Arnaud ETE

MSc in
Energy System and the Environment

Optimization of the HARI stand-alone energy system with TRNSYS

Individual Project

Friday 22nd September 2006

Abstract

The project aims to assess the viability of a stand-alone hydrogen-based energy system. This will be achieved using software models that could be applied in the design of similar hydrogen and renewables systems. The suitability of the selected tools for this tasks will also be assessed.

The assessment will be based around the case study of the Hydrogen and Renewables Integration (HARI) project at West Beacon Farm in Leicestershire. This project investigates methods of storing the energy generated by intermittent renewable sources using hydrogen. A hydrogen system comprising an electrolyzer, a pressurised gas store and fuel cells has been added to an existing renewable energy system which includes wind turbines, PV arrays and micro-hydro generators to feed commercial and domestic loads on a local mini-grid. The local electricity distribution network is centred around a 620V DC bus. The HARI project illustrates the concept of “Hydrogen Economy” with the ultimate objective of achieving grid independence for West Beacon Farm once become self-sufficient.

In this project the HARI system is modelled and simulated with the program TRNSYS, developed by the University of Massachusetts, in parallel with another modeling and optimization software (HOMER).

The specific objectives of the work are as follows.

The first objective was simply to evaluate the ability of TRNSYS to model the HARI system.
The second objective was to use HOMER and TRNSYS in parallel to compare the operation of both programs and to optimize the size of the HARI system components and thereby improve its performance.
Thirdly, a methodology was established from the modelling process.
This methodology was finally applied in a different context: the HARI system relocated into a more Northerly climate (Glasgow); this was undertaken to determine the impact of weather changes on the optimal configuration of the system.

The main outcome of the project was that the optimization process developed and applied to the HARI system predicted the potential for a significant reduction in the size of the system components, thereby reducing the system cost and improving its performance. The geographic relocation of the project indicated that the optimization process was applicable on different scenarios.

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A. Introduction and objectives

1. Aims and objectives of the project

Stand-alone power systems are used by many communities around the world that have no access to grid electricity. But whereas most of these stand-alone systems are still based on fossil fuel power production, the use of renewable energy within these systems is growing as a consequence of rising fuel prices and environmental concerns. The integration of wind and solar energy system based on a long-term seasonal storage of hydrogen is considered as a promising solution to overcome the limitations associated with the intermittency of renewable sources.

The Hydrogen and Renewables Integration (HARI) project at West Beacon Farm (WBF) in Leicestershire is part of the research program at CREST (Centre for Renewable Energy Systems Technology), at Loughborough University. This project aims at investigating methods of storing the energy generated by intermittent renewable sources such as wind and solar energy. The project, which was actually conceived with the ultimate objective of achieving grid independence for WBF once become self-sufficient, constitutes the first illustration of the concept of "Hydrogen Economy" in action within the UK.

But this hydrogen-based technology is far from being mature, with only a few examples throughout the world. This is still an expensive technology and developing software models of these stand-alone power systems is therefore essential to simplify the design of future similar systems. The main objective of this project was therefore to model a stand-alone power system (the HARI project, described later), optimize the size of its components and evaluate its performances under different geographical and weather conditions.

More specifically, this report presents two models of the HARI system developed on the TRNSYS and HOMER simulation platforms. The results of these models are analysed and compared in order to estimate the accuracy of the simulations. Both models can then be used complementarily using the strong points of each program to determine the optimal size of the system. HOMER is used to find a first approximation of the optimal system, and TRNSYS is then used to refine the previous results.

The specific objectives of the work are therefore to evaluate the ability of TRNSYS to model the HARI system, to compare the operation of HOMER and TRNSYS, to establish a methodology using both programs in parallel to optimize the size of the HARI system components and thereby improve its performance, and finally to determine the impact of weather changes on the optimal configuration of the system.

This report is organised in 6 parts. The next part describes the HARI project and the different elements that compose the power system. A crucial aspect of this project, the control strategy developed at WBF to control the HARI system, is part of this description. Parts C and D describe the models developed with HOMER and TRNSYS. The methodology for the optimization process and the results of the simulations are presented in part E. Finally, the effects of the relocation of the HARI system in Glasgow precede the conclusion of this report.

2. The Hydrogen Economy

The term "Hydrogen Economy" has different definitions depending on people who use it, but in its purest sense, it represents an energy systems relying exclusively on renewable energies for its primary resource and hydrogen for energy storage.

All hazards of greenhouse gases are therefore eliminated in this system where all the primary energy will come from renewables (and nuclear power potentially). But in a stand-alone renewable energy system where the primary energy resource is totally dependent upon the weather, the output of such a resource cannot be controlled and it is inevitable that the power supply rarely matches the fluctuating demand of the system's loads. Some form of balancing mechanism is absolutely necessary, as well as some form of energy storage.

Batteries are able to compensate this mismatch over short periods, but they become expensive, bulky and inefficient beyond a few days. Lead acid batteries for example suffer from self-discharge, limited charge rates, high maintenance requirements and short lifetimes.

On the other hand, hydrogen offers long-term and large-scale capacity storage achievable at a lower cost. At times of surplus of electricity production from the renewables, hydrogen can be produced through electrolysis of water (electrical energy transformed into chemical energy) and stored for later use. When there is a shortage of power from the renewable sources to power the loads on the system, the stored hydrogen can be converted back to water via fuel cells, releasing electricity to match the demand. The production and consumption of hydrogen are actually used as a load balancing mechanism. Moreover, hydrogen presents both a means of storing grid power and of providing transport fuel. Vehicles will then be able to run without emitting any hazardous gas, while providing the performances we expect from conventional engines – something that batteries have never been able to achieve. Combining the needs of balancing supply and demand on the electricity grid with providing fuel for transportation, hydrogen produced from renewables is the energy medium that can offer a pollution-free energy system for the future.

