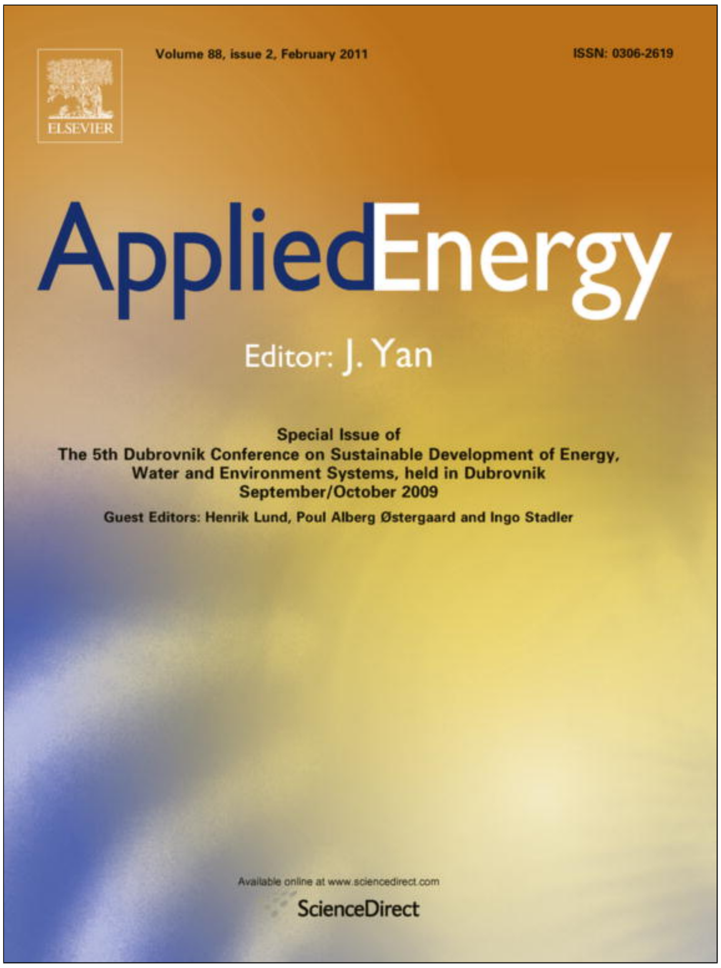
Volume 88, issue 2, February 2011
ISSN: 0306-2619
ELSEVIER
AppliedEnergy
Editor: J. Yan
Special Issue of
The 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik
September/October 2009
Guest Editors: Henrik Lund, Poul Alberg Østergaard and Ingo Stadler
Available online at www.sciencedirect.com
ScienceDirect

Applied Energy 88 (2011) 508–517

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

How to achieve a 100% RES electricity supply for Portugal?

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ARTICLE INFO

Article history:
Received 11 September 2009
Received in revised form 6 September 2010
Accepted 7 September 2010

Keywords:
Renewable energy
H_2RES
Sustainable energy planning
Energy storage
100% Renewable systems
Portugal

ABSTRACT

Portugal is a country with an energy system highly dependent on oil and gas imports. Imports of oil and gas accounted for 85% of the country's requirements in 2005 and 86% in 2006. Meanwhile, the share of renewable energy sources (RES) in the total primary energy consumption was only 14% in 2006. When focusing only on electricity production, the situation is somewhat better. The share of RES in gross electricity production varies between 20% and 35% and is dependent on the hydropower production in wet and dry years. This paper presents, on a national scale, Portugal's energy system planning and technical solutions for achieving 100% RES electricity production. Planning was based on hourly energy balance and use of H_2RES software. The H_2RES model provides the ability to integrate various types of storages into energy systems in order to increase penetration of the intermittent renewable energy sources or to achieve a 100% renewable island, region or country. The paper also represents a stepping-stone for studies offering wider possibilities in matching and satisfying electricity supply in Portugal with potential renewable energy sources. Special attention has been given to intermittent sources such as wind, solar and ocean waves that can be coupled to appropriate energy storage systems charged with surplus amounts of produced electricity. The storage systems also decrease installed power requirements for generating units. Consequently, these storages will assist in avoiding unnecessary rejection of renewable potential and reaching a sufficient security of energy supply.

1. Introduction

Sustainability is becoming the major goal in many communities. One of the crucial tasks in reaching sustainability is solving the problem of how to ensure adequate energy for development from locally present resources and cost effectiveness. This becomes even more important as the era of cheap fossil fuels is nearing the end due to limited resources, a large increase in consumption in the developing world and complex political situations in the regions rich in fossil fuels (oil and natural gas). In this situation, a mix of renewable energy sources distributed around the world appears to be a promising sustainable solution.

The utilization of renewable sources is interesting to communities that did not have access to fossil fuels and where the economy of scale cannot be applied. Consequently, renewable technologies are the only solution for meeting energy needs. Islands and rural communities represent such places with many of them setting up goals to supply 100% of their energy needs from renewable sources. Numerous calculations have been undertaken using proposed different renewable energy solutions for transforming the islands to independent sustainable energy systems. Calculations and scenarios for the Porto Santo Island, Portugal and Mljet Island, Croatia are given in [1–5].

In the EU, there is strong political, public and economic support for all renewable energy technologies. Directive 2001/77/EC aims to meet 12% of electricity production from RES by 2010 and the new RES directive 2009/28/EC is setting the RES target for 2020 at 20% of gross energy consumption. The most recent initiatives have already begun the process of transforming EU's energy supply to 100% RES. On the 15th April 2010, RE-thinking 2050 [6] was launched in the European Parliament under the patronage of Maria da Graça Carvalho, a member of the European Parliament. The European Renewable Energy Council (EREC) outlines the process, towards a 100% renewable energy system for the EU, as the only sustainable option in economic, environmental and social terms. Prior to this initiative, the idea to ensure 100% renewable energy supply on a larger scale and in the larger communities has been tackled by INFORSE – the International Network for Sustainable Energy. INFORSE has developed the Vision2050 models for global, regional and national scales. These models demonstrate the way

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doi:10.1016/j.apenergy.2010.09.006

large societies can eventually supply 100% of their energy needs from renewable sources by 2050 [7].

