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Lund, Henrik; Goran Krajacic, Neven Duic; da Graca Carvalho, Maria

Published in:
3rd Dubrovnik conference on sustainable development of energy, water and environment systems

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

Two Sustainable Energy System Analysis Models. A comparison of methodologies and results

Henrik Lund*
Department of Development and Planning
Aalborg University, Denmark
e–mail: lund@plan.aau.dk

Neven Duić, Goran Krajačić
Power Engineering Department
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e–mail: Neven.Duic@fsb.hr

Maria da Graça Carvalho
Research Group on Energy and Sustainable Development
Department of Mechanical Engineering
Instituto Superior Técnico, Lisbon, Portugal
e–mail: maria@navier.ist.utl.pt

ABSTRACT

This paper presents a comparative study of two energy system analysis models both designed with the purpose of analysing electricity systems with a substantial share of fluctuating renewable energy.

The one 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 analyses has mostly been conducted for Denmark, which already today has a CHP share of 50 percent and a wind power share of approximately 20 percent of the electricity demand. The model has been used to investigate new operation strategies as well as investments in flexibility in order to utilise wind power and avoid excess production.

The other model (H2RES) has been designed to simulate the integration of renewable sources and hydrogen into island energy systems. The H2RES model can use wind, solar and hydro as renewable energy sources and Diesel blocks as back up. The load in the model can be represented by hourly and deferrable electricity load of power system, by hydrogen load for transport and water load depending on water consumption. The H2RES model has also integrated hydrogen loop (fuel cell, electrolyser and hydrogen storage) in order to increase the penetration of intermittent renewable energy sources or to achieve 100% renewable island. Beside the hydrogen storage, H2RES supports batteries and reversible hydro as energy storages. The latest version of H2RES model has integrated grid connection with 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 the methodologies and results of mutual benefits and with the purpose of identifying improvements of both models.

* Corresponding author

INTRODUCTION

Utilization of renewable energy has become an important objective of many countries and government's around the world [1-4]. Renewable energies provide for a clean and sustainable approach to energy production, it helps to ensure security of energy supply [5] and it helps in meeting Kyoto Protocol objectives[6-9]. Integration of renewable energy for power production, along with appropriate policies and regulations on the rational use of energy, is therefore very important for achieving sustainable developments [10]. Utilization of renewable energy is especially suitable for remote areas and islands [10-12]. And some countries have already increased the share of renewable energy in the energy supply [13], including strategies of 100 percent renewable islands.

However, increasing the share of renewable energy raises a number of problems related to the intermittent nature of renewable energy sources and fluctuations in their intensity throughout the day. One problem is to generate enough renewable energy, another problem is to match a load which also has its own fluctuations. The outcome of fluctuations in renewable energy sources and load results in a situation, in which sometimes substantial excess is generated while at other moments there is a lack of generated energy. One solution for such balancing problem 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 there is excess of generated energy and used when there is a shortage. Energy systems with heat demands also has the possibility to implement heat storage capacities to integrate fluctuations in renewable energy [14].

Such integrated approach to the utilisation of renewable energy into 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 energy systems which try to increase the share of renewable energy. However, computer models are developed for different purposes and for different technologies and temp to focus on 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 serves for evaluation of the economic and technical feasibility of a large number of technologies and account for variations in costs and energy resource availability [15]. The model include most of the relevant technologies, but not al 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 details of specific technologies, like Hydrogems [16]. Such models are often too detailed for energy planning purposes and often lack other relevant technologies. RETScreen software can be used to evaluate the energy production, life-cycle costs and greenhouse gas emission reductions for various types of proposed energy efficient and renewable energy technologies but it does not provides tools for joint energy balancing with different renewable energy sources [17].

The model EnergyPLAN has been designed for national and regional analyses and it is described in more detail in following chapter. The H_2RES computer model, which is designed to simulate 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 fluctuations of renewable energy generation and energy system load. It is presumed that there are no big fluctuations in one hour period, but if fluctuations are significant the used period for balancing should be even smaller.

THE EnergyPLAN MODEL

The EnergyPLAN model is a deterministic input/output simulation model. General inputs are demands, capacities and the choice of a number of different regulation strategies, putting 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 [13, 18].

The EnergyPLAN model is designed to analyse different regulation strategies of complex energy systems including district heating as well as electricity supply. The model is able to calculate different strategies for the optimisation of closed systems with no exchange of electricity as well as 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 to analyse a number of scenarios of the implementation of substantial inputs of renewable energy into the Danish electricity supply both form a technical point of view as well as from a market exchange point of view [19-22].