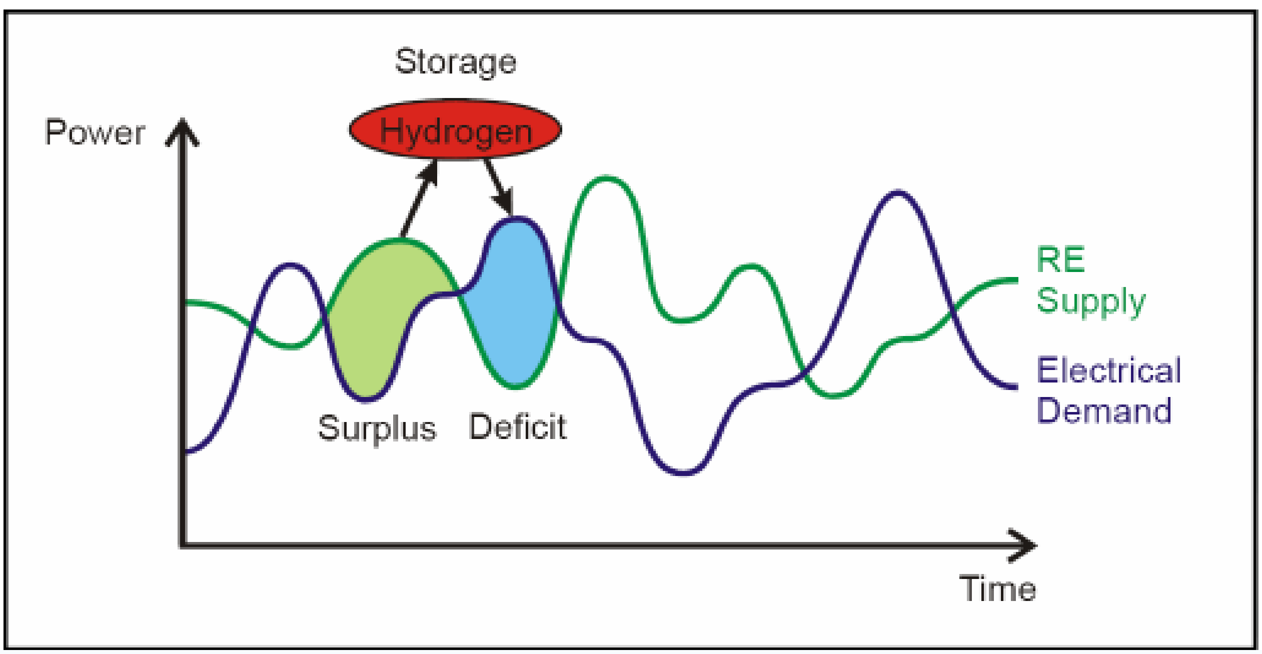


Figure 1: Hydrogen used as a load-balancing mechanism [2]

B. Description of the HARI project

The Hydrogen and Renewables Integration (HARI) project, joint winner of the "Non-profit Organisations" category of the 2006 Eurosolar UK Awards, is a research initiative investigating a stand-alone energy system that associates a complete renewable system and a hydrogen energy storage system. It is part of the research program at CREST (Centre for Renewable Energy Systems Technology), at Loughborough University. It constitutes the first large scale illustration of the concept of "Hydrogen Economy" in action within the UK.

1. West Beacon Farm

West Beacon Farm (WBF) in Leicestershire is a family home that has been converted to demonstrate an integrated sustainable energy generation network providing independence from fossil fuels. More accurately, what is generally refered to as the West Beacon Farm (WBF) system is, in fact, spread across two interconnected sites that are very close to each other: the West Beacon Farm site itself and the Beacon Energy (BE) offices at Whittle Hill Farm. In 1969, the land of West Beacon Farm was very bleak, with only few trees. The priority was therefore to plant thousands of trees, which has enhanced the farm, enriched the biodiversity and at the same time added to the capture of carbon dioxide in the atmosphere. When in the 1980's the public awareness was being raised and the UK's increasing reliance on imported energy was also being highlighted, it was decided to replace the oil fired boiler in the farmhouse with a ground source heat pump system. A 4kW wind turbine and 3kW of photovoltaic arrays were installed shortly after that to make the heat pump a self-sufficient system powered entirely by renewables. The site has now become one of the world's best examples of renewable energy in practice. The technologies on site include:

- two 25kW two-bladed wind turbines (now 17 years old),
- a total of 13kWp of PV arrays spread across the two sites,
- 3.05 kW of micro-hydro generators,
- a hydrogen energy system,
- a water conservation system where rainwater is the only source,
- a sustainable transportation system with electric and hybrid cars.

Heating - The farm is heated by a Biklim TOTEM CHP. This propane fuelled CHP unit is approximately 95% efficient and is rated to generate 15kW of electricity and 38kW of heat. Although LPG is a fossil fuel, its combustion is cleaner than standard fuels, with relatively low emissions of greenhouse gases. Gas from a biomass gassifier or hydrogen generated by an electrolyzer could also be used to fuel the unit.
Additional heating is generated by a water sourced heat pump system using the water from the lake of the farm. About 4.5 units of useful heat are produced for each unit of electricity consumed by the heat pump and compressor. Since all the electricity required is produced by renewable sources, this heat pump is one of the cleanest and most efficient home heating systems possible.

Water - West Beacon Farm is not connected to the mains water network. The only source of water on the site is the rain. The rainwater is collected from the rooftop and filtered before being stored in a 6,000 litre underground storage tank. It is then filtered three more times before being stored in a second tank. At this stage it is suitable for all use except drinking. Drinking water passes through a ultra-violet filter and then a purifier.

Transport - An electric car with a range of 120 miles and a top speed of 75mph was bought in 1997. A Toyota Prius hybrid was also bought in 2003. It combines a petrol engine with an electric motor to produces 89% less CO_2 emissions than a conventional car.
The next developments should be the integration of a small 2kW fuel cell into a vehicle and the construction of a hydrogen refuelling station to service the vehicles.

2. The installed system at WBF

On figure 2 can be seen the HARI system existing at WBF. On the left part of the figure is described the renewable system whereas the right part represents the recent hydrogen system.

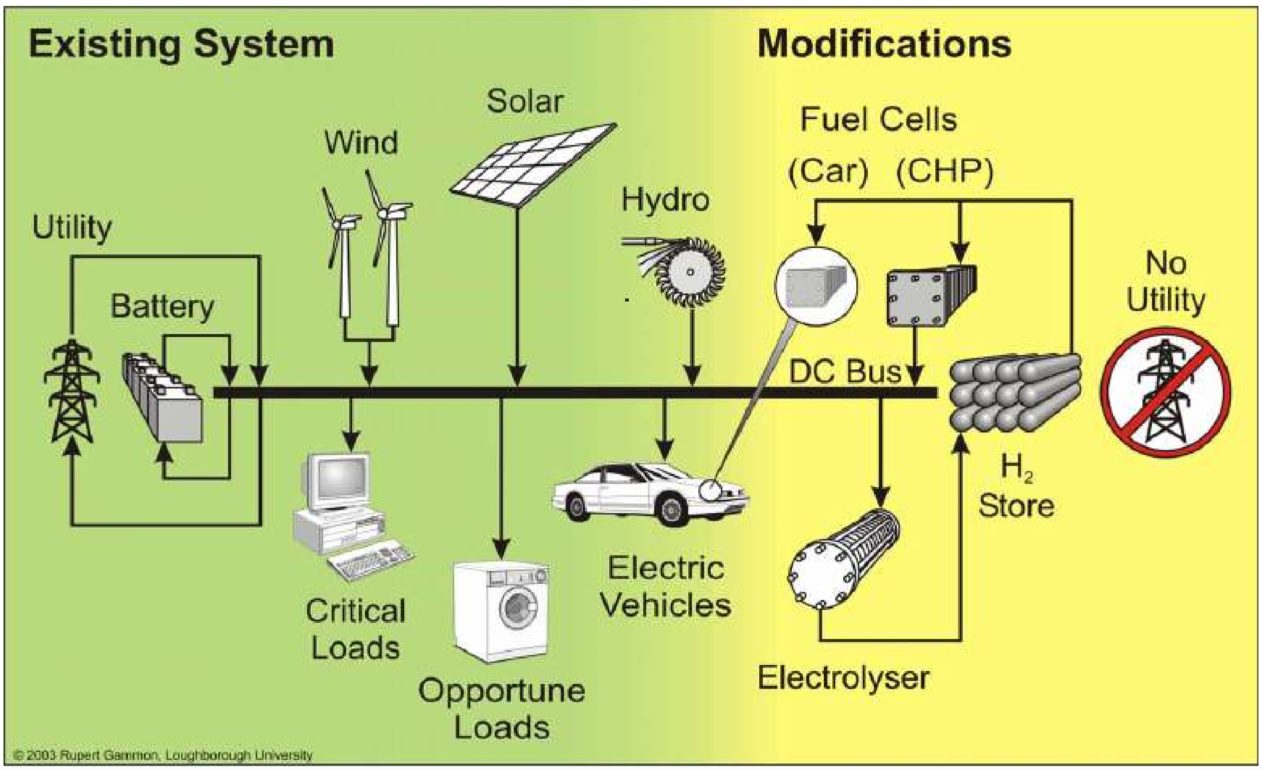


Figure 2: The installed system at West Beacon Farm [2]

a. Installed generators

- **Wind**: Two Carter 25kW wind turbines constitute the main generators on the system and supply the bulk of the energy. These are two-bladed stall-regulated machines with gearboxes and squirrel-cage induction generators, designed for direct-on-line grid connection. The turbines deliver some 3-phase 415V AC.