The design of a 100% RES system with an optimal mix of energy sources under the current policy is a challenge faced by many energy planners and policy makers. A discussion on what constitutes a 100% RE system and how it may be assessed is presented in this paper [8], where a series of optimisation criteria are reviewed and subsequently applied to an energy system model of Western Denmark. This optimisation may be implemented in accordance with economic objectives or by focusing on technical and operational aims and within these two main groupings, several different criteria may be applied to the design process. Economic optimisation criteria include for instance, total energy system costs, capacity costs and the costs to society. From a technical and operational perspective, optimisation criteria include fuel savings, CO_2 emissions, reserve/back-up capacity, required condensing mode power generation, minimisation of import/export, and the elimination of excess power generation. All of these criteria can be applied in assessing how well a system integrates renewable energy [8]. In addition to these criteria, systems may be analysed in either island mode or connected to surrounding areas. The same author proposes multi-criteria analyses as a solution for optimisation, since it may better reflect the diversity of considerations faced by decision-makers by considering several criteria. However, the methodology still requires the user to quantify preferences by assigning weights to different criteria and establishing a procedure for normalisation [8].

Authors in [9,10] using the case of Denmark, discuss the problems and perspectives of converting current energy systems into 100% renewable energy systems. The conclusion obtained is that this development is possible. The necessary renewable energy sources are currently available. The renewable energy system can be created if further technological improvements in the energy system are carried out [10]. The paper [9] presents the use of 100% RES system in large communities and countries. In this case Denmark will have to consider to which degree the country shall rely mostly on biomass resources, which will involve the present use of farming areas, or mostly on wind power, which will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design. In terms of methodology, the conclusion is that the future design of a 100% renewable energy system is a very complex process. A broad variety of measures must be combined in order to reach the target and each individual measure must be evaluated and coordinated with the new overall system. The authors' success in calculating a 100% RES was based on an innovative democratic process that combines a creative phase involving contribution by a number of experts and a detailed analytical phase coinciding with technical and economic analyses of the overall system. In a forward and backward process, each proposal was formed by combining the best detailed expert knowledge and the possibility of the proposal fitting properly into the overall system, in terms of technical innovation, an efficient energy supply and socio-economic feasibility [9].

Beside economic issues, technical problems challenging systems that are to become 100% renewable mostly relate to intermittency issues and matching fluctuations in demand, since RES sources (wind, solar and wave) are not controllable and display an intermittent behaviour even on minute or hourly levels. Other sources like hydropower and biomass are not intermittent but are more variable on a seasonal level.

In [11], the authors studied the management of surplus electricity production (SEP) from a fluctuating renewable energy source while in [12] the author analysed the ability of different energy systems and regulation strategies to integrate wind power input from 0% to 100% of electricity demand. Large-scale optimal integration of wind, solar and wave power is described in [13].

In [14], the authors introduce the principle of storage and relocation in an energy system design, and propose that the storage and relocation potential of a technology option be found by comparing options according to the respective storage and relocation coefficient. They also propose a new generation of energy systems such as the CHP plant equipped with a heat pump and cold storage, recommending that it be integrated with the production of transport fuels and mobility sector. A similar problem is tackled in [8], where the author analyses the manner in which wind power can be expanded to satisfy 20–40% of the demand by using heat pumps for integration. Heat pumps are not the only technology that can assist in integrating wind power, however the pumps are moderately priced and are an energy efficient technology. This is in contrast to costly electricity storage technologies based on, for instance, vanadium redox batteries or hydrogen, which also have poor cycle efficiencies. Technologies such as compressed air energy storages (CAES) have yet to be proven economically attractive as demonstrated by Ref. [15]. The modelling of the Denmark energy system, in papers [8–15] is done on an hourly basis by using the energy planning tool EnergyPlan, a computer program that can be used for planning 100% RES systems. The authors in [16] make a comparison of various models used in the planning and simulation of 100% RES systems. The authors reviewed 37 tools and provided adequate information necessary in identifying a suitable energy tool for analysing the integration of renewable energy into various energy systems under different conditions.

The current Portuguese energy policy is not directed towards building a 100% RES system, but is steadily moving towards it. It aims to make renewable sources contribute to 60% of electricity generation by 2020, providing the expected results of the strategy: surpassing 7000 MW of hydroelectric capacity; increasing the installed wind energy capacity to 8500 MW by 2020, and increasing the installed solar energy capacity to 1500 MW over the same period [17].

The purpose of this paper is to present a possible solution for introducing a 100% renewable electricity supply in Portugal and in determining how the H_2RES energy-planning model should be used in calculating larger power systems.

2. The H_2RES computer programme

The H_2RES model is designed to support the Renewislands methodology [1] and is primarily used in balancing the hourly time series for water, electricity, heat and hydrogen demand, as well as appropriate storages and supply. The main purpose of the model is energy planning on islands and in isolated regions, which operate as stand-alone systems, but can also serve as a planning tool for power producers utilizing renewable energy sources connected to larger power systems. Over time, the model has evolved and several new modules have been developed such as wave, biomass, solar heat and desalination modules.

Several papers describe the H_2RES model with its detailed operation [1–3,5]. The main characteristic of the H_2RES model is that it uses technical data from equipment, hourly meteorological data for intermittent sources and according to the description in [3], energy balancing is regulated using equations.

The version that has been used for calculating 100% RES electricity production in Portugal has been updated with the wave module that is able to calculate wave power production at 17 different locations.

The wave module contains two main parts, wave data and the wave power matrix. Wave data is described by two wave parameters, i.e. significant wave height and the wave energy period or power period. For each hour, the values of these two parameters are used to interpolate power output from wave generator's power matrixes. Currently, the model uses only the power matrix from Pelamis energy converters [18] but can be easily adopted for other machines.

The H_2RES model is further improved to calculate energy from run-of-river hydro power plants separately from storage hydro plants. In order to avoid energy losses, all water flow is utilized, meaning that all the energy from run-of river plants is firstly taken by the system as it is presumed that these plants do not have large storages and thus neither the capability to store or control water flow for more than a few hours.