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 form 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. photovoltaic and wind power input divided into onshore and offshore, as well as traditional power plants (condensation plants). Meanwhile the model can be used to calculate other renewable energy sources than wind and PV, such as for example wave power. And the model can store electricity by using pumps for hydro storage or batteries as well as converting electricity to 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 consumption of electricity, including flexible demand and electricity consumption from the transport sector, if any. The second set is the capacity of photovoltaic and wind power, including a moderation factor, in order to adjust the relationship between the wind capacity and the correlating electricity production. Also this part defines solar thermal, industrial CHP heat production inputs to district heating. The third set is capacities and operation efficiencies of CHP units, power stations, boilers and heat pumps. And the last set specifies some technical limitations; namely the minimum CHP and power plant percentage of 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, 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 by replacing it with 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:

- the system needs a certain degree of grid-stabilising capacity
- 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 to make technical calculations and not to make strategies to optimise exchange of electricity on an external market. Additional only calculations on electricity supply and not district heating has been included into the analysis.

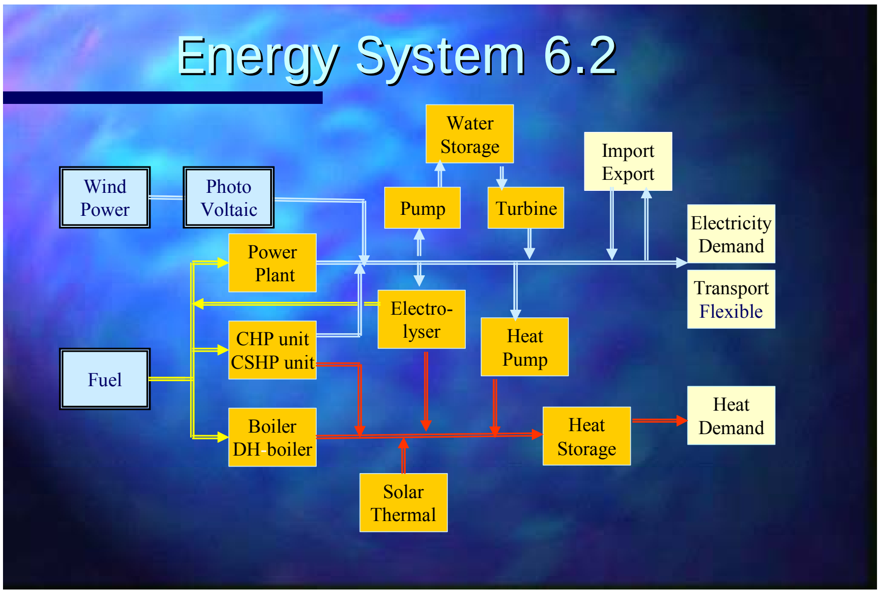

Fig. 1. EnergyPLAN scheme

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, hydro storage and a turbine. And the other is an electrolyser able 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). Also a fuel-storage can be specified. The principle of the EnergyPLAN energy system including the two new possibilities is show in the diagram.

The electricity storage is described in the model as a hydro-storage consisting of the following components: Pump (converting electricity to potential energy) defined by a capacity and an efficiency; Turbine (converting potential energy to electricity) defined by a capacity and an efficiency; Storage (storing energy) defined by a capacity. Meanwhile the hydro-storage can be used to model any kind of electricity storage such as for example batteries.

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

The turbine is used to empty 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 numbers: The electricity production of the power plant, the storage content multiplied by the turbine efficiency, or the maximum capacity of the turbine.

To correct the calculations from errors due to 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 beginning content is defined as the resulting content in the end of former calculation. Such procedure is repeated until the difference is insignificant.

Here the pump/turbine hydro storage has been used to model the electrolyser/FC H2-storage in the case described below.

THE H_2RES MODEL

The H_2RES model 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 model is energy planning of islands and isolated regions which operate as stand alone systems but it can also serve as planning tool for single wind, hydro or solar power producer connected to bigger power system.

Wind velocity, solar radiation and precipitation data obtained from nearest meteorological station are used in H_2RES model. The wind module uses the wind velocity data at 10 m height, and adjusts them to the wind turbines hub level and for a given choice of wind turbines, converts the velocities to the output. The solar module converts the total radiation on the horizontal surface to the inclined surface, and then to 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 the reservoir. Load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, puts a part or all of wind and solar output into the system and discards the rest of the renewable output. The excess of 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 unsatisfied electricity load it is covered from Diesel blocks or from mainland grid where such connection exists. The model can also optimise the supply of water and hydrogen demand.