- **Solar PV**: There is a total of 13kWp PV power spread across the two sites. 6kW feeds directly into the electrical system at WBF and 4kW at Beacon Energy. The PV system situated at BE does not currently feed back into the main system at WBF, but its integration is part of the work going on to upgrade the system's mini-grid. A third PV array at the WBF site does not feed directly into the mini-grid, but drives a borehole pump that helps to fill an artificial lake.
The fixed array of photovoltaic panels connected to the electrical network comprises 3kWp of monocrystalline modules and 3kWp of polycrystalline modules. The PV arrays deliver a 120V Direct Current.
It can be added that the future installation of an integrated PV and Graetzel cell system that combines solar electricity production and electrolysis in one device is investigated even if the questions about this device are still numerous.

Figure 3: PV arrays at West Beacon Farm [4]

- **Hydro**: An 850W low-head (2m) cross-flow hydro turbine generating from a river that flows through the grounds and a 2.2kW high-head (20m) Turgo hydro turbine running from water flowing from a storage lake are installed. Therefore the total hydro capacity is 3.05kW.

- **Combined Heat and Power unit**: As mentioned above, a TOTEM combined heat and power unit (CHP), based on a Fiat internal combustion engine generates 15kW electrical and 38kW thermal energy. It currently runs on LPG but it is planned in the long-term to convert it to run on hydrogen gas.

b. Hydrogen system

In the HARI project, hydrogen production, storage and usage facilities have been added to the existing renewable energy system at West Beacon Farm to test the feasibility of a stand-alone renewable energy system. The hydrogen system consists of a 36kW electrolyzer, a 2856Nm^3 pressurized gas store and two fuel cells: a 5kW unit and a 2kW unit set up to provide Combined Heat and Power (CHP) output.
It is also planned to include fuel cell vehicles on the site that will be fuelled by its green hydrogen. This should extend the scheme beyond a simple electrical supply system by modeling a complete hydrogen economy.

- **Electrolyzer**: The electrolyzer is a high-pressure (25bar) alkaline type manufactured by Vandenborre Hydrogen Systems (VHS). It can produce up to 8 Nm^3 of hydrogen gas per hour, which requires a power of 36kW. The output of the electrolyzer can be controlled, providing a

corresponding variation in electricity consumption. However, in order to ensure the purity of the hydrogen produced, the minimal production is 20% of the rated capacity.
Due to the very rapid variations of power coming from the wind turbines which threatens to shorten considerably the electrolyzer's lifetime (this will be detailed in the next section), advanced batteries are used to provide short-term energy storage, smooth the short-term fluctuations in electrical input and therefore minimise the cycling of the electrolyzer.

Figure 4: The electrolyzer used at WBF [2]

- **Hydrogen storage facility**: For the hydrogen storage, the technology of metal hydride would be very attractive for the HARI system, but pressurized storage of gaseous hydrogen was the only commercially viable option at that time. The hydrogen store consists of 48 mild steel cylinders, each with a volumetric capacity of 0.475Nm³ and a wall thickness of 38mm for a weight of about one ton. These cylinders would provide a total of 576Nm³ of stored hydrogen at 25bar. But since the cylinders can withstand a pressure of 137bar, a 4kW hydraulic compressor (able to pump up to 11Nm^3/h at a feed pressure of 25bar with a ratio of 1:8) is used to raise the hydrogen pressure, providing 2856Nm³ of hydrogen at full capacity. This gives an equivalent storage capacity of about 3800kWh when the hydrogen is converted back to electricity, providing up to 3 weeks of cover without any renewable energy input.

The compressor used at WBF [1]

Avoiding leakage was one of the biggest challenges of running a hydrogen system. Besides helium, hydrogen has the smallest molecular size of any element, which means that hydrogen molecules can escape through the tiniest openings, where all other gases couldn't pass. All leaks have been eliminated at West Beacon Farm, which represents an outstanding performance.

Eventually, it is planned that a metal hydride store will be tested at the site in collaboration with the University of Birmingham.

Figure 5: The hydrogen store at WBF [2]

- **Fuel cells:** The fuel cells are both Proton Exchange Membrane (PEM) type. The first one is manufactured by Intelligent Energy and is designed for CHP operation. It generates up to 2kW of electricity at 24V DC, and 2kW of heat, and is connected to the heating system. This fuel cell is also able to supply up to 4kW of electricity for short period (around 15 minutes).

The second fuel cell is a Plug Power unit supplied by SiGen. It can generate 5kW electrical power at 48V DC, but doesn't operate as a CHP device. There is also provision for a further fuel cell unit to be added to the system.

Figure 6: Intelligent Energy 2kW FC [1]

Figure 7: Plug Power Gencore® 5kW FC [1]

- **Battery**: The battery used at West Beacon Farm is a sodium nickel chloride (NaNiCl) type, called the Zebra battery and developed by Beta Batteries. It replaced an old 120 kWh lead-acid battery accumulator. Zebra batteries, which work at high temperatures (around 300°C), have an energy density around 100Wh/kg (three times that of lead-acid batteries) and the whole capacity range can be utilised. They can be directly connected to the DC bus with a standard industrial drive. The battery voltage is 620V nominal and its nominal capacity is 20Ah.

Figure 8: The 2kW nickel sodium chloride Zebra battery [1]

c. Summary of HARY components and WBF layout

Sub-system	Manufacturer/Supplier/ Model Designation	Rated Performance	Cost (in £) (indicative)
Electrolyser	Hydrogenics (formerly Vandenborre)	8 Nm^3/hour of H_2, 34 kW, 2.5 MPa (25 bar) rated	143,000
Fuel Cell (1)	Intelligent Energy, CHP Unit	2 kW (el), 2 kW (th), 24 V_{DC}	25,000
Fuel Cell (2)	Plug Power GenCore, supplied by SiGen Ltd	5 kW (el), 48 V_{DC}	20,000
H_2 Compressor	Hydro-Pac supplied by BOC	11 Nm^3/hour, 3.75 kW, 8:1 compression ratio	59,000
H_2 Storage	Supplied by BOC	48 Cylinders, each 0.475 m^3, 13.7MPa (137 bar) max pressure, 2856 Nm^3 total H_2 capacity	122,000
Wind Turbines	Carter Wind Turbines	2 x 25 kW two bladed stall-regulated, pitch over-speed	50,000
Solar PV	BP	13 kW total, mixed poly-crystalline and monocrystalline	60,000
Hydro-electric	Installed by Dulas	850 W Cross-flow with 2 m head; 2.2 kW Turgo with 25 m head	67,000
Integration System	Control Techniques and bespoke converters from Loughborough University	Various	49,000

Table 1: Summary of HARI sub-systems [1]

