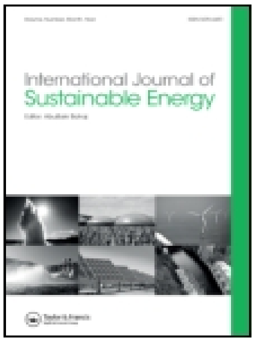

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The role of hydrogen-based energy storage in the support of large-scale wind energy integration in island grids

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To confront problems concerning large-scale integration of renewable energy sources, introduction of energy storage constantly gains ground. Benefits stemming from the adoption of energy storage include exploitation of otherwise rejected energy, increased reliability of energy supply and improved operation of a given power system overall. In this regard, contribution of such systems in achieving large-scale integration of wind energy into island grids is currently considered. More precisely, fuel cells and hydrogen storage (FC–HS) are investigated, in comparison with conventional batteries. For this purpose, a simulation algorithm is developed to study the energy performance of different FC–HS configurations used to recover wind energy curtailments. The developed algorithm is then applied to a representative Aegean island of medium–high quality wind potential. Results obtained indicate that FC–HS may become attractive in comparison with conventional batteries, only in the case that the use of hydrogen surplus to cover other energy flows is also put forward.

Keywords: wind energy; island grids; hydrogen-based storage; fuel cells; battery storage

1. Introduction

Increased interest is recently noted in the concept of distributed generation (DG), with renewable energy sources (RES) technologies called to play a critical role in the shift attempted from centralised power generation to DG patterns. At the same time, there are several remote areas across the globe that rely on electricity grids of small-scale (micro-grids), normally employing oil-fired power generation solutions (Kaldellis and Zafirakis 2007). On the other hand, in many of these regions one may encounter medium to high-quality RES potential that encourages installation of solutions such as wind power and photovoltaics (Kaldellis 2002; Kaldellis, Zafirakis, and Kondili 2010).

A descriptive example of such a region is the Aegean Sea (Figure 1), located at the eastern part of the Greek mainland. The specific region comprises numerous scattered islands and is determined by a high-quality solar potential year-round, as well as by the presence of numerous areas with medium–high or even high-quality wind potential. On the other hand, under the current electricity supply status, such micro-grids cannot facilitate large-scale integration of RES and especially wind energy (due to its stochastic intermittency), owing to their inherently limited flexibility and the need to satisfy operational limitations of local thermal power stations (e.g. technical minima of the

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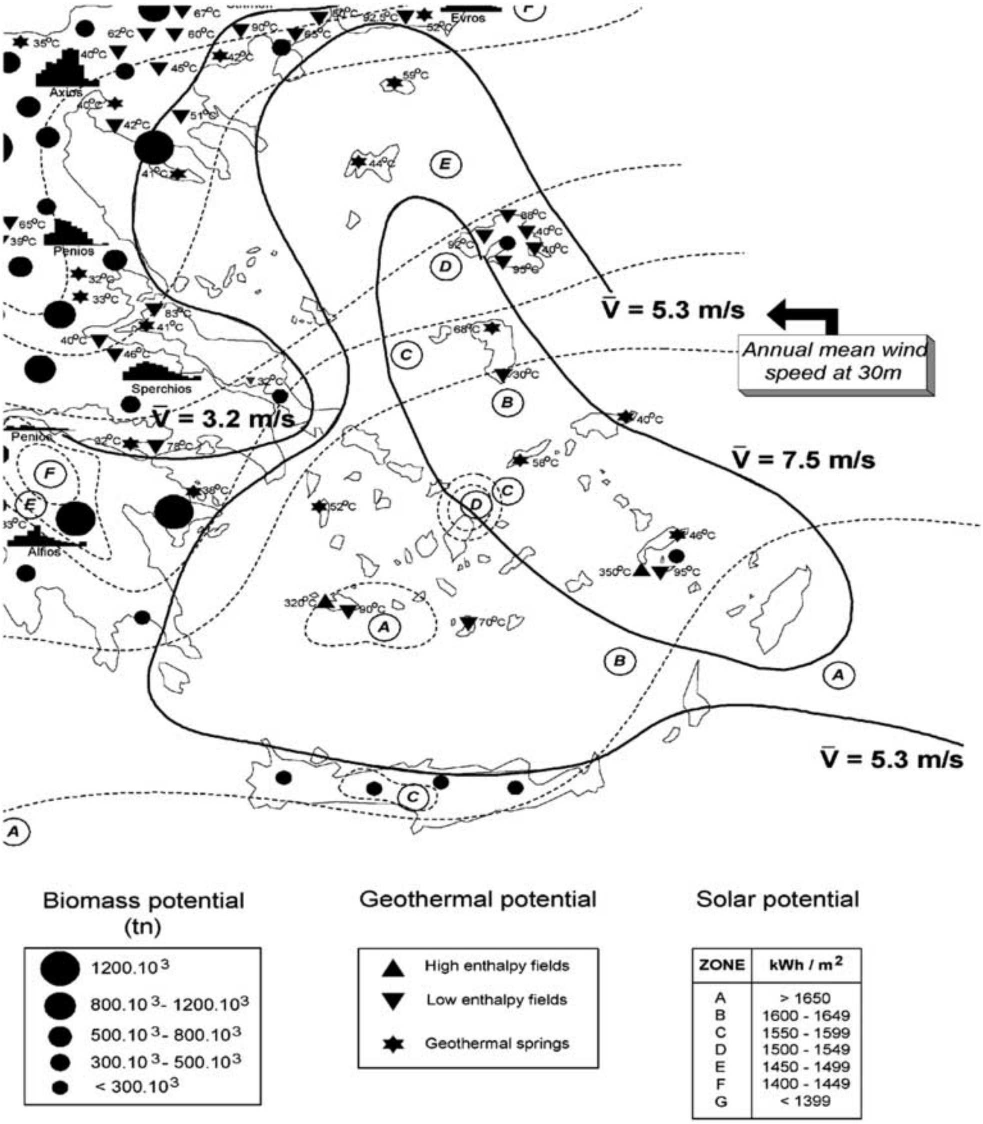

Figure 1. RES potential across the Aegean Sea.

local stations) in combination with a highly variable electricity demand. As a result, contribution of RES to the local electricity demand satisfaction is up to now restricted to maximum values in the order of 10% on an annual basis, reflected also by the share of the respective installed capacity (Figure 2). In this context, it is important to note that it is even under the current RES participation that RES energy curtailments are encountered in these isolated micro-grids, clearly suggesting that further increase in the corresponding installed capacity implies more considerable rejection of RES generation (Kaldellis et al. 2004; Kaldellis, Kavadias, and Filios 2009).