The H_2RES model can calculate interconnections with other power systems, but exporting electricity is only possible when 100% intermittent penetration is allowed. This possibility has been altered for calculations relating to Portugal in order to allow the exporting of surplus intermittent electricity but under the assumption that a certain amount of regulation will be ensured from the exported side. Exporting above the penetration limit is possible and has been proven in practice as wind power alone accounts for more than 100% of the electricity demand in the Western Denmark area or more than 50 h in 2007 [8]. The reduction in necessary capacity credits is relevant in thermal systems, and it is typically even more important in renewable energy-based systems, in which fluctuations are to a large extent uncontrollable. This makes interconnected systems an interesting option for integrating electricity produced from RES. The integration of fluctuating renewable energy by means of interconnection relies on either the magnitude of the system into which the renewable energy source is integrated or the natural variability of production and demand in the larger area of which the system forms [19]. In [8] the author has investigated the best approach for system analysis, island mode, connected mode or connected island mode and concluded that designing a system functioning in island mode enables system operators to decide freely whether to import or export, rather than being forced into making decisions due to external non-controllable factors. In another study, the possibility of wind energy replacing installed conventional generation capacities is investigated. The results indicate that existing data does not provide clear evidence of a significant capacity credit of wind energy in Germany solely based on the geographic and metrological wind availability [20]. This could be increased significantly by adding storage facilities in the form of pumped hydro storage or by aggregating larger geographic areas through interconnections.

3. H_2RES and its application in power systems in Portugal

Portugal's power system is based on thermal power units, which mostly use fossil fuels as primary energy sources. The total installed capacity amounting to 13.6 GW in 2006 comprises 5.8 GW from thermal power plants with an additional capacity of 1.3 GW from thermal power plants classified as producers with special status (PRE), such as CHP and in smaller amounts waste, biomass, and biogas facilities [21]. In total, 53% of the installed capacity comes from thermal units. The installed power in hydro power was also high, i.e. 4.6 GW with an additional 365 MW from hydro power plants acting as special producers (smaller plants) totalling 36% of the installed power capacity. The remaining installed power generating capacity amounting to 11% or 1.6 GW, is derived from the wind power plants whereas a very small amount or 3.4 MW relates to installed solar photovoltaics [22].

3.1. Power consumption and production

Total power demand in 2006 was 49,176 GW h, an increase of 2.6% with respect to 2005 [21]. Yearly power production according to type of technology and fuel is presented on Fig. 1, while Fig. 2 presents the same data on weekly basis for 2006. PRE represents special status generation, producers such as wind, biomass, CHP, small hydro.

3.2. Application of the H_2RES model

3.2.1. Power load

Real hourly data from 2006 has been used (see Fig. 3 [23]) for hourly balancing of the power system in Portugal. The peak load in 2006 was 8777 MW with the lowest off-peak value at 3171 MW.

3.2.2. Thermal power plants

Installed power from thermal power plants has been inserted into H_2RES according to [21]. Based on the type of fuel used, power plants had the following installed power: 1776 MW for coa1, 1476 MW for fuel oil, 236 MW for fuel oil and natural gas, 197 MW for gas oil and 2166 MW for natural gas. Installed capacity from waste, biomass and biogas power plants was removed from the installed capacity from PRE producers [22] and were treated in the H_2RES model separately using the biomass module.

3.2.3. Wind power

Wind data, used in the H_2RES model, is mostly collected from the reports [22,24]. Total installed power in 2005 amounted to 1047 MW compared to 1681 MW in 2006. Similar to data presented in Fig. 4, Portugal has been divided into six continental (onshore) areas called Faro, Lisbon, Coimbra, Viseu, Braga, and Bragamca, and two offshore areas, Sagres and Peniche. For these locations, the hourly wind speed necessary for the calculations has been obtained from the METEONORM program [25]. Since this program uses wind speeds that are measured at meteorological stations which are mainly installed in urban or hidden places and not at the wind turbine sites, a necessary wind speed adjustment has been applied using monthly correction factors defined

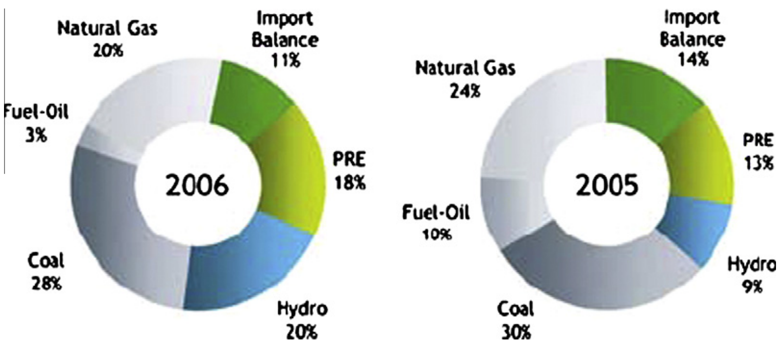

Fig. 1. Power supply in 2006 and 2005 per type of fuel and production technology [21].

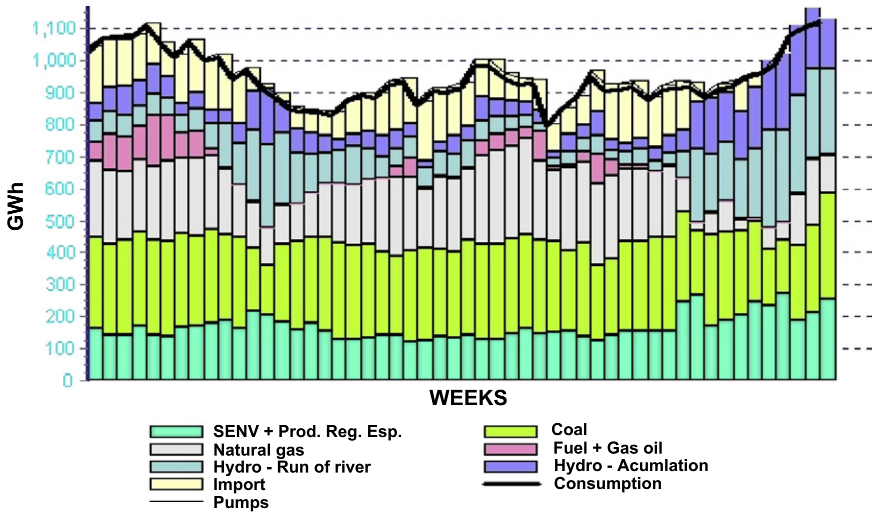

Fig. 2. Weekly power consumption and supply in 2006 per type of fuel and production technology [21].