Table 1 summarizes the main characteristics of the different components of the HARI system. The total cost of the stand-alone energy system installed at West Beacon Farm can be evaluated around £595,000. On the next figure is presented the layout of the HARI system at WBF:

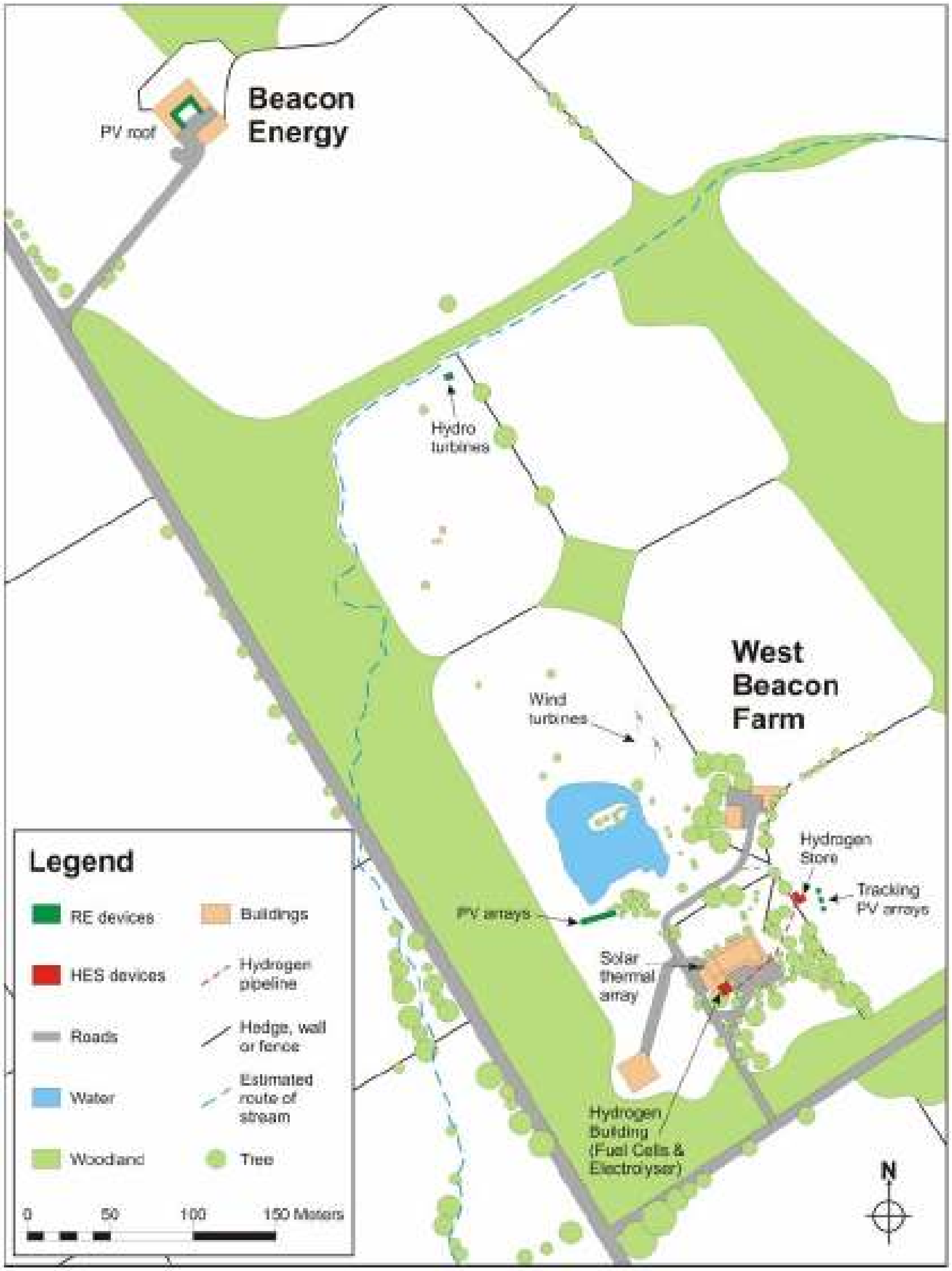


Figure 9: Map of the HARI project site [1]

3. Electrolysis from renewables

Electrolyzers are considered as a mature technology when operated from a continuous steady-state power supply. However, the work carried out at CREST has already shown that powering them from intermittent energy sources such as renewables will require significant modifications in order to improve their efficiency, durability and cost in this particular use. The intermittency of the electrolyzer's operation threatens to shorten considerably its lifetime (the number of ON/OFF switching cycles for the electrolyzer is limited to 2500 before its performances start to degrade substantially). We can note that whereas the electrolyzer was rated at 36kW when purchased, due to the intermittency and variability of the renewable energy supply, it has already degraded and now consumes more like 39kW (thankfully, this appears to have stabilised).

When the electrolyzer is switched off, hydrogen in the cathode causes the potential of the cell stack to reverse, causing corrosion of the cell membranes and reducing lifetime of the electrolyzer. This is the reason why a limit on the number of on/off cycles is defined by the manufacturers. A minimum current is also imposed to maintain the hydrogen gas purity. Another problem is the limited operational range of the electrolyzer (between 20 and 100% of rated power). Indeed, this means that there would be peaks of surplus energy from renewables too big to be absorbed by the electrolyzer and troughs where the surplus production is beneath the range. It appears clearly that intermittency leads to a number of inefficiencies, which may be eliminated or at least reduced significantly by modifying the design of the system and developing an effective control strategy. Moreover, it appears that low pressure systems are preferable for a use with renewables, since dynamic supply damages components and wastes energy in existing pressurized electrolyzers.

As mentioned before, these operational constraints of the electrolyzer require some form of short-term energy storage to smooth the short-term fluctuations in electrical input. As described in the previous section, this has been achieved using a 2kW, high temperature Zebra battery. This hybrid approach benefits of advantages of the two technologies with the batteries that provide an efficient short-term and low-volume storage and the hydrogen providing long-term and bulk storage. Optimisation of the technology for this type of application is still a major part of the ongoing work initiated by this project. It is interesting to notice that 190 batteries such as the one used would be necessary to replace the hydrogen storage, for a cost of £3.9M and a volume of $26.3m^3$.

4. WBF infrastructure

The technologies studied in the HARI project being intended to be applied in a domestic environment, safety and aesthetic considerations are very important. A new building being required to install the new components of the hydrogen system, it was particularly important to avoid the construction of a building resembling to an industrial plant: this hydrogen building needed to follow the style of the other existing buildings on the site.

Figure 10: View of the hydrogen building at WBF [1]

For safety considerations, the building has been divided into two zones: a safe zone and a hazardous zone. The hazardous zone contains the electrolyzer, the fuel cells and the compressor in three different rooms. An advanced ventilation system has also been installed to ensure that any potential hydrogen leaks are managed safely.

