have three main differences: First, the H_2RES model focuses on small islands, while the EnergyPLAN model focuses on large regions. Second, the H_2RES model focuses on technical analyses, while the EnergyPLAN model includes both technical and market exchange analyses. Finally, the H_2RES model includes only the electricity supply, while the EnergyPLAN model also includes the district heating supply. Consequently, the EnergyPLAN model has been used for calculating technical scenarios including only electricity supply.

On the other hand, the H_2RES model contains the following three possible technical solutions to the integration of RES: hydrolyses, batteries and pump storage. Such technologies have not previously been part of the EnergyPLAN model, and consequently, the model has been expanded to include such technologies as part of the work.

Table 1
H2RES and EnergyPLAN results for three different scenarios for 2010

	Model:	H_2RES			EnergyPLAN		
	Scenario:	6	12	18	6	12	18
Input:							
Demand	MWh/yr	4633	4633	4633	4633	4633	4633
Transportation[b]	MWh/yr			290			290
Wind	kW-inst.	733	1160	1160	733	1160	1160
Photo-voltaics	kW-peak	1199	7820	8330	1199	7820	8330
RES-limit	Per cent	100	100	100			
Min.stab.load	Per cent				0	0	0
Electrolyser[c]	kw		4000	4000		4000	4000
Fuel cell[d]	kw		1800	1800		1800	1800
Grid/power plant	kw	7676	7676	7676	7676	7676	7676
H2 storage	kWh		1,87,500	2,16,000		1,87,500	2,16,000
Results:							
RES:	Potential	3.33	12.42	13.04	3.33	12.49	13.11
(GWh/yr)	Rejected	1.01	0.00	0.00	1.02	0.00	0.00
	Stored[a]	—	0.04	0.03	—	0.00	0.00
Generation:	Wind	1.06	2.92	2.92	1.04	2.98	2.98
(GWh/yr)	PV	1.26	9.50	10.12	1.27	9.51	10.13
	Grid/PP	2.31	—	—	2.33	—	—
	FC	—	1.69	1.68	—	1.69	1.89
	Total	4.63	14.11	14.72	4.64	14.18	15.00
Consumption:	Demand	4.63	4.63	4.63	4.63	4.63	4.92
(GWh/yr)	Electrol	—	5.76	6.18	—	5.63	6.29
	Export	—	3.73	3.92	—	3.91	3.78
	Total	4.63	14.12	14.73	4.63	14.17	14.73
Key figures:	RE supp	50	268	282	50	270	283
(% of demand)	Excess	22	81	85	22	84	82
	Loss	100	386	403	100	391	406

[a]Potential electricity production from stored H_2, i.e. stored H_2 multiplied by efficiency of FC.
[b]H_2 demand for transport defined in electric input for H_2 production.
[c]Electrolyser efficiency = 0.6 in all calculations.
[d]FC efficiency = 0.5 in all calculations.

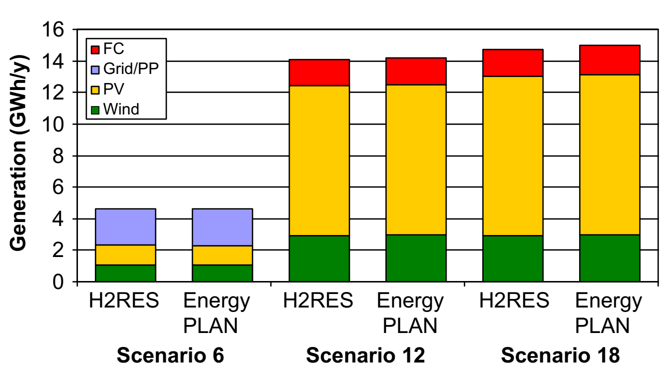

Fig. 7. Annual electricity generation for 2010.

Within the framework of making technical analyses of the electricity supply, the two models only have the following minor differences:

- When setting the limits for the allowed rate of electricity production from fluctuating sources at a certain hour, the H_2RES model defines a limit in per cent of the demand. Instead, the EnergyPLAN model defines a minimum share of the production, which must come from units able of supplying ancillary services and thereby stabilise voltage and frequencies in the electricity supply.
- When using H_2 storage, both models have to deal with the issue of an eventual difference in the stock between the beginning and the end of the calculation. The H_2RES allows for such difference and provides the possibility of defining initial storage content. The EnergyPLAN model determines by iteration a solution in which the initial storage content is set so that the final content becomes exactly the same. Consequently, the EnergyPLAN model does not demonstrate any differences between the stock in the beginning and the end of the calculation.
- When defining how to use H_2 for transportation the H_2RES model tells the fuel cell not to operate when the amount of hydrogen is lower than the amount needed for the transportation supply. The EnergyPLAN

model simply denies an extra electricity demand for transportation.

The computer models are valuable tools for energy balancing and energy planning, particularly for calculating energy systems with integrated renewable energy sources. By using the models, the share of renewables in the energy system can be significantly increased without unnecessary or unexpected costs. As shown in the case of Island of Mljet, by using both computer models, Mljet can become a 100% renewable island concerning the electricity consumption and hydrogen transport.

The EnergyPLAN model has been improved through the work on this paper and by inspiration of the H_2RES model. Even though the two models have different focuses and historical backgrounds, they can both be improved by mutual inspiration. Furthermore, both models come to more or less the same results when analysing the same cases.

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