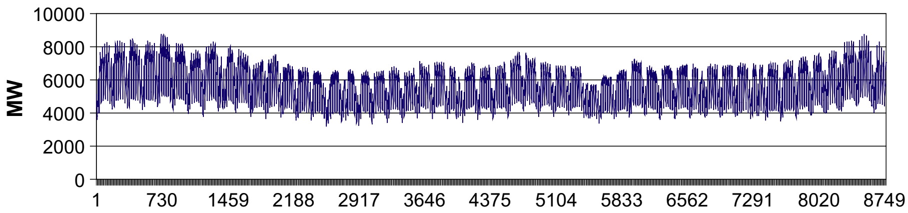

Fig. 3. Hourly power load for Portugal in 2006 [23]. Data provided by ENTSO-E.

to match production in 2006 with the data presented in [22]. The adjustment has been carried out using simple monthly correction factors.

Two models of wind turbines, the 2 MW Vestas V90 and 5 MW Re-Power, with their associated power curves have been incorporated into the calculations. The smaller turbine represents current installations and that will be built by 2020 while the 5 MW model is used for new installations in the 100% renewable scenario. There are unavoidable uncertainties in assessing wind energy potential at a site. To quantify these uncertainties, the author in [26] presents a numerical procedure for evaluating the uncertainty caused by the variability of natural wind and power performance. These uncertainties increase when all turbines in a certain region are represented by one measurement and one type of turbine.

3.2.4. Solar power

In 2006, there were around 3.4 MW of installed solar power plants in Portugal [22]. Since then, there has been much progress in the construction of other solar PV power plants. The Amareleja plant is located near the southern town of Moura (Alentejo), with approximately 262,080 solar panels spread over more than 250 ha and with 46 MW of installed power. Another completed solar PV plant is the Parque Fotovoltaico Hércules at Brinches, Serpa, with an installed capacity of 11 MW and annual electricity generation of more than 18 GWh. Another interesting project, the Tavria thermal solar power station, is currently under construction and will have installed capacity of 6.5 $MW_{e,}$ generating approximately 12 GW h of electricity per year [27]. In the H_2RES model, all power plants have been treated as solar PV-photovoltaics plants installed in a single location in southern Portugal. Hourly solar radiation for the location has been obtained using the METEONORM program. All PV modules have been treated as fixed modules under an optimal radiation angle. Total efficiency of the solar PV plant was set to 15%.

3.2.5. Wave power

There are several demonstrational wave power plants currently installed or under construction in Portugal. Parque Aguçadoura with 2.25 MW consists of 3 × 750 kW Pelamis machines and 2 MW the plant Archimedes Wave Swing, with both installations located are at Póvoa de Varzim, the CEO Douro, a 1 MW installation at Porto do Douro, AQUABUOY with 2 MW located at Figueira da Foz. As explained in the second chapter, all wave power plants in the calculations are represented by the Pelamis machines [18]. The hourly wave data used in calculations has been obtained from forecasting models described in [28,29].

3.2.6. Biomass

According to [22], in 2006 the total installed capacity of power plants using biomass was 477.2 MW, of which 357 MW was from CHP plants, 24 MW from plants without CHP, 88 MW from waste incineration and 8.2 MW from biogas facilities. The total bioenergy electric power potential in Portugal from forest biomass was estimated to be 6%. Forest biomass potential consists mainly in both eucalyptus and pine thinning and cleanings, representing 55% of the total forest biomass production in Portugal [30]. Additional potential could lie in production from *Miscanthus*, a giant perennial rhizomatous grass. In study [31], the authors estimated electricity production from *Miscanthus* in Portugal to be 2.8 T Wh annually which presents 5.7% of the current demand. In [32], the estimated bioenergy potential in Portugal is 26,366 GW h/year, of which 8378 GW h/yearly comes from energy crops used in biofuel production. The use of biomass should be maximised in local plants due to expensive transport costs. To get a better overview of the local potential, it would be desirable to follow the methodology stated in [33], where a detailed analysis of the whole region has been conducted. The authors carried out an analysis of the potential from the biomass residues using the Geographical Information Systems (GIS) database and statistical analysis. The authors concluded

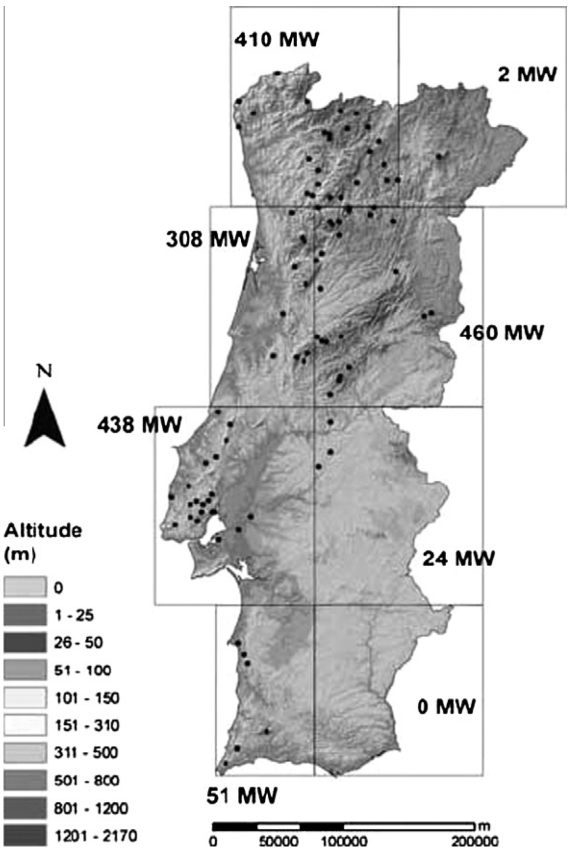

Fig. 4. Spatial distribution of wind capacity in Portugal, 2006 [24].

that the annual biomass residue potential for the Marvão region is about 10,600 tonnes, corresponding to an energy production potential of about 106,000 GJ. The Marvão region covers an area of 154.9 km^2 (less than 0.2% of Portugal) and with an average forest cover rate of about 49%. Although the H_2RES model accepts up to five different types of units for biomass energy conversion, and since there was no specific data on biomass collection for the whole of Portugal, an equal distribution of biomass throughout the year was assumed. This was represented by a group of biomass source with a lower heating value of 14 GJ/t and a biomass to electricity conversion efficiency amounting 25%. In 2010, the installed biomass capacity will amount to 250 MW [34]. It will be also possible to utilize in Portugal energy from municipal waste incineration. According to RES technology roadmap, a 100 MW target of installed capacity for anaerobic waste treatment units has been established [34].