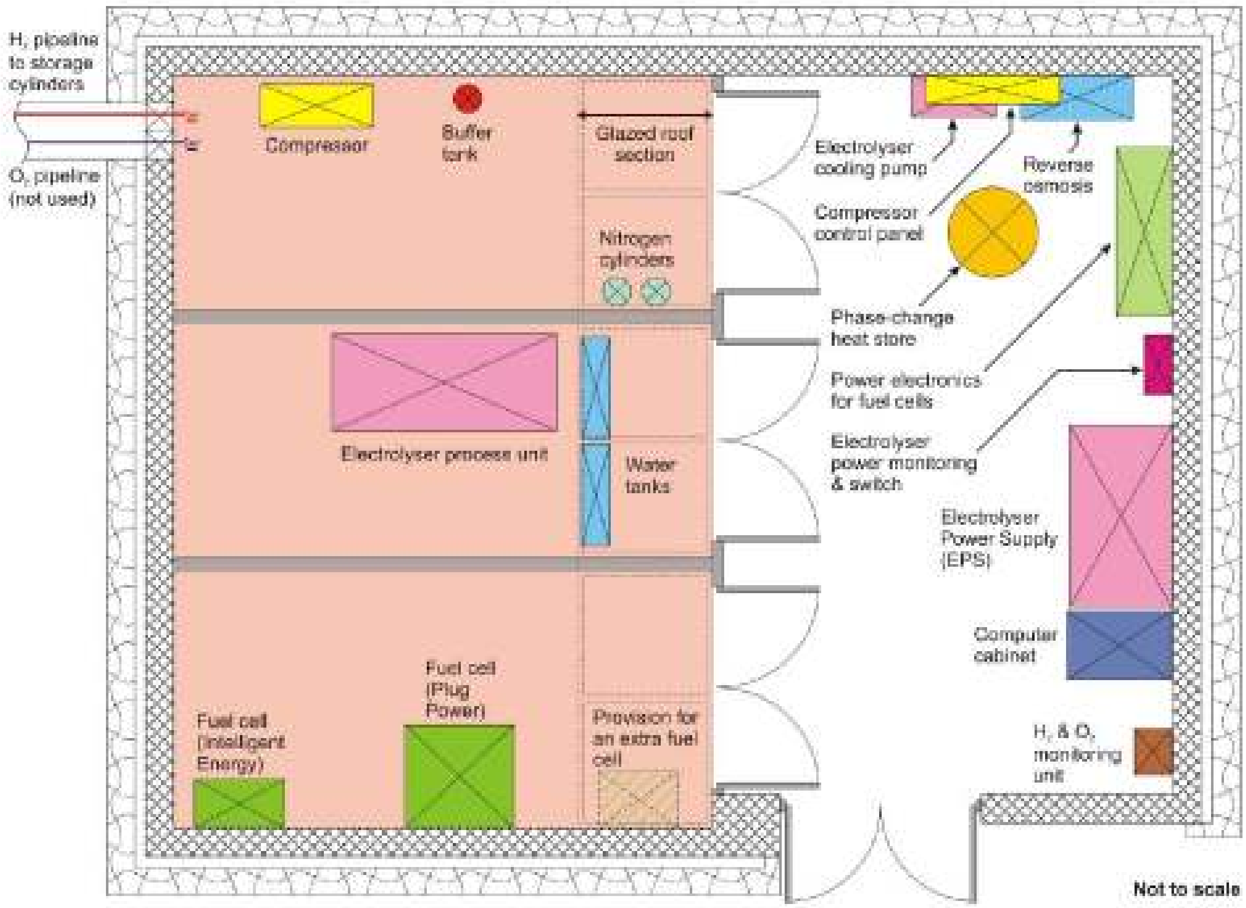


Figure 11: Layout of the WBF hydrogen building [1]
(the pink shaded area is the hazardous zone and the white area is the safe zone)

5. Components integration and electrical network at WBF

The following figure shows an overview of the stand-alone power supply system being installed at West Beacon Farm. The electrical network, which has evolved in a piecemeal fashion because of the addition of various sustainable energy components over the years, makes the overall system far from ideal and needs to be rationalised. The main part of this upgrade involves the establishment of a $620V_{nominal}$ DC bus that will act as the backbone of the entire system where the various generators, loads and storage system are interconnected. This will allow an easier balancing of instantaneous electrical supply and demand between all the various energy technologies involved and allow the deployment of relatively low cost standard industrial drives to connect the various elements of the network. Indeed, in this new system, the rotating generators, such as the wind turbines, are connected through standard industrial drives operating in regenerative mode, whereas the DC devices (electrolyzer, fuel cell and PV arrays) use bespoke DC/DC converters.

The system supplies single and three-phase power to a residential house and offices. The average total load is about 4kW, divided into critical and deferrable loads. The main load is the heat pump, which heats the house but the system is designed to make this a deferrable load.

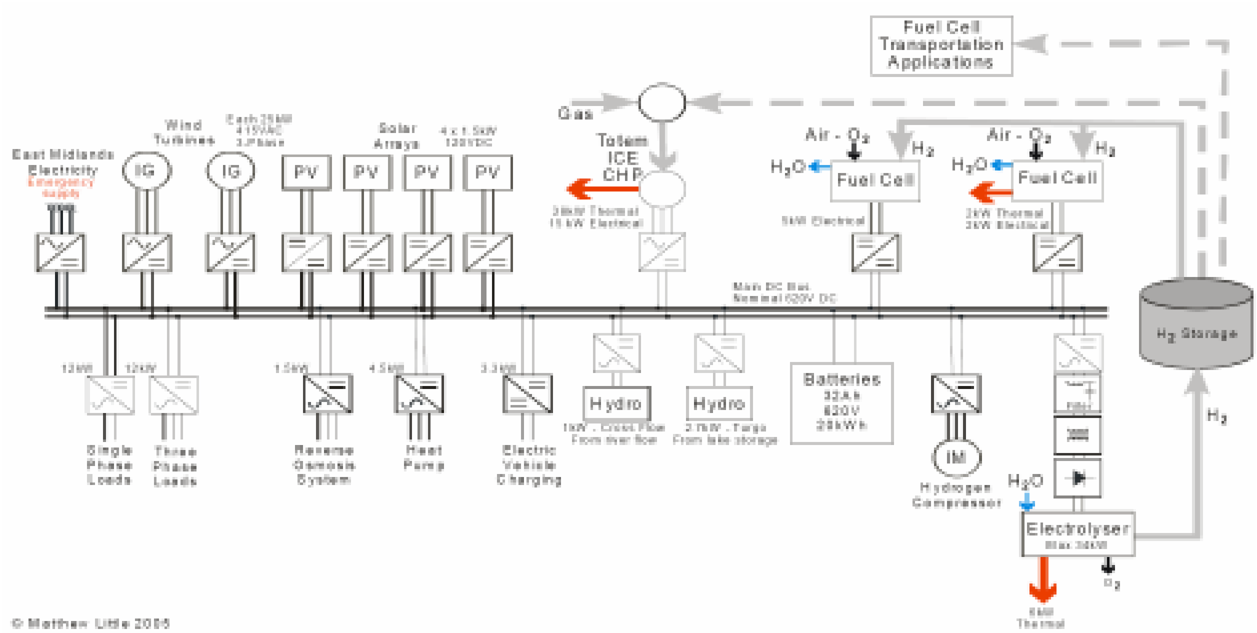


Figure 12: The West Beacon Farm stand-alone power supply [6]

a. Central DC bus

The nominal voltage of the DC busbar is 620V. Indeed, standard 400V AC rectified to DC is 560V, which represents the minimum voltage at which the industrial drives will function correctly. In order to allow some margin, the voltage 620V has been chosen. The electrical system was designed around a central DC bus instead of the usual AC bus for the following reasons:

- AC power supplied to the loads is separated from that of the generators, which allows the power quality provided to the loads (voltage, frequency and purity of waveform) to be maintained independently of the fluctuations of the available wind power, as long as the voltage of the DC bus is kept within broad limits.
- The wind turbines can be operated at variable speed, resulting in a small increase in energy capture despite the losses in the converters. Moreover, by absorbing the rapid variations in wind power thanks to the inertia of the wind turbines, the power delivered to the DC bus is smoothed and mechanical stresses on the turbine structure are reduced.
- The additional cost of the many power-electronic converters of the electrical network is rather lower than firstly expected. Indeed, many electrical loads are already equipped with power-electronic converters. They can therefore be run from DC with just little modifications. Many modern wind turbines also use power-electronic converters and could easily be adapted to generate DC. Similarly, electrolyzers, fuel cells or PV panels are commonly connected through this type of converters.