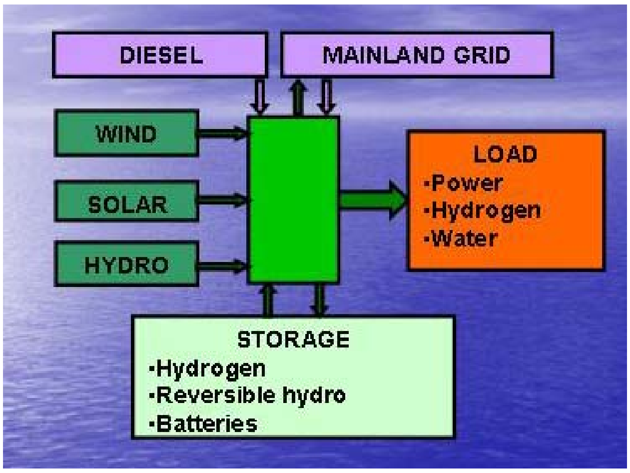

Fig. 2. H_2RES scheme

The wind module of H_2RES system is designed to accept 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 horizontal surface which than have to be adjusted for inclination of PV array or it can use directly radiation on tilted surface. The adjustment of solar radiation to inclination angle is done by monthly conversion factors which are calculated by RETScreen or PV-GIS program. Efficiency data for PV modules and other components (inverter, line losses, etc.) can be obtained from producer and they serve for calculation of the hourly PV output. For the hydro module hourly precipitation data can be either obtained from the nearest meteorological station, or can be estimated 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 free surface 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 is available for storage, desalination or some other kind of dump load. The excess of electricity can be exported if island has a connection with mainland grid. The storage module can be either based on an electrolysing unit, hydrogen storage unit, and a fuel cell, or hydro pumping storage, reversible fuel cell or batteries. The input into the storage system is limited with the chosen power of electrolyser, pumps or batteries charging capacity, so the renewable excess power that is even superfluous to the storing facility, or cannot be taken to the storage system because the storage is full, has to be dumped or rejected. In islands there is also often need for desalination of seawater, which might be a good destination of dumped load, or water pumps, or refrigeration units.

THE ISLAND OF MLJET

The Island of Mljet is situated in southern Dalmatian archipelago, 30 km west from 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, 37 km long, total area of island is 100,4 km^2 and the highest peak is Veli Grad (514 m). The climate is Mediterranean; an average air temperature in January is 8.7 °C and in July 24 °C. The large part of the island (72%) is covered with thick green forests of Aleppo pine, especially around the two salty lakes in the north-western part of island which has been declared as "national park" since 1960. National Park Mljet (Fig. 3) with its lakes, Malo Jezero (Small Lake) and Veliko Jezero (Big Lake) which are connected by canals to the sea, are nature's masterpieces. Small forested island of Saint Mary in the Big Lake, within the National Park, is a setting for a 12th century Benedictine monastery.

Fig. 3. National park Mljet

In the year 2001 the Island of Mljet had population of 1111 people. Economy is based on farming, viticulture, production of wine, olive growing, cultivation of medicinal herbs, fishing and tourism. The regional road (52 km) runs throughout the island. Mljet has ferry lines with Peljesac and Dubrovnik.

The power system of Island of Mljet is connected to the mainland grid with two undersea cabels. In year 2002 the peak load was 1018 kW and yearly electricity consumption of 2,696 MWh. The yearly increase of consumption in all calculations was set to 7 %. Figure Fig. 4 represents load curve for year 2002.