3.2.7. Hydropower

Portugal is one of the European Union countries with the highest exploitable potential of hydropower. It is also one of the countries with the lowest hydro capacity growths over the last 30 years, remaining at around 54% of its exploitable potential. As has already been mentioned, Portugal in 2006 had in its hydropower plants 4582 MW of installed power with an additional 365 MW from PRE producers. According to [35], storage hydropower plants possessed an installed capacity of 2287 MW and a maximum storage capacity of 3082 GW h with the ability to store up to 7716 mil. m^3 of water. The installed hydropower plants accounting for 2295 MW and 365 MW from PRE are treated in the H_2RES calculations as run-of-river. Portugal also has a large installed capacity in pumped hydro storage power plants and according to [36], their capacity in 2006 was 1048 MW. The water data for the hydropower production has been simulated in accordance with rainfall measurements in Bragamca (the northeast Portugal) and obtained from the METENORM program. The data also included weekly power production from hydropower plants and obtained from the REN website. The hydro module in H_2RES accepts only one reversible or storage hydropower plant with upper and lower reservoirs, which means that all storage hydro is combined with the storage capacities aggregated and treated as a single power plant. This assumption could lead to certain errors if hydropower plants are required to work at a full load capacity longer than two days in a period without natural or pumped water inflow into the upper reservoir, as illustrated on Fig. 5. The possibility of the module including evaporation from the reservoirs has not been incorporated in the calculations, as it requires additional detailed data concerning reservoir surfaces. Hydropower is clearly a priority and one of the principal commitments in the national energy policy. High Potential Hydroelectric Dams National Program (PNBEPH) identifies the viability and development of hydroelectric plants and aims to identify and prioritise investments in hydroelectric power plants due for completions by 2020. The program seeks to achieve a hydroelectric power installed capacity exceeding 7000 MW by 2020 in Portugal, providing an additional capacity of 2000 MW [37].

3.2.8. Grid – import/export capacity

The grid import/export capacity in 2006 was 1200 MW [38] and there are also plans for increasing the capacity to over 3000 MW by 2014 [39].

3.3. The H_2RES reference scenario for Portugal in 2006

A reference scenario has been used for testing the H_2RES model and its preparation for 100% RES simulation in Portugal. Fig. 6 shows the results of the H_2RES calculation for the reference scenario. A comparison of H_2RES results and data from the literature in the bibliography is given in Table 1. As the model does not support hourly financial analysis, there is also no possibility of optimising the operation of the power plants with respect to marginal costs, and hence this was the main reason why importing electricity was replaced with fossil fuel generation. Due to the number of installed power of wind turbines increasing in 2006 at almost a linear rate, and an additional 634 MW since the start of the same year, in order to obtain similar results in achieved production, installed wind power in 2006 in H_2RES was reduced to one half of the new installations. The H_2RES model is a simulation model calculating for each run output based on one the parameters set for whole year.

3.4. H_2RES Portugal 2020 – open system calculation

In this scenario, the power from renewable units has been increased until reaching the goals set for 2020 [17]. Once the increas-

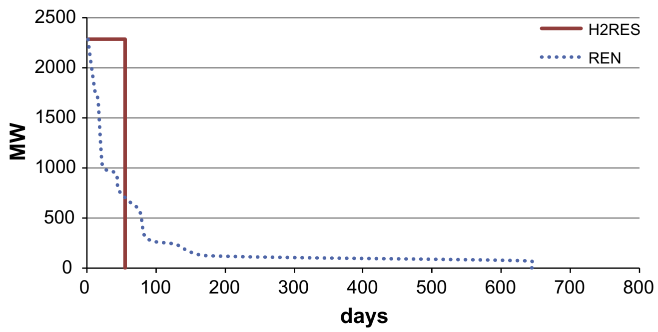

Fig. 5. Operation of the hydro storage power plants from full storages and maximal load in the period without inflow of water to the upper reservoirs.

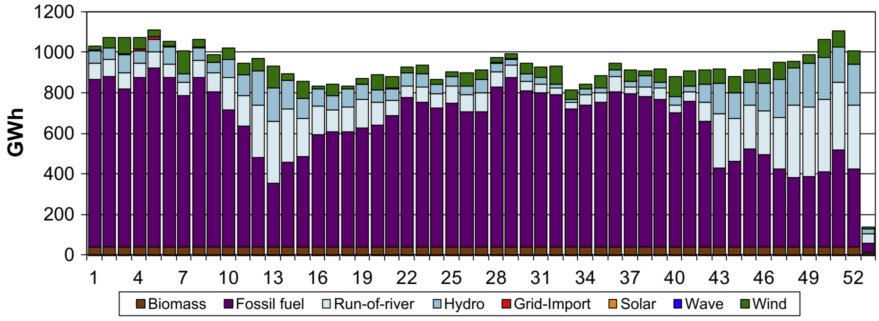

Fig. 6. Calculated weekly power production in 2006.

Table 1
Comparison of electricity production in 2006. H_2RES results and data from literature.

Supplying demand (GW h)	H_2RES		Literature	
Wind	2811	5.7%	2892	5.8%
Solar	4.6	0.0%	3.4	0.0%
Wave	0	0.0%	0	0.0%
Run-of-river	6911	14.1%	6866	13.8%
Biomass	1998	4.1%	1945	3.9%
Hydro	4360	8.9%	4319	8.7%
Fuel cell	0	0.0%	0	0.0%
Batteries	0	0.0%	0	0.0%
Grid-Import	51	0.1%	5441	10.9%
Fossil Fuel	32,964	67.1%	28,399	57.0%
Total	49,099	100%	49,865	100%

ing the power, the grid was expanded to allow exporting of all power that should otherwise be rejected. The intermittent limit was set to 80%. Primary generation is presented on Fig. 7. The scenario where demand is met in Portugal in the year 2020 is presented in Fig. 8. In this case, new biomass production is increased to 793 GW h. The results for weekly energy balancing and power production, pump consumption and RES export are given in Fig. 9. According to data provided in [37], the turbine power of storage and reversible hydropower plants was expanded to 2779 MW, while pump power was increased to 1889 MW. The remaining hydropower increase of 794.25 MW in order to reach strategy goals was added to run-of-river. Additional energy production in 2006 amounted to 4034 GW h for storage hydro systems and 2063 GW h or 30% for run-of-river production. Storage and reversible hydropower plants operated in turbine mode for 4816 h at a total capacity factor of only 28%, whereas in pumping mode the plants operated for only 1356 h accounting for a total capacity factor of 10%. Without expanding grid export capacity, exported electricity totalled 1.8 TW h with the rejected intermittent potential at 156 GW h. With the additional 2510 MW of grid export capacity, the system was able to export all intermittent potential. It is interesting to note that with additional new grid capacity, the system could operate without fossil fuel production by importing 9.43 TW h of electricity, resulting in a total import–export balance of 7.47 TW h. If the guaranties of renewable origin could be obtained for imported electricity, under the assumption that the system could also import ancillary services and with the same consumption as in 2006. Portugal could reach a 100% renewable electricity supply by 2020.