- The AC/DC inverters shown on figure 12 are standard industrial drives available at low cost.
- No synchronous machine or diesel engine will be needed in the system.
- The connection of multiple drives onto a common DC bus is proven technique in industrial applications.

But using a DC bus also presents some drawbacks, particularly for cost considerations because of the relatively low use of DC systems compared to AC systems.

b. Power-electronic converters

AC/DC converters
The AC/DC converters of the system are standard industrial drives widely used in industry. They are reliable, efficient and very cost effective. As required for the generators, the power flow in the transistor-bridge stage can be reversed.
The domestic and office loads (shown at the bottom left on figure 12) are also fed through standard industrial drives configured to provide a constant 50Hz at 400/230V. The efficiency of AC/DC converters usually lies around 90%.

DC/DC converters
The DC/DC converters that connect the electrolyzer, fuel cells and PV arrays to the DC bus are necessary to operate each of these devices at the optimum points on their current-voltage characteristic curves. All DC/DC converters installed at West Beacon Farm are actually DC/AC/DC converters because of their higher efficiency.

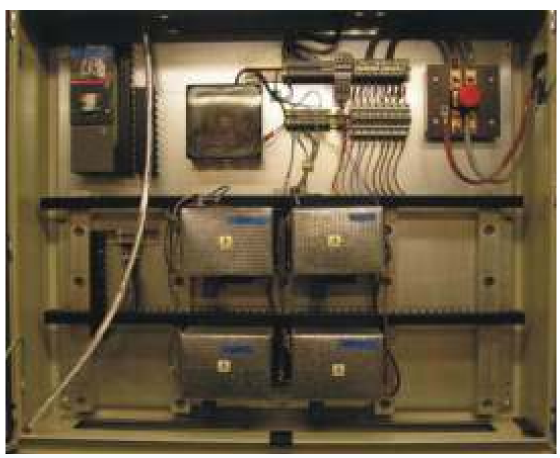


Figure 13: The bespoke DC/DC converters [6]

The step-down DC/DC converter connecting the electrolyzer uses a standard industrial drive which converts the 620V DC to a controlled three-phase AC voltage. A transformer then increases the current, and lastly a diode bridge rectifier provides the DC to the electrolyzer stack.
The converters required for the fuel cells and PV arrays are more complex and had to be designed especially for this system. A two-transistor forward converter topology was selected as a basic building block as shown on the following diagram.

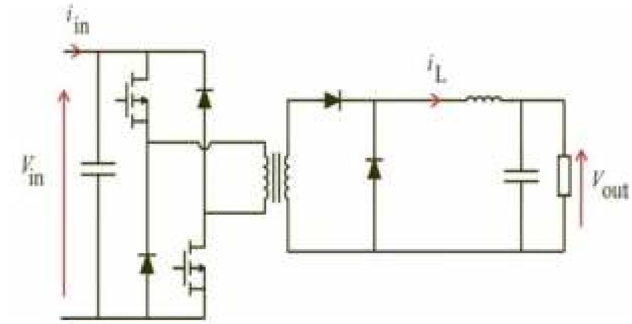


Figure 14: Two-transistor forward converter diagram [6]

Of course, inefficiencies are involved in converting the voltage levels of the different components to that of the DC busbar. This can be divided in a standing load and a proportional efficiency.

c. Power conditioning model in TRNSYS

The power conditioning components used in TRNSYS can invert DC power to AC power, transform AC to DC power or be used as DC/DC converters. Here is briefly described the mathematical model of the power conditioner.

The power loss in a power conditioner is mainly dependent on the current running through it and can be described as following:

$$P_{\text{loss}} = P_{in} - P_{out} = P_0 + \frac{U_s}{U_{out}} P_{out} + \frac{R_i}{U_{out}^2} P_{out}^2$$

where P_0 is the power loss when there is a voltage through the conditioner (W), U_S is the set point voltage (V), R_i is the internal resistance (Ω), P_{out} is the power output (W) and U_{out} is the voltage output (V).

From the previous equation can be derived a relationship between the input power P_{in} and the output power P_{out}, introducing the nominal (maximum) power P_{nom} of the conditioner:

$$\frac{P_{\text{in}}}{P_{\text{nom}}} = \frac{P_0}{P_{\text{nom}}} + \left(1 + \frac{U_s}{U_{out}}\right)\frac{P_{out}}{P_{\text{nom}}} + R_i P_{\text{nom}}\left(\frac{P_{out}}{P_{\text{nom}}}\right)^2$$

In TRNSYS, either the input power or the output power can be entered as an input depending on the use of the power conditioner. For example, in the HARI system, the input is known for the power conditioner placed before the electrolyzer whereas the output is known for the power conditioner of the fuel cell.

The efficiency of the power conditioner can simply be calculated using the following expression:

$$\eta = \frac{P_{out}}{P_{in}}$$

6. System of control

The renewable energy sources and a part of the loads installed at WBF are intermittent, variable and therefore largely unpredictable and uncontrollable. On the other hand, other components like the storage elements and deferrable loads can be controlled. A control strategy seems therefore indispensable at WBF, whose main objective is to achieve reliable and efficient operation of the system taking into consideration the constraints associated with the life-time of the components.

a. Power supply control

The main requirements of a power supply system are to supply the necessary power to the loads, keep all the system components within their operational limits and use the available power in an efficient way.

Many AC loads require that their supply voltage and frequency to stay within tight tolerances. With a traditional AC-connected system, this requirement implies that the voltage and frequency are tightly controlled throughout the system, which is quite difficult to achieve.
A DC-based system splits up the voltage and frequency requirements of the load from the generators thanks to power-electronic converters and a central DC busbar. This provides a better power quality for the loads and allows components to be run at different or variable speeds. Another advantage of separating the loads on the system is that non-critical loads can be deferred for periods with more available power from renewables, which increases the overall system efficiency.

The main objective of the system control is actually to ensure that the voltage on the DC busbar stays within the operational limits of the power-electronic converters under all possible conditions. In a stand-alone power system using a battery as an energy buffer like the HARI system, the on/off switching of the electrolyzer and the fuel cell can be based on the state of charge (SOC) of the battery.
Without the battery to provide short-term energy storage, maintaining the voltage on the busbar would require a very rapid control of the electrolyzer to balance the power flowing in and out of the DC bus capacitors. Such a system would increase the number of on/off switching cycles of the electrolyzer and therefore shorten its life-time. Thanks to the battery, the voltage of the DC bus can be hold largely constant and the control challenge becomes to maintain the battery state of charge. This can be achieved because the Zebra batteries have a 100% coulombic efficiency which allows the SOC to be precisely determined and used for system control.