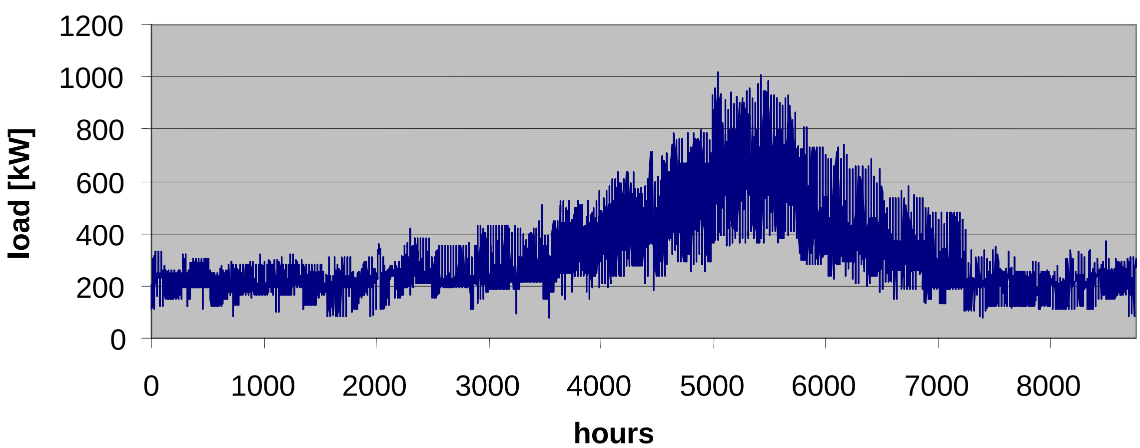

Fig. 4. Hourly average electricity system load, 2002.

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

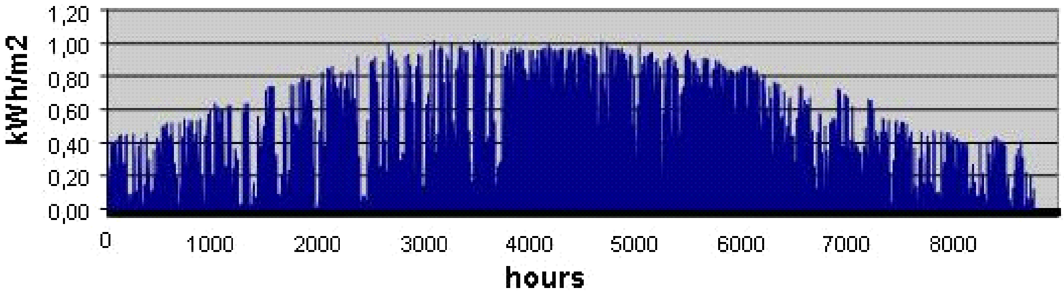

Fig. 5. Hourly average solar radiation intensities on horizontal surface, Dubrovnik

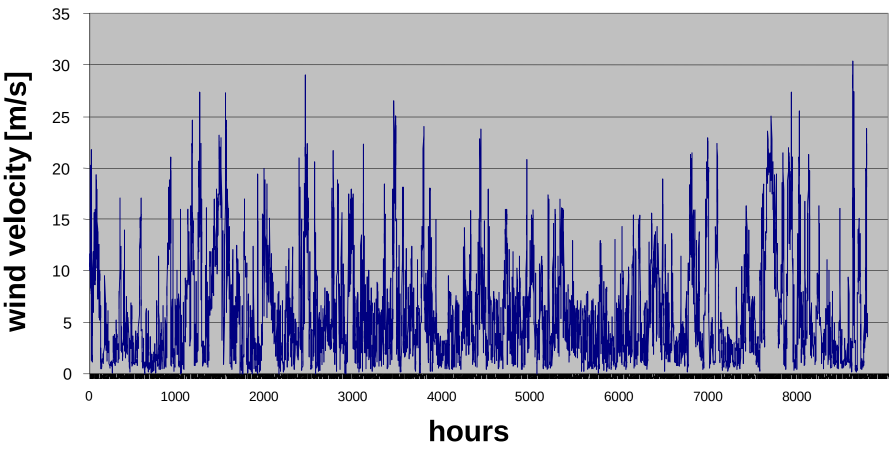

Fig. 6. Hourly average wind velocities at 10 m height, Mljet

RESULTS

Eighteen different scenarios of Mljet have previously been calculated on the H_2RES model for the years 2005, 2010 and 2015 [23]. All the same scenarios have been calculated on the EnergyPLAN model for year 2010. And 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 where 100% of electricity in satisfying the demand can come 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 H_2RES model. The extra excess of electricity which could not be stored because of limited capacity of electrolyser or hydrogen storage could be exported to the mainland grid. In all presented scenarios the amount of exported electricity was kept close to 30% of yearly RES potential.

The scenario 6 does not have integrated energy storage, so for given optimization conditions 50% of consumption is satisfied from RES and rest is covered from the mainland grid. The scenario 12 has integrated hydrogen loop and it represents 100% renewable scenario concerning the electricity, the scenario 18 represents same situation and the only difference is that it has added hydrogen load for transport so it is 100% renewable scenario concerning both, the electricity and transport. The yearly electricity generation for three scenarios calculated on both models is presented on **Fig. 7**.