Considering the above, to confront the problem of limited RES participation in island regions (Duić, Lerer, and Carvalho 2003) two are the main alternatives widely discussed, i.e. interconnection of island regions with mainland areas (Georgiou, Mavrotas, and Diakoulaki 2011) and introduction of energy storage and smart grid aspects (Stadler and Bukvić-Schäfer 2003). In this

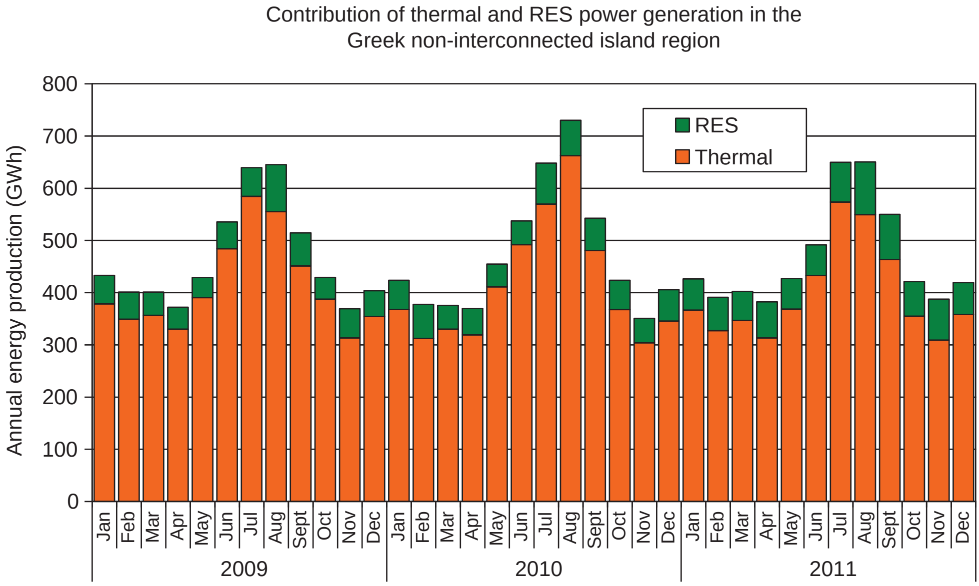

Figure 2. Contribution of RES in Aegean Sea islands in terms of installed capacity.

context, the current study emphasises on the second option and more specifically on the role of contemporary energy storage technologies to support large-scale integration of wind energy in island networks.

There are various contemporary energy storage technologies (Zafirakis 2010), either more mature or emerging that may interact with RES (Kaldellis, Zafirakis, and Kavadias 2009) and achieve increased energy autonomy for the micro-grid each time investigated, largely reducing or even eliminating the contribution of oil power generation. At the moment, application field of contemporary energy storage technologies covers a wide range, i.e. from power quality to energy management applications, with each of the existing energy storage technologies holding a certain area that is determined by its operation principle and characteristics, commercial size, maturity, etc. (Figure 3). When considering wind energy support (Daim et al. 2011) at the level of island grids, energy storage systems that may support energy management applications (i.e. of considerable storage capacity and power output) should be taken into account. To this end, despite of their maturity and bulk-scale character, both pumped hydro and compressed air energy storage (Zafirakis and Kaldellis 2010; Zafirakis and Chalvatzis 2014) depend largely on the local topography and are thus often infeasible to operate.

Between the remaining two energy management alternatives (i.e. the various battery solutions and hydrogen-based technologies), we currently take into account the grown interest recently noted in hydrogen (Amoo and Fagbenle 2013) and investigate the performance of hydrogen-based configurations (Askari et al. 2013). Operation of such systems is based on the exploitation of waste or surplus energy amounts, in order to produce hydrogen through electrolysis and then use it to produce electrical energy with the use of the appropriate fuel cells (FCs). In this regard, contribution of such systems in achieving large-scale integration of wind energy into island grids is currently considered. On top of that, conventional, large-scale battery energy storage is also presently examined, so as to obtain a comparison with the technology of FC and hydrogen storage (FC–HS).

For this purpose, an integrated simulation algorithm is developed, investigating in detail the energy performance of different size wind-FC–HS configurations. The developed algorithm is

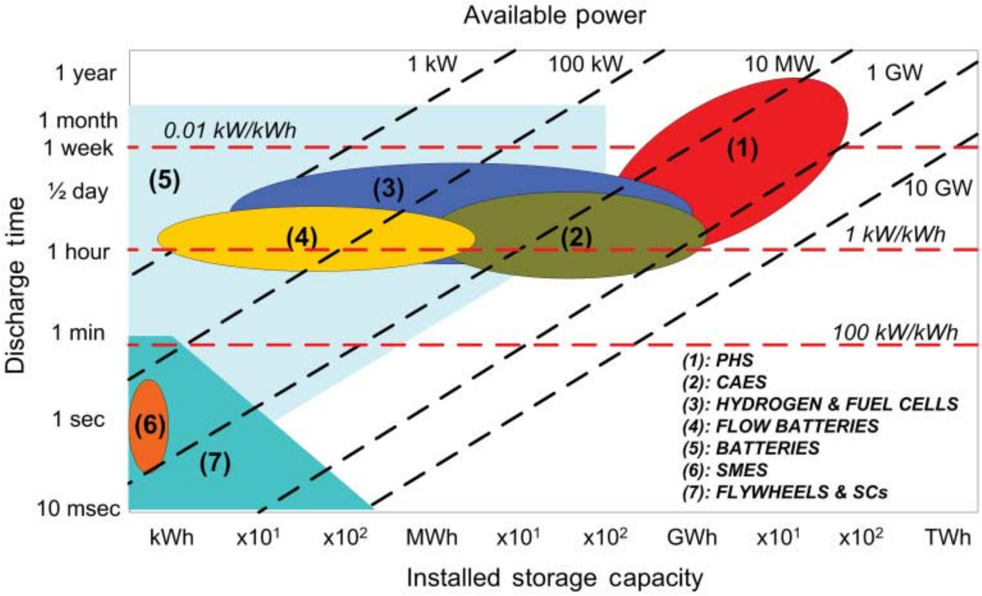

Figure 3. Application map of contemporary energy storage technologies.