The electrolyzer and fuel cells determine the energy flow in and out of the hydrogen tanks and must therefore be controlled. Additionally, some of the loads may be controlled, like the reverse-osmosis unit (that delivers fresh water to a large storage tank) or the heat-pump. It can finally be added that the system can be supported by grid electricity in case of emergency.

b. Control parameters and description of the control strategy

Whereas the Zebra battery will provide short-term smoothing to protect the electrolyzer, some instantaneous control is now required to maintain the battery's state of charge. Ideally, the battery SOC should be kept high in order to provide a buffer to the system. However, some margin and hysteresis consideration are necessary to take into account the response time of the electrolyzer. As the SOC decreases, the fuel cells will operate. If the fuel cells cannot cope with the reduction of the state of charge, some other generator must operate (a bio-diesel generator for example) even if it would be better to minimise the operation of such a back-up.

The following diagram presents a visualisation of the battery SOC based control system:

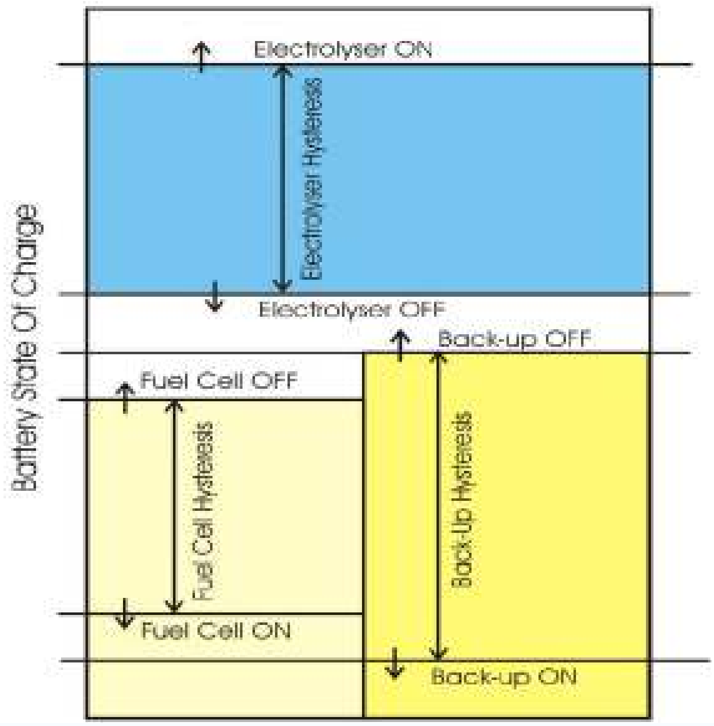


Figure 15: State of charge control [6]

The system represented on figure 16 is called *five-step charge controller* and illustrates the control of the electrolyzer and the fuel cell using the SOC of the battery (control described previously without the back-up generator, but the model is the same). The on/off switching set points for the electrolyzer and the fuel cell (El_{up}, El_{low}, FC_{up} and FC_{low}) can be observed on this graph. The control signals for the electrolyzer and the fuel cell γ_{EL} and γ_{FC} can only reach the values 0 (OFF) or 1 (ON).
Additionally, the battery needs to be protected from overcharging or undercharging, which is why some protection thresholds for high and low SOC are introduced in the control strategy.

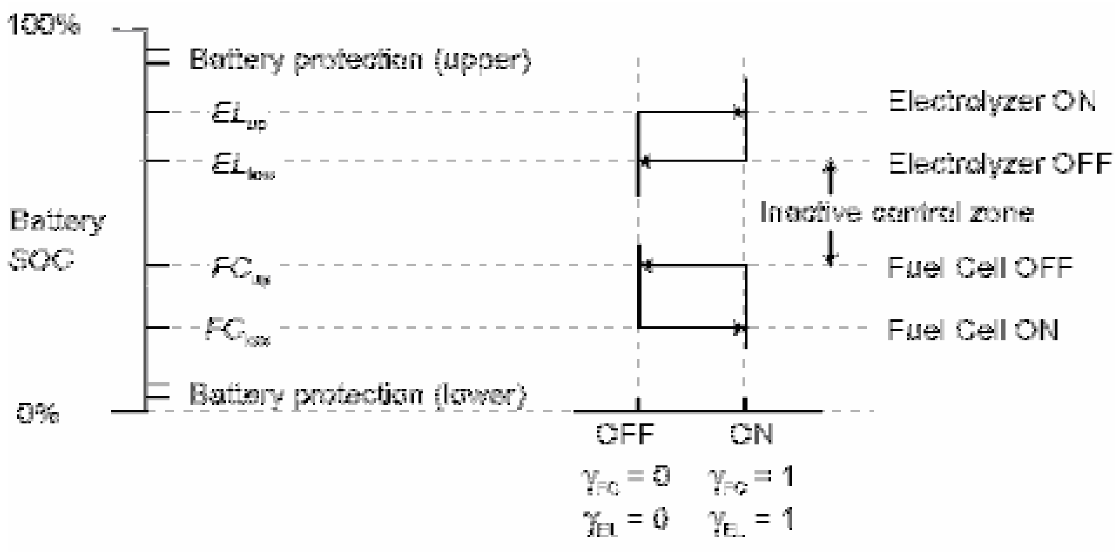
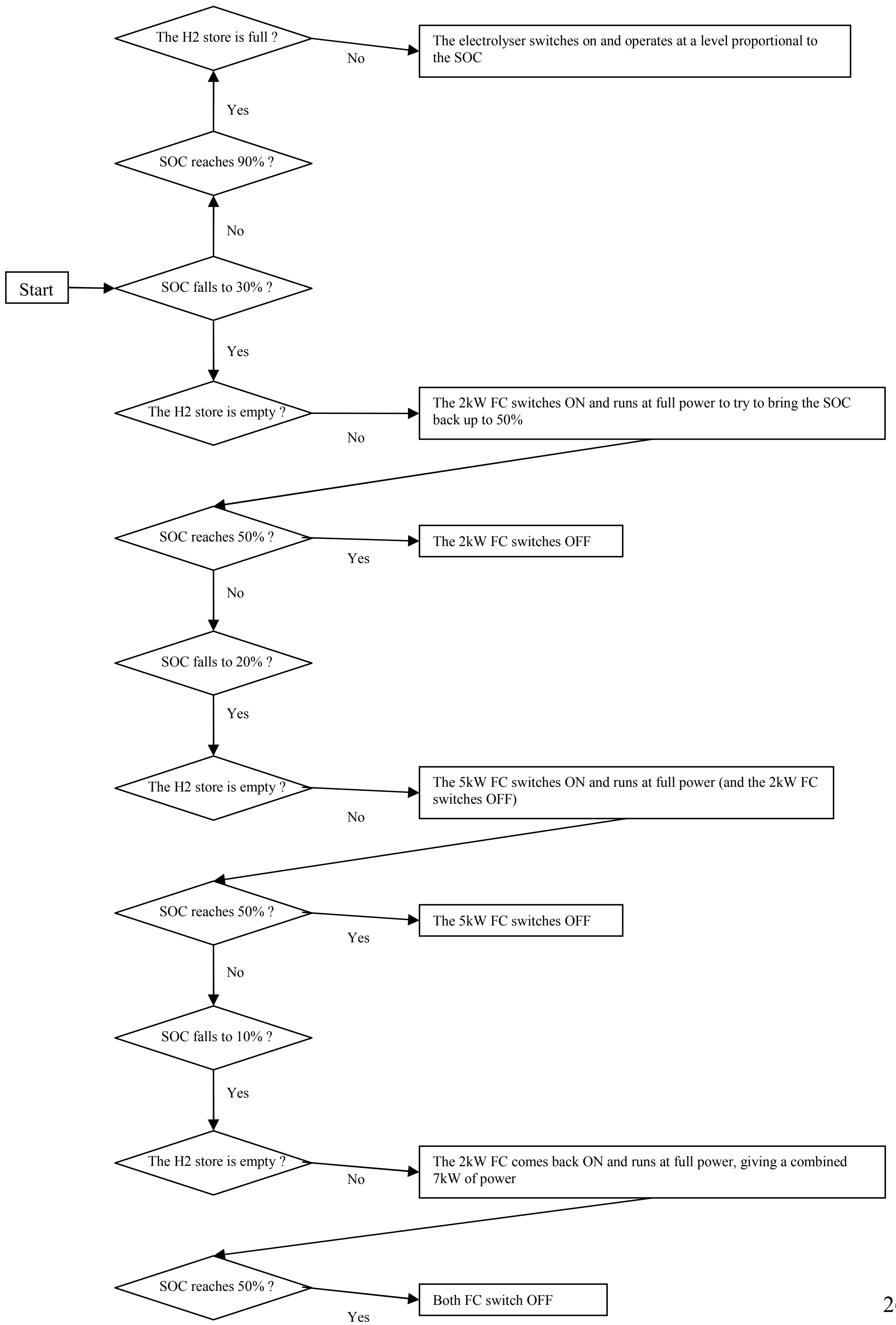