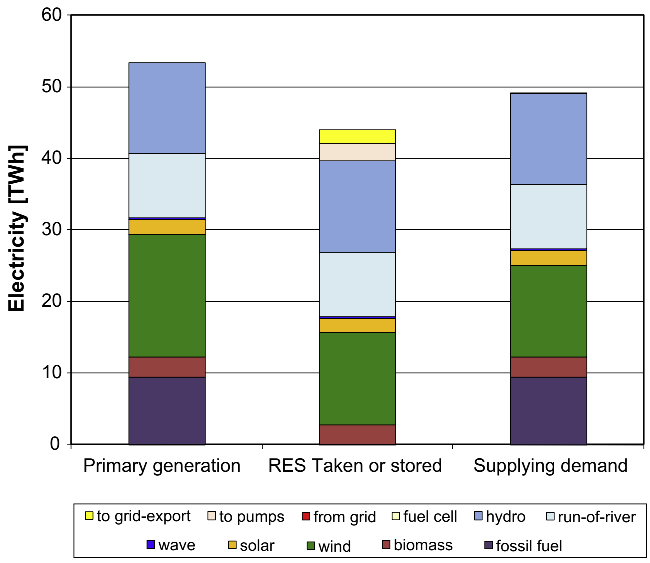

Fig. 7. Primary generation in Portugal 2020. H_2RES calculation.

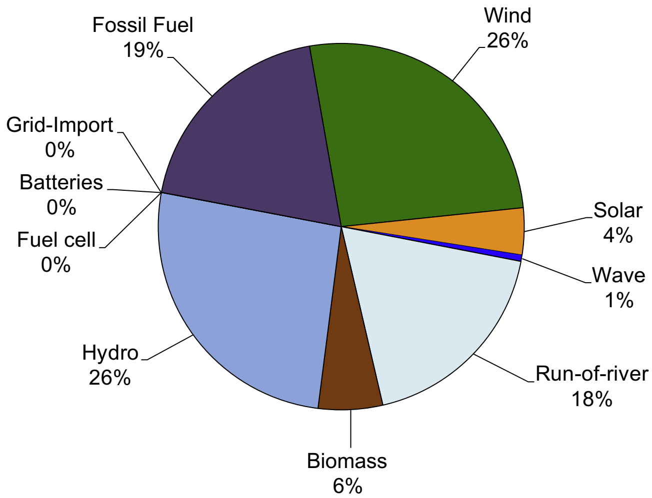

Fig. 8. Supplying demand in Portugal 2020, H_2RES calculation.

3.5. A H_2RES 100% RES scenario – closed system calculation

Similar to open system calculation, another analysis of the 100% RES scenario has been conducted with the main assumption in energy balance being that the Portuguese power system is a closed system, implying no connections for electricity import/export with Spain.

In this scenario, planned installations in the Portuguese energy strategy for 2020 have been further expanded to achieve a 100% RES scenario. There are no intermittent limits in the calculations

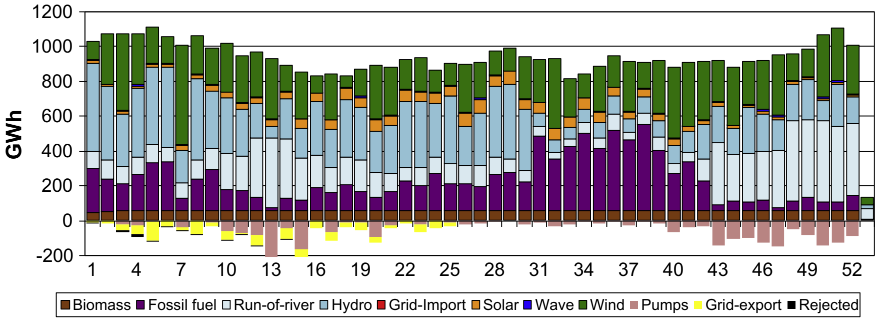

Fig. 9. Calculated weekly power production, pump consumption and RES export in Portugal 2020 scenario.

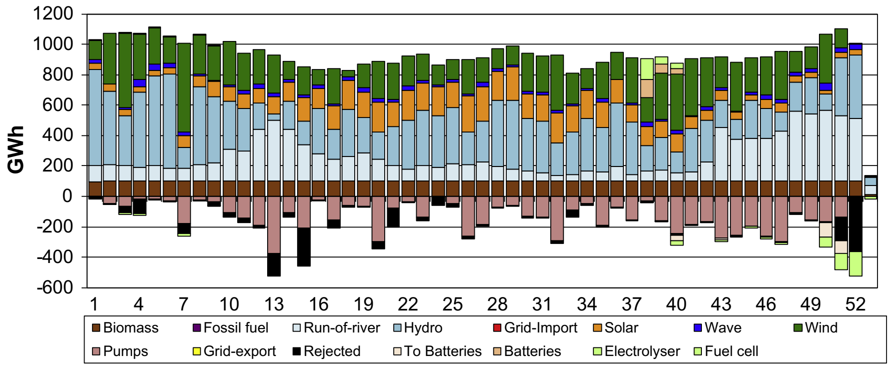

Fig. 10. Calculated weekly power production, storage consumption and rejected RES potential in 100% RES scenario.

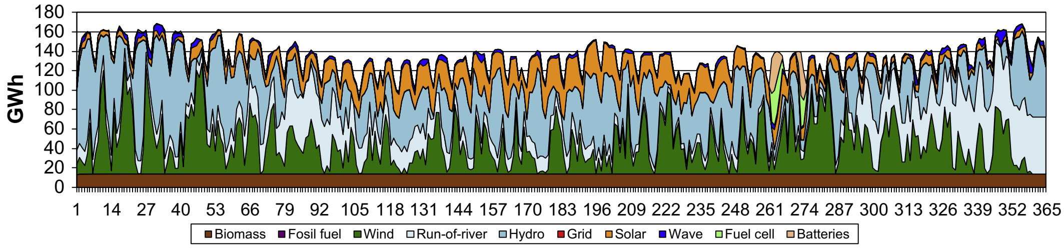

Fig. 11. Calculated daily power production in 100% RES scenario.

as it was assumed that units such as hydropower plants, biomass facilities and large 5 MW wind turbines would possess some degree of frequency and voltage control. Results for weekly and daily energy balancing for a 100% RES scenario are shown in Figs. 10 and 11. Energy from biomass and waste is constant under the assumption that collection during the year remains the same. The power of installed components for 100% renewable electricity production is shown on Fig. 12.