then applied for a representative island grid of the Aegean Sea, with medium–high-quality wind potential. Results obtained indicate that the solution of FC–HS may become attractive in comparison with conventional battery energy storage, in case that exploitation of hydrogen surplus to cover other energy flows (e.g. transportation needs) is also taken into account.

2. Description of the proposed configuration

As already seen, at the broader area of the Aegean Sea, on the eastern part of the Greek mainland, there are several non-interconnected island grids scattered across the archipelagos that appreciate medium–high-quality wind potential. In this context, in cases that the local landscape does not encourage installation of bulk energy storage solutions, such as pumped hydro storage, wind-based electrification of small–medium-scale islands can also be supported by either battery storage or FC–HS (Figure 3). Considering the above, emphasis is currently given on the solution of FC–HS, aiming at the determination of energy-autonomous wind-FC–HS configurations (Figure 4) that may achieve zero load rejections for the entire year, through the use of a sizing algorithm currently developed (Figure 5). The developed algorithm is an extension of past algorithms (Kaldellis 2004; Kaldellis, Koronakis, and Kavadias 2004, Kaldellis, Kondili, and Filios 2006, Kaldellis, Zafirakis, and Kavadias 2012) concerning the integration of different RES and energy storage technologies and on top of producing energy-autonomous configurations is also able of providing the detailed (hourly) energy balance analysis of any given configuration.

When considering hydrogen-based energy storage, the main disadvantage corresponds to the low system round-trip efficiency, which by including the hydrogen production stage (electrolysis is currently considered) is estimated in the order of 40%. The losses are detected during the electrolysis for the hydrogen to be produced, during the stage of storage, and finally during the electricity-generation process via the FC. The FC component alone, however, may for certain types exceed efficiencies of 60%. On the other hand, among the technology main advantages one may encounter the high energy density due to the use of hydrogen, the negligible self-discharge

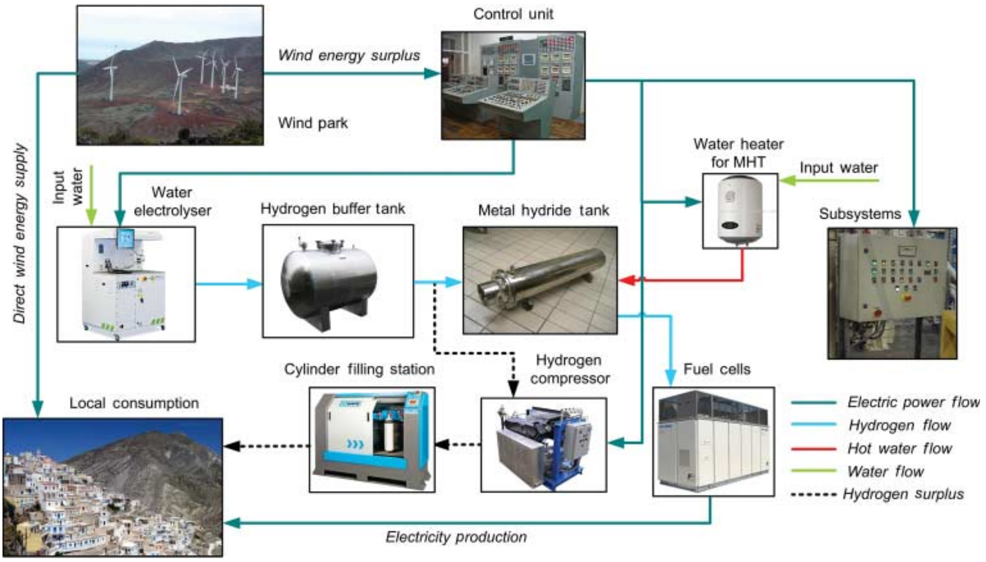

Figure 4. Description of the proposed wind-FC–HS configuration.

and the wide range of applications, including integration with RES (Nelson, Nehrir, and Wang 2006; Kasseris, Samaras, and Zafeiris 2007; Samaniego et al. 2008; Eroglu et al. 2011; Raju and Khaitan 2012; Beccali et al. 2013). Considering the above, the proposed configuration main components include the following (Figure 4):

- A wind farm (or wind farms) comprising a number of wind turbines (determined by the respective non-dimensional power curve vs. wind speed, see also Figure 6), with total capacity ‘N_{wp}’.
- An alkaline electrolyser of nominal power ‘N_{electr}’ and certain characteristics, e.g. operational temperature range, operational pressure and current–voltage curves (see also Figure 7 where a 26 kW of 21 cells operating at 15 bar is used as the reference), with ‘N_{electr}’ being predetermined, in accordance with the maximum wind energy surplus appearing, i.e. ‘N_{electr}’ $\geq$ ‘$N_{\mathrm{wp\text{-}surplus\text{-}max}}$’, considering also any future local demand/wind power increase.
- A HS configuration, including a buffer storage tank that receives purified hydrogen (99.999% purity – purified after the electrolysis unit) and delivers it primarily to the metal hydride tank of certain energy storage capacity ‘E_{ss}’ in order to operate the FC, and secondarily to a hydrogen compressor in order for the produced hydrogen to be stored in high-pressure cylinders/vessels (e.g. 220 bar).
- A FC configuration of a certain power output ‘N_{fc}’, comprising a number of proton exchange membrane cell stacks connected in series (see also Figure 8 to obtain the current and power density curves of a single reference cell of $\sim$ 0.28 kW) determined so as to cover the maximum appearing energy deficit at the demand side (i.e. load demand that cannot be covered directly by the wind park) during the entire year, i.e. ‘N_{fc}’ $\geq$ ‘$N_{\mathrm{d\text{-}def\text{-}max}}$’.
- The rest, balance of system components, including control units and other peripherals such as water supply systems and piping.