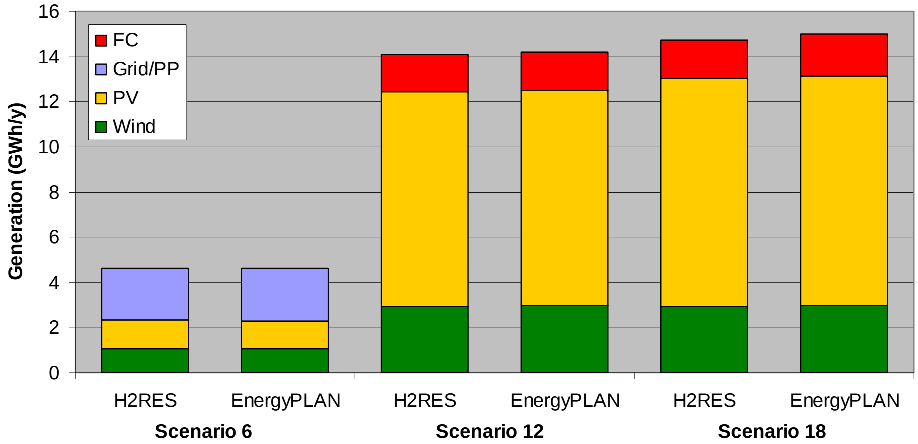

Fig. 7. Yearly electricity generation for 2010

Table 1. H_2RES and EnergyPLAN results for three different scenarios for 2010

	Model:	H_2RES			EnergyPLAN		
	Scenario:	6	12	18	6	12	18
Input:							
Demand	MWh/y	4633	4633	4633	4633	4633	4633
Transportation**)	MWh/y			290			290
Wind	kW-inst.	733	1160	1160	733	1160	1160
Photo voltaic	kW-peak	1199	7820	8330	1199	7820	8330
RES-limit	Percent	100	100	100			
Min.stab.load	Percent				0	0	0
Electrolyser ***)	kW		4000	4000		4000	4000
Fuel Cell ****)	kW		1800	1800		1800	1800
Grid / power plant	kW	7676	7676	7676	7676	7676	7676
H2-storage	kWh		187500	216000		187500	216000
Results:							
RES:	Potential	3.33	12.42	13.04	3.33	12.49	13.11
(GWh/y)	Rejected	1.01	0.00	0.00	1.02	0.00	0.00
	Stored *)	-	0.04	0.03	-	0.00	0.00
Generation:	Wind	1.06	2.92	2.92	1.04	2.98	2.98
(GWh/y)	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/y)	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*

*) Potential electricity production from stored H_2, i.e. stored H_2 multiplied by efficiency of FC.
**) H_2 demand for transport defined in electric input for H_2 production.
***) Electrolyser efficiency = 0.6 in all calculations.
****) FC efficiency=0.5 in all calculations.

CONCLUSION

The EnergyPLAN and the H_2RES models do both have a focus on the integration of fluctuating renewable energy sources into the energy supply. And both models calculate each hour during a period of one year. Meanwhile, the models have three main differences: The first is that the H_2RES focus on small Islands while the EnergyPLAN model focuses on large regions. The second is that the H_2RES focus on technical analyses while the EnergyPLAN include both technical as well as market exchange analyses. And finally the H_2RES model includes only the electricity supply while the EnergyPLAN includes the district heating supply as well. Consequently, here the EnergyPLAN model has been used to calculate 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.

Within the frame work of making technical analyses on the electricity supply the two models have only small differences, which are:

- When setting limits for how much electricity production from fluctuating sources are allowed in a certain hour, the H_2RES model defines a limit in percent of the demand. The EnergyPLAN model instead 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 has do deal with the issue of eventual difference in the stock between the beginning and the end of the calculation. The H_2RES allows for such difference and provide the possibility of defining initial storage content. The EnergyPLAN model determine 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 has no difference.
- 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 needed for the transportation supply. The EnergyPLAN model simply dines an extra electricity demand for transportation.

The computer models are valuable tools for energy balancing and energy planning, particularly for calculating of energy systems with integrated renewable energy sources. By using them the share of renewables can be significantly increased with out unnecessary or unexpected costs. As it has been shown in case of Island of Mljet with using the both computer models it was proven that Mljet can become the 100% renewable island concerning the electricity consumption and hydrogen transport.

The EnergyPLAN have been improved by the work on this paper and from inspiration of the H_2RES model. Even though the two models have different focus and historical background they have been able to inspire one and each other for improvements. Also they have been able to come to more or less the same results when analysing the same cases.

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