The installed power from wind turbines reached almost 10 GW and is only 1.5 GW more than planned by the new energy strategy. A total of 640 MW of new installations were added as off-shore units. The rest were added to current locations, by replacing old and small turbines with 5–6 MW units. Consequently, a lot of space could be saved at good windy locations. The second largest installations, shown in Fig. 12, are the turbines and pumps in storage systems and reversible hydropower plants. In the closed system, calculations resulted in a biomass potential of 20.75 TW h, producing 5.18 TW h of electricity or around 11% of total demand (see Fig. 13).

Furthermore, pumped hydro, batteries and fuel cells (hydrogen loop) have been used in calculations as possible energy storage technologies. Battery storage and retrieval efficiencies have been set to 92% in calculations, with electrolysis efficiency set at 78% and fuel cells at 60%. The aggregated capacities of all storage units are presented on Fig. 14.

4. Discussion

In the H_2RES model, only one unit was used to simulate reversible hydro storage, which is usually enough in simulating islands or particular units connected to larger systems. However, when used for simulation of large power systems with different types of hydropower plants and respective reservoir capacities, it would be desirable to optimise the system at a more detailed level using as much of the available technical details for existing and planned power plants as possible. In this way, PHS systems will achieve improved total capacity factors and certain errors due to the aggregation of installed power and storage capacities will be avoided. Moreover, as energy planning is carried out by simulating power systems at an hourly rate, it will be desirable to try to optimise the operation of systems according to market behaviour, which is

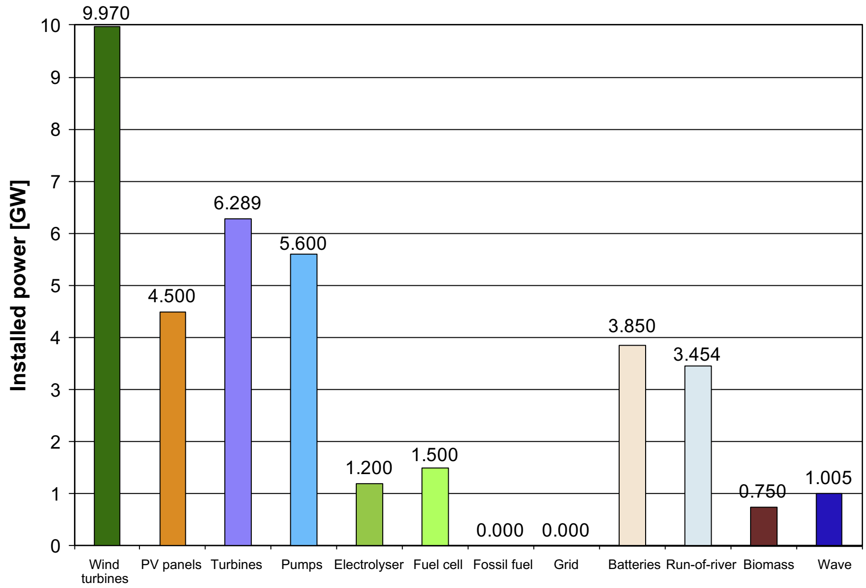

Fig. 12. Installed power for 100% renewable electricity production in Portugal.

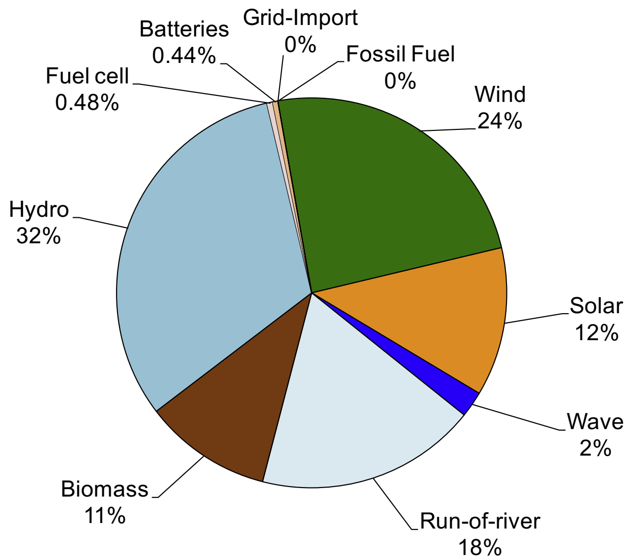

Fig. 13. Supplying demand in 100% RES scenario – closed system calculation.

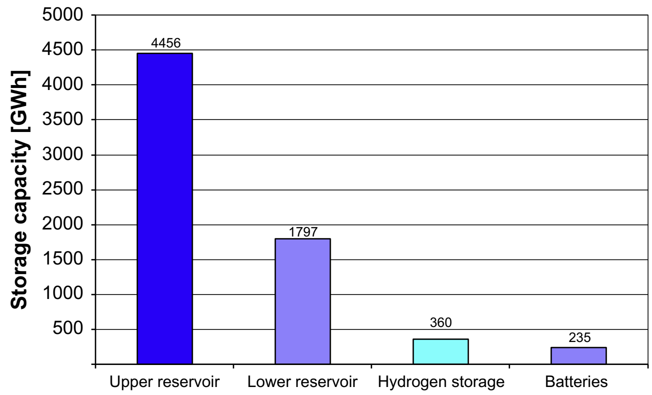

Fig. 14. Installed capacities of energy storages for 100% RES Portugal – closed system calculation.

already done by models such as EnergyPlan or by the market-equilibrium model explained in [40]. This model has been used to analyse the Iberian market and the different conditions faced by generation companies: the scenarios for CO_2-emission prices, hydro conditions, demand, fuel prices and renewable generation. According to the model in [40], the authors have calculated 33% of RES electricity in the Iberian market by 2012. Therefore, it will be interesting to see the results of their model for a 100% RES system for the Iberian market, since the authors are looking at the whole issue of sustainability.