In this context, the main problem variables currently taken into account for the sizing of the proposed configuration correspond to the wind park capacity and the metal hydride tank energy storage capacity. At the same time, the main problem inputs require detailed wind speed

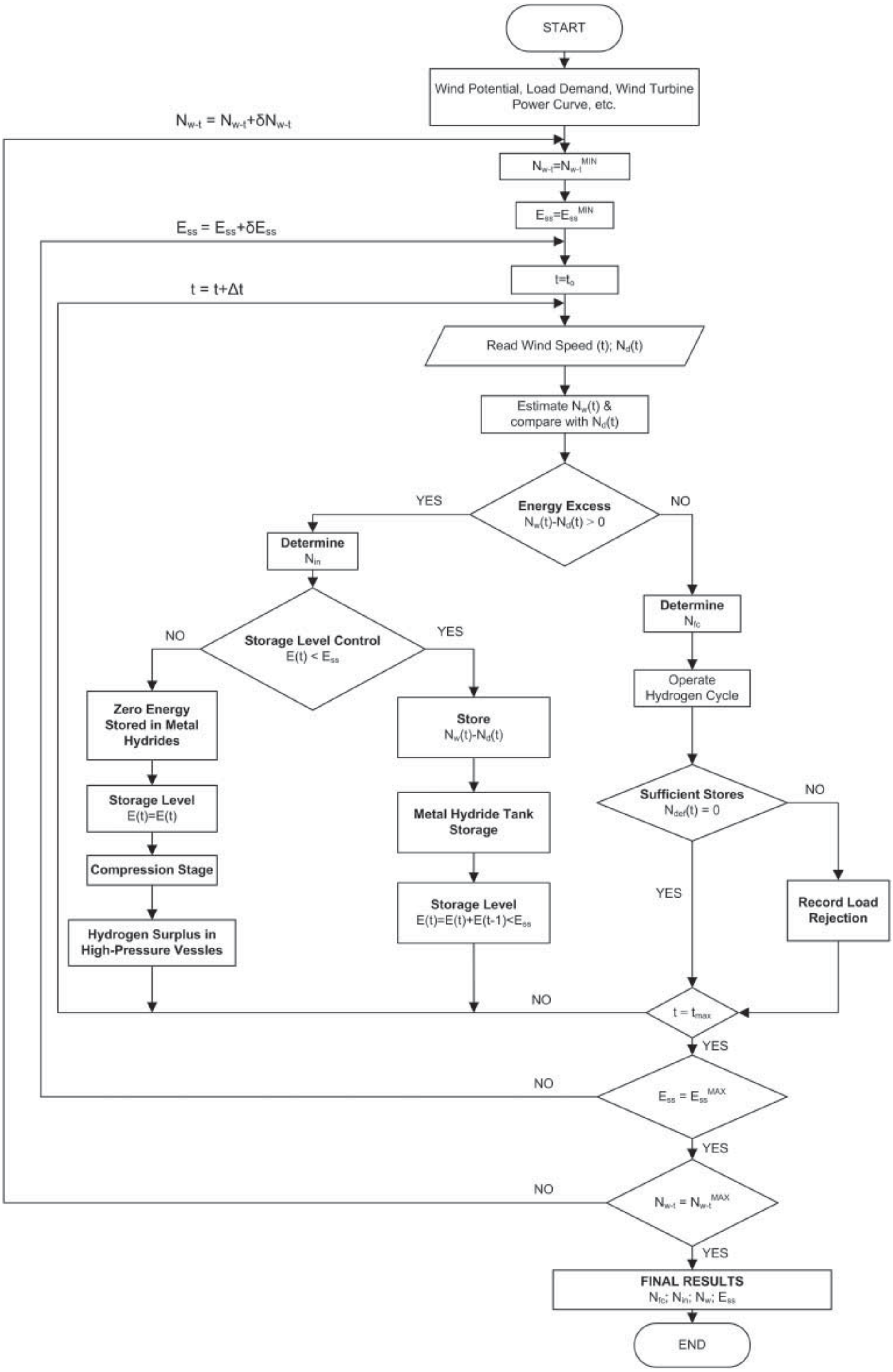

Figure 5. The wind-FC–HS algorithm.

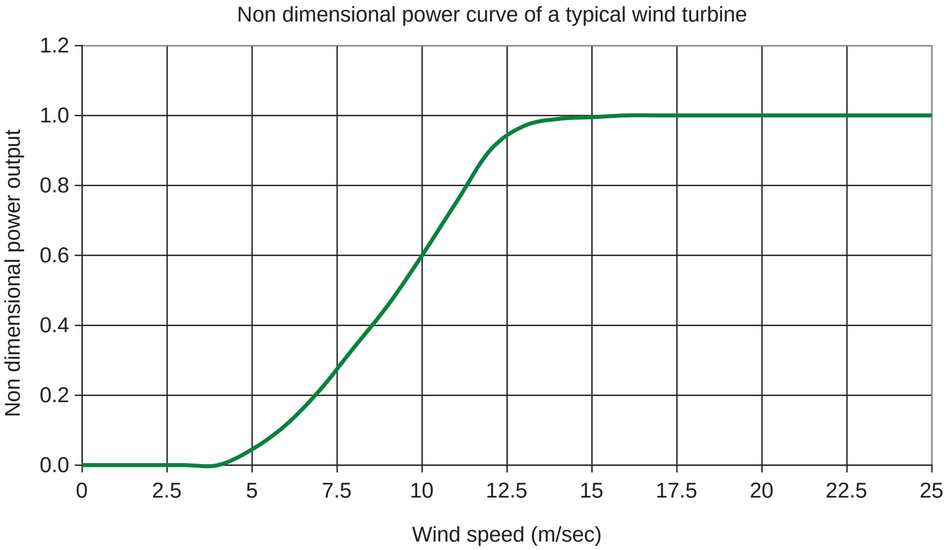

Figure 6. The reference non-dimensional wind turbine power curve.

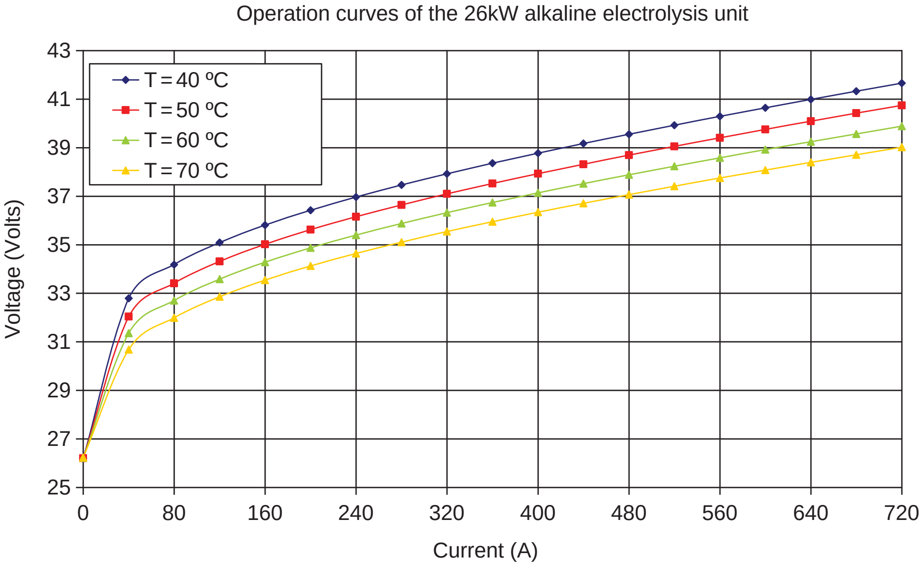

Figure 7. The current–voltage curves of the reference electrolysis unit.

measurements along with the hourly electricity load demand of the system under investigation. Furthermore, the technical characteristics of the main system components are also required (Figures 6–8), while to simulate operation of similar systems, a sizing algorithm (the wind-FC–HS algorithm) has been developed (Figure 5).

Recapitulating, the operation scenarios of the proposed configuration include the following:

- In case that wind energy production is sufficient to cover energy demand, wind energy is fed directly to the local consumption and any appearing energy surplus is used to operate the electrolysis unit and feed the FCs through the metal hydride tank. In case that hydrogen

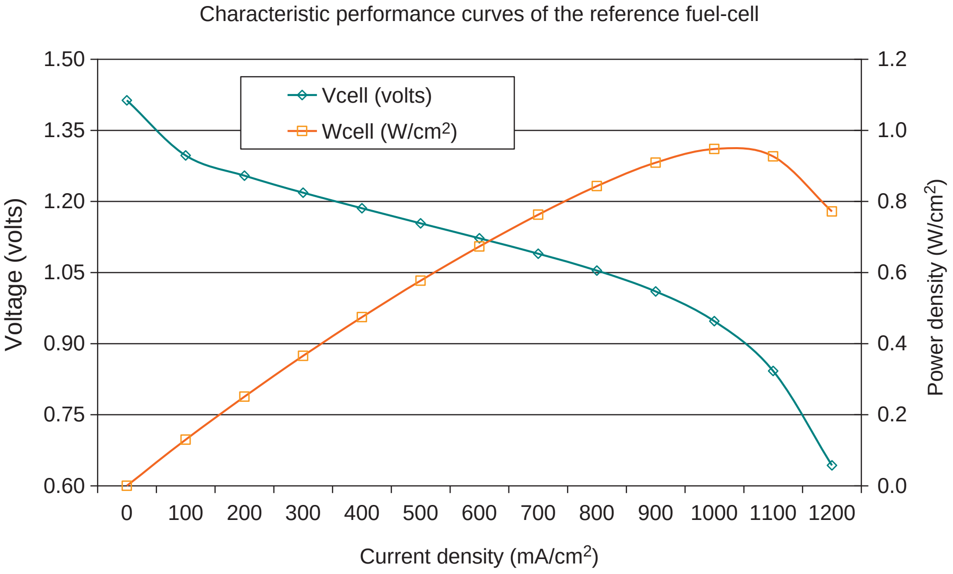

Figure 8. The current and power density vs. voltage curves of the reference FC.

produced cannot be fully absorbed by the metal hydride tank, hydrogen surplus is forwarded to the compressor, in order to fill high-pressure hydrogen cylinders/vessels for the satisfaction of other energy flows (e.g. transportation needs).

- In case that wind energy production is not sufficient to cover the respective load demand, the required quantity of hydrogen is used in order to operate the FC and cover any appearing energy deficit.

As a result, given a wind park capacity value, the hours of load rejection per year are recorded under a fixed metal hydride tank energy storage capacity, while to obtain minimum hours of rejection the storage capacity is gradually increased within a predefined range of variation. Furthermore, in the case that energy autonomy is not achieved, the wind park capacity is also increased, up to the point that 100% energy autonomy is obtained on the basis of using the wind-FC–HS solution.

3. Case study characteristics

For the application of the proposed solution, the area of the Aegean archipelagos has been selected as case study. The specific region is located on the east side of the Greek mainland and comprises hundreds of scattered islands that are in their majority not appreciating interconnection to the mainland electricity grid. Furthermore, the entire area is favoured by high-quality solar potential, ranging between 1300 and 1800 kWh/m^2.a (Moustris et al. 2008), while in several of the islands, medium–high-quality wind potential is also met (Vogiatzis et al. 2004). To this end, as already mentioned, there are several studies evaluating the solution of wind-pumped hydro schemes (Kapsali and Kaldellis 2010; Kaldellis, Kapsali, and Kavadias 2010; Kapsali, Anagnostopoulos, and Kaldellis 2012), designating their suitability and cost-effectiveness for medium–large-scale island areas that also present the landscape characteristics required for the implementation of such configurations (i.e. water reservoirs of sufficient capacity at considerable elevations). On the other hand, restrictions posed in most cases concerning the application of pumped hydro storage could be by-passed by the use of more compact wind-FC–HS or wind-battery schemes, suitable for small–medium-scale island applications.