In both stated future scenarios, system stability was addressed using intermittent limits or the assumption that current and new RES units acting as biomass and hydro power plants will provide adequate ancillary services. Ancillary services, rendered in order to maintain voltage and frequency stability by controlling active and reactive power, are normally supplied from large dispatched central stations. Alternatives to these stations are required as production share decreases in systems with high RES shares, which are mostly represented by smaller decentralised units [41]. In the same paper, the author has demonstrated the possibility of integrating large quantities of wind power into an electrical power system, under the condition that certain requirements are fulfilled. Wind power and small-scale CHP plants must be able to supply ancillary services units [41]. There is also the possibility that new wind turbines may supply all types of ancillary services by the use of power electronics, as explained in [42] for the Doubly Fed Induction Generator (DFIG) wind turbine. In addition to the ancillary services issue, there are also other localised (e.g. grid congestion) problems since most of RES sources are not distributed evenly in the area.

Portugal already has a large quantity of reversible hydro in its system. As a proven technology, the new storage installations in 100% RES should be mostly reversible power plants that could be carried out as extensions to already existing storage power plants, and is treated in [37]. Pumped hydro storage plants could also be built near existing lakes or reservoirs where a suitable height elevation exists. A possibly interesting approach for identifying potential PHS locations is explained in [43]. Other storage technologies exist such as compressed air and hydrogen production, but at their current cost and level of technological development, they could only be carried out to a smaller extent.

A 100% RES scenario relies a lot on hydro energy, which can vary significantly between wet and dry years. As presented in [27], large hydropower plants possess capacity factors ranging from 11.8% to 43.2% in the period between 1997–2009. The capacity factor in large hydropower plants in 2006 was 26.3%, making it the most average year with regards to hydropower production in the mentioned period. In order to have a stable supply and due to the large variability of hydro, planning should also be conducted for the worst case scenarios in dry years. This will lead to increased reserve capacities installed by other technologies, but which will then have low usage during the wet years. Another approach for a secure supply could be the optimisation of system operation at hourly and seasonal levels, where some controllable sources could be saved for a longer period of time.

From the 17 identified locations for wave power plants examined in H_2RES, only 10 were selected for large installations (50 or more units). The capacity factors on these locations range from 10% to 13%, meaning that Pelamis wave energy converters will work with very low load factors, at a smaller percentage than described in [44,45]. This means that wave data and power matrices should be additionally checked or the Pelamis machines will need to be fitted in Portugal for operation. Meteorological data from METEONORM and H_2RES results should be compared to actual measured wind speeds and solar radiation at the selected sites or compared with real production when available for certain installations in operation. Biomass and waste potential should also be verified if new detailed studies are published and managed according description given in [46].

With the current renewable energy policy and strategy for the expansion of RES installations by 2020, and taking into account a RES share in electricity consumption amounting to 35.1% in 2009, comprising of 40% wind energy and 46% hydro energy, Portugal provides a good example of an experimental region targeting a 100% RES electricity supply by applying pumped hydro and other storage technologies.

5. Conclusion

Presented are modelling results of three electricity production scenarios in Portugal's power system, a reference scenario for 2006, and a Portugal 2020 scenario drawn up according to the new energy strategy for 2020 and the 100% RES scenario. All scenarios are modelled using H_2RES software and they will need further, more detailed elaboration. In both future scenarios, electricity demand was the same as in 2006, hence an additional forecast should be made to include increases or decreases in demand. Possible energy efficiency measures may significantly decrease demand, for instance, improved building insulation resulting in reducing electricity requirements for air conditioning during the summer or heating during the winter. The use of solar thermal collectors for hot water heating or absorption cooling could also decrease electricity consumption.

Closed system calculations enabled a better overview of accessible energy technologies but also point out certain limitations of the H_2RES program that has restricted development of more detailed and optimised results. The used model accepts only a single reversible hydro installation, and this should be reprogrammed in order to gain quality results that will enable modelling of larger energy systems with more geographically dispersed units. There is no automatic optimisation of the model based on cost, and the environmental and social parameters arising from each technology. By optimising these parameters, the model will provide more sustainable solutions that should now be calculated separately.

Without cost optimisation, the order of generation and priority of storages is set deterministically by the limitation equations in the model. Consequently, if there is no penetration limit, the model forces a certain technology to its maximum or to the maximum available potential, without giving priority to lower costing technology or production during certain hours.

The current 100% RES solution is favours hydro and wind power. Wind power should be implemented using installations with big reversible or pumped hydropower plants and could be achieved by installing bigger wind turbines and storage systems. Hydrogen and batteries could become a storage solution for large future systems once the technology further progresses, and once it become possible to combine these storages into a transport system.

If Portugal is to fulfil all the goals set out by new energy strategy and if it undertake additional grid expansion, which will allow it to exchange (export–import) only RES electricity, theoretically it will then be possible to achieve a 100% RES supply within 10 years time. Energy efficiency measures could speed up and make the converting process to 100% RES system even easier. Achieving a 100% RES electricity supply in a closed system will take more effort and certainly be more financially demanding as there are additional installations on the production and storage side that will be in operation for a small number of hours. In order to calculate optimal solution, using models for energy planning that carry out energy balancing on an hourly basis, it will be necessary to include more detailed operational planning amongst the system units. This will result in a full exploration of existing and planned assets without the necessary erroneous estimations of required installed power and the size of RES units and energy storage systems.

Covering 100% of electricity demand from renewable energy sources is just one big step in achieving a 100% renewable energy system. The effects of energy production from renewable energy sources could be multiplied if a whole energy system is calculated and if energy and other resources flows are integrated. Hydro storage and pumping could be easily and effectively integrated with fire protection and irrigation. This can further be integrated with biomass and biofuel production. Integrating power, heat and cold generation provides maximal efficiencies. Finally, energy demands in the transport sector could be easily coupled with power production using hydrogen or batteries in electric vehicles.

Acknowledgements

The authors would like to thank the European Commission and its DG RTD for supporting the projects RenewIslands – Renewable Energy solution for Islands and ADEG – Advanced Decentralised Energy generation systems in the Western Balkans, the Ministry of Science, Education and Sport of the Republic of Croatia, which is supporting the project Smart Energy Storage for Sustainable Development of Energy Systems and the Portuguese Ministry of Economy and Innovation for financing the PRIME Programme, which is supporting the project EDEN – endogenous new energies (EDEN) that has resulted in this work.

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