In this regard, the proposed solution is accordingly applied to an electricity system that is representative of a small–medium-scale Aegean island (peak demand of approximately 2 MW during the summer period and annual energy consumption in the order of 7.5 GWh), favoured at the same time by a wind potential that is determined by an annual average wind speed in the order of 7.3 m/s. More precisely, both wind speed measurements and detailed load demand (on an

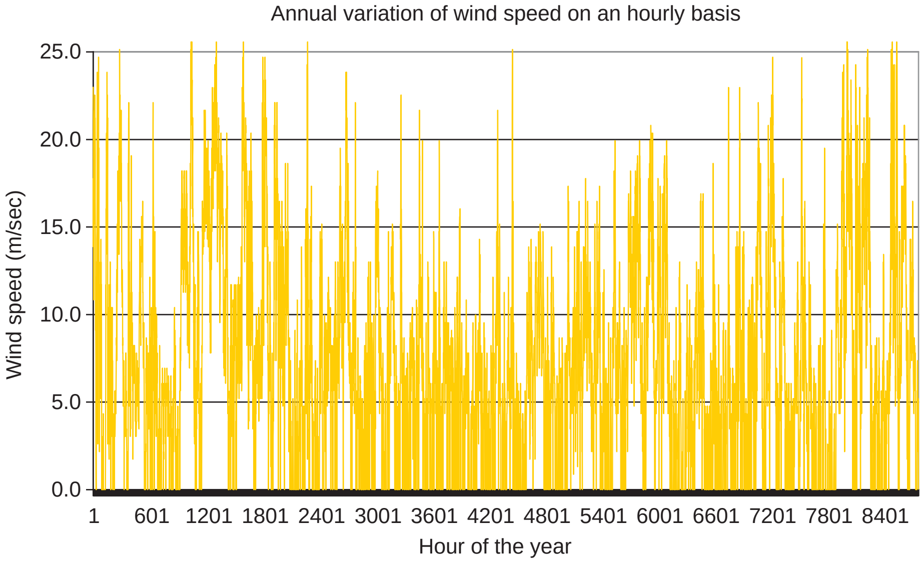

Figure 9. Wind speed measurements for the area of investigation.

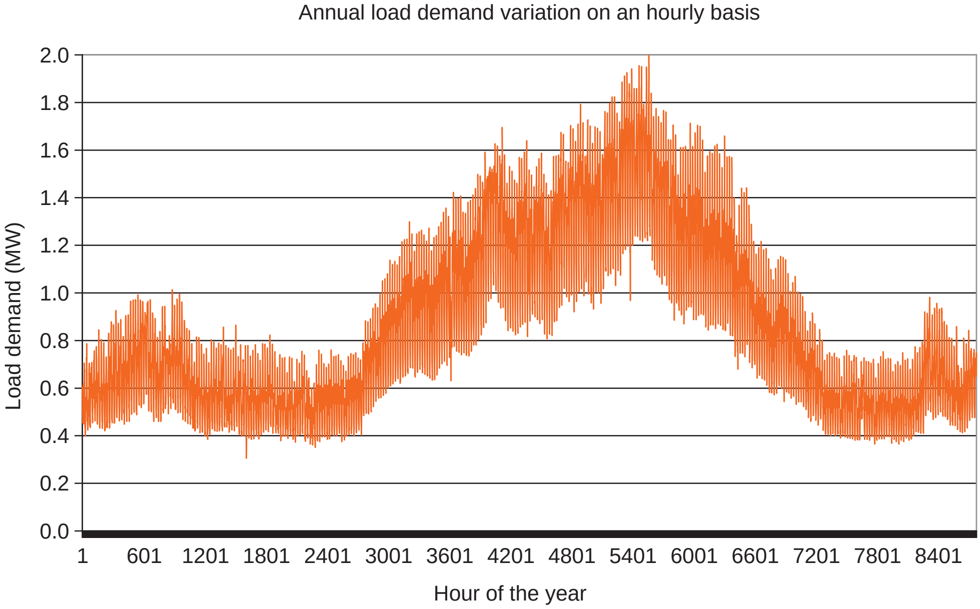

Figure 10. Hourly load demand for the area of investigation.

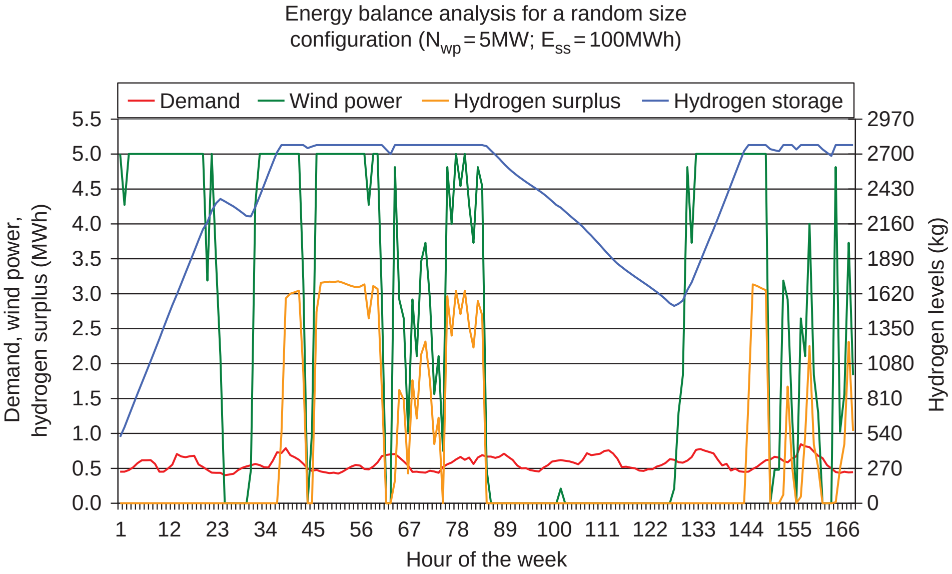

Figure 11. Energy balance analysis of the proposed solution.

hourly basis) are used in order to perform sizing of the proposed solution, with the respective data given in Figures 9 and 10.

4. Application results

Results obtained from the application of the proposed algorithm are given in the following figures, considering also variation of both the wind park and the employed storage capacity (i.e. $N_{wp} = 2 - 12$ MW, $E_{ss} = 50 - 400$ MWh). Prior to the analysis of sizing results, potential of the algorithm to reflect the hourly energy balance of the proposed configuration is presented in Figure 11, where operation of a representative wind-FC–HS system is examined for a one-week period. As one may see, in cases of increased wind energy contribution, energy surplus is used in order to increase HS levels up to a maximum that is determined by the available energy storage capacity, while in case that the metal hydride tank is full, hydrogen surplus appears, that can be used, as earlier seen, for filling high-pressure hydrogen cylinders/vessels.

On the other hand, when an energy deficit appears, i.e. when wind energy production is not sufficient to cover the local demand, the storage level is reduced since the required amount of hydrogen is drawn in order to operate the FCs.

Accordingly, the energy autonomy levels achieved by the proposed solution are examined. More precisely, in Figure 12 the solution of wind-FC–HS is examined for the area investigated in terms of hours of load rejection per year. According to the results obtained by the algorithm, parallel increase in wind power and storage capacity is as expected gradually reducing hourly load rejections per year. In this context, the selected range of variation of input parameters produces energy-autonomous configurations only for wind park capacities above 10 MW, requesting at the same time energy storage in the order of 350–400 MWh, reflecting in this way the importance of energy losses occurring during a full system cycle.

At the same time, however, due to the fact that in order to deal with the low efficiency of the entire process, the wind power capacity has to be increased considerably, hydrogen surplus that

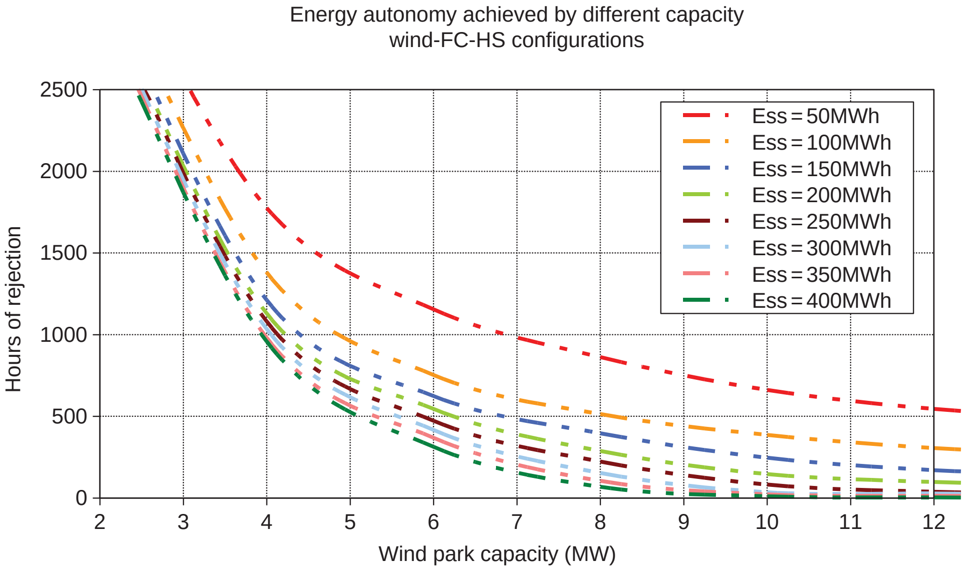

Figure 12. Energy autonomy levels achieved by different size wind-FC–HS configurations.

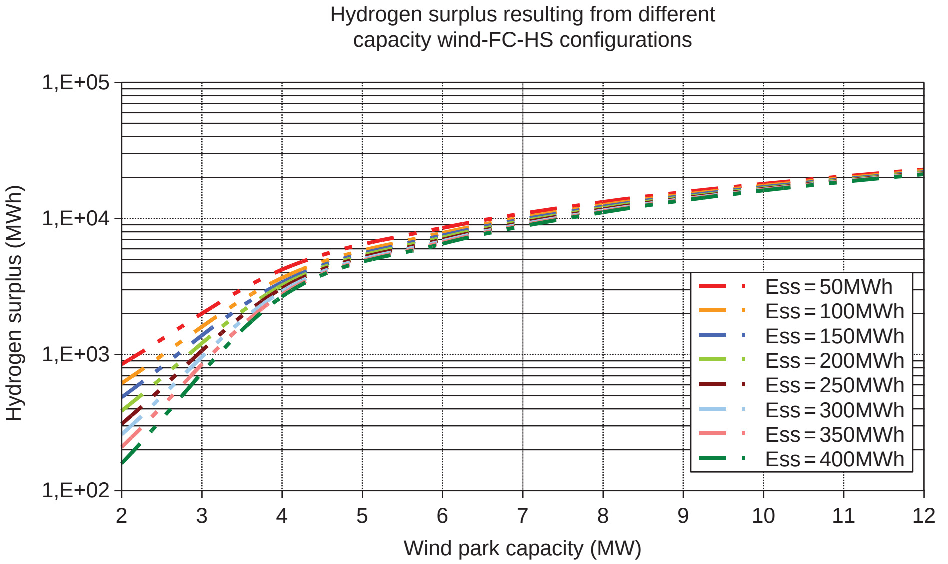

Figure 13. Hydrogen surplus in relation to wind power variation.

could be potentially exploited with the use of compressors is also notable. In fact, as one may see in Figures 13 and 14, energy content of the produced hydrogen surplus increases with the increase in wind energy production (Figure 13) and may even reach 50% of the annual wind energy yield for the higher wind capacity values (Figure 14).

Finally, for comparison purposes, results obtained from the examination of conventional lead acid batteries, as an alternative to the FC–HS solution, are given in the final Figure 15. In this context, lead acid batteries of total round-trip efficiency in the order of 70% (including also converters' and other components' energy losses) and 65% depth of discharge are currently examined. Based

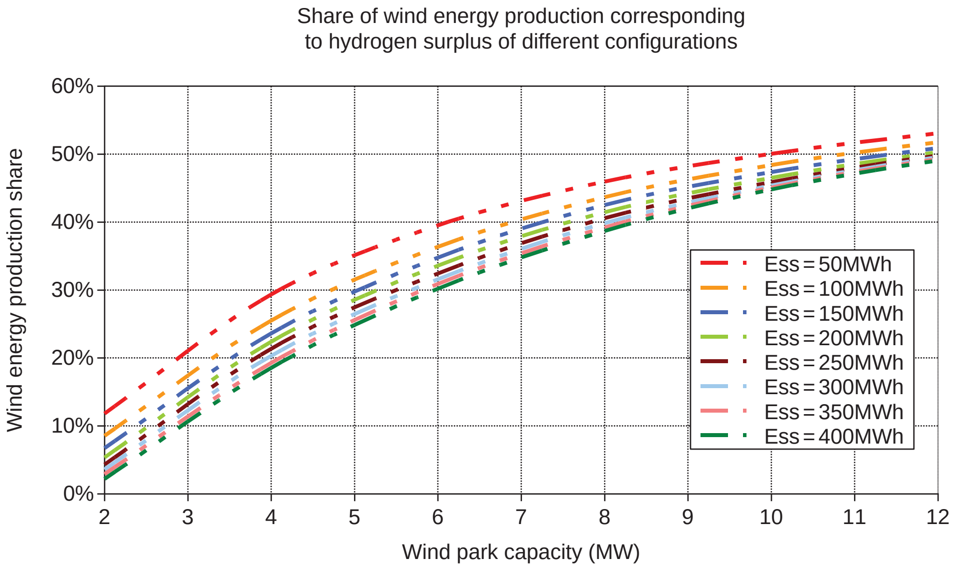

Figure 14. Share of wind energy production turned to hydrogen surplus.

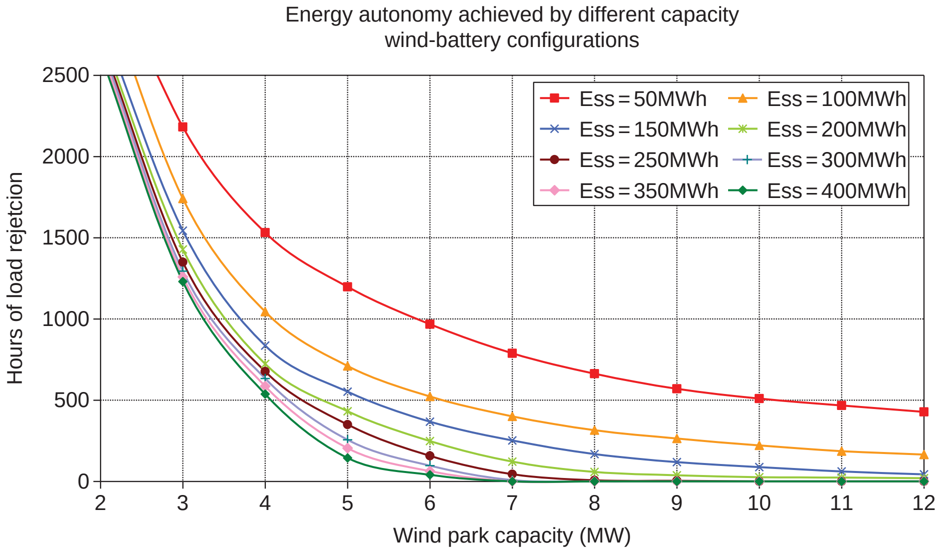

Figure 15. Energy autonomy levels achieved by different size wind-battery configurations.

on the results obtained, the battery storage solution achieves energy autonomy even if 7MW of wind power capacity are installed, while in the case of using the highest energy wind park capacity, the respective energy storage capacity required drops to 200 MWh., i.e. much lower than the respective of the FC–HS solution.

To this end, if also taking into account that hydrogen-based energy storage is determined by extremely high investment costs, at the moment battery storage seems to comprise the optimum energy storage solution in order to promote large-scale integration of wind energy. On the other hand, however, if considering that hydrogen surplus could in the future be exploited in order to cover other energy flows on top of electricity needs (e.g. transportation and heating needs of the islanders), as well as the fact that the service period of battery storage is considerably lower, further investigation of costs on a life-cycle basis is required so as to designate the optimum energy storage configuration, which will of course also depend on the characteristics of the island region each time examined.

5. Conclusions

Large-scale integration of wind energy requires different support measures to be put forward. Of special interest in this context is the introduction of energy storage techniques in island electricity grids suffering from low penetration levels of wind energy and RES in general. In this way, recovery of considerable wind energy curtailments may be achieved, while also ensuring the maximum exploitation of such regions' high-quality wind potential. Implementation of similar solutions could also reduce or even eliminate dependence of these areas upon oil imports required to secure electricity supply. Considering the above, we are currently investigating the potential of hydrogen-based energy storage to support large-scale wind energy integration in island grids.

For this purpose we develop an appropriate sizing algorithm, able to evaluate the energy performance of different wind-FC–HS configurations, and apply it to a representative isolated island region of the Aegean Sea that appreciates medium–high wind potential. According to the results obtained, owing to the considerable energy losses occurring during the operation of an FC–HS configuration, the required system size increases remarkably, especially if comparing this with the results obtained from the application of battery storage instead. On the other hand, as the wind park capacity increases, hydrogen surplus that may potentially accrue is considerable. To this end, further investigation is required in order to evaluate the economic performance of such a system and determine the optimum size that will also take into account satisfaction of additional energy flows such as transportation and heating needs through exploitation of the hydrogen surplus.

Acknowledgements

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