Figure 16: Control strategy for the electrolyzer and the FC based on the battery SOC [14]

The detailed control strategy of the HARI system is as following:

The control strategy relies entirely upon the SOC, measured as a percentage, of the battery. The objective is to keep it floating at around 50%. When it falls to 30%, the 2kW fuel cell is switched on to try to bring it back up to 50%, at which point it switches off. If it is not sufficient and the SOC continues to fall, the 5kW fuel cell switches on (and the 2kW FC switches off) at 20%. Again, this will switch off when the SOC% reaches 50%. If the 5kW fuel cell is unable to bring the SOC back to 50% and it continues to fall down to a level of 10%, then the 2kW fuel cell comes back on, giving a combined 7kW of power trying to recharge the battery. Both fuel cells continue to run until 50% SOC is achieved, at which point they both switch off. In all these cases, when switched on, the fuel cells will run at full power. The electrolyzer is switched on when the SOC reaches 90%, operating at a level that is proportional to the SOC, and switches off when it has brought the SOC down to 50%. Of course if the hydrogen store is full, the electrolyzer cannot run. In the same way if the hydrogen store is empty (i.e. if only the cushion gas is left), the fuel cells cannot run. In other cases, the hydrogen storage level is ignored.

This control strategy is represented on the following flowchart:


The H2 store is full ?
No
The electrolyser switches on and operates at a level proportional to the SOC
Yes
SOC reaches 90% ?
No
Start
SOC falls to 30% ?
Yes
The H2 store is empty ?
No
The 2kW FC switches ON and runs at full power to try to bring the SOC back up to 50%
SOC reaches 50% ?
Yes
The 2kW FC switches OFF
No
SOC falls to 20% ?
Yes
The H2 store is empty ?
No
The 5kW FC switches ON and runs at full power (and the 2kW FC switches OFF)
SOC reaches 50% ?
Yes
The 5kW FC switches OFF
No
SOC falls to 10% ?
Yes
The H2 store is empty ?
No
The 2kW FC comes back ON and runs at full power, giving a combined 7kW of power
SOC reaches 50% ?
Yes
Both FC switch OFF

c. Optimisation of the control strategy

The choice of the optimal control strategy is a crucial element in the design of a stand-alone power system [15]. Indeed, small changes made in the control strategy can significantly affect the performance of the system. But it is a complicated task because of the significant number of variables to consider.

HOMER (that will be presented in section *D*) is an optimisation model that uses relatively simple strategies to obtain an optimal design of a renewable system by selecting the most appropriate control strategy. The program HYDROGEMS, compatible with TRNSYS, can simulate accurately hydrogen-based systems but is not an optimisation program. Finally, Hybrid2 is another program applied to hydrogen-based systems that can generate many control strategies. But it is a simulation program, not an optimisation tool. These different modelling tools use hourly intervals for their calculations, assuming that all the involved variables are constant throughout these intervals.

- **Control strategy of a stand-alone power system**

The total net present cost of the system, which includes the investment costs and all future costs during the lifetime of the system, is the parameter to minimize in the optimisation process. It is therefore necessary to simulate the system throughout its lifetime.

As a basic control rule in a stand-alone power system, the energy produced by renewables must be preferentially used to feed the loads. For every hour, if the renewable sources produce more energy than is demanded, the surplus power (P_{charge}) can be used to charge the batteries or to produce H_2 in the electrolyzer. This is the c*harge process*. The decision to use the spare energy to charge the batteries or to produce H_2 depends on the value of P_{charge}. If, on the contrary, the renewable sources produce less energy than demanded, the deficit power ($P_{discharge}$) should be produced either by the battery, the CHP unit or the fuel cells. This process is called *discharge*. To produce the cheapest energy, the costs of providing the required energy using each technology must be evaluated.

- **Charge process**

If an excess of energy is produced for one hour, this energy is used to charge the batteries and/or to produce hydrogen in the electrolyzer before storing it in the hydrogen tank. Depending on which of the two techniques has the lowest cost of cycling energy (i.e. the operating and maintenance cost for one hour, including the depreciation and replacement costs), either the batteries are charged as much as possible with the spare energy or the electrolyzer works at its highest possible power.

The cost of cycling the energy corresponding to a certain power P (kW) through the batteries during one hour can be calculated as (in £):

$$C_{cycling\_bat} = \frac{P.1000C_{bat}}{C_N N_{bat\_p} U_{DC} N_{cycles\_eq} \eta_{global\_bat}}$$

where C_{bat} (£) is the battery bank acquisition cost, C_N (Ah) is the nominal capacity of the battery, N_{bat_p} is the number of batteries in parallel, U_{DC} (V) is the DC bus voltage and N_{cycles_eq} is the average of a battery lifetime in equivalent full cycles. Finally, η_{global_bat} is the overall efficiency of the batteries. The O&M costs of the batteries are not considered in $C_{cycling\_bat}$, since it is assumed that they are fixed during the year and therefore do not depend on the performance of the batteries.

The cost of cycling the energy corresponding to a certain power P (kW) during one hour, where the energy is stored as hydrogen in the tank, later becoming fuel cell energy, is (in £):

$$C_{cycling\_Ely-FC} = \frac{(C_{Ely} / Life_{Ely}) + C_{O\&M\_Ely} + (C_{FC} / Life_{FC}) + C_{O\&M\_FC}}{\eta_{Ely}\eta_{FC}}$$

We can observe that $C_{cycling\_Ely\_FC}$, unlike $C_{cycling\_bat}$, does not depend on the power since the electrolyzer and the fuel cell lifetimes, $Life_{Ely}$ and $Life_{FC}$ (h) have been considered independent of the power, as well as $C_{O\&M\_Ely}$ and $C_{O\&M\_FC}$, the O&M costs of the electrolyzer and the fuel cell (£/h). C_{Ely} and C_{FC} (£) are the electrolyzer and fuel cell acquisition costs. η_{FC} (kWhoutput/kgH_2) represents the amount of electrical energy output for each kg of H_2 consumed in the fuel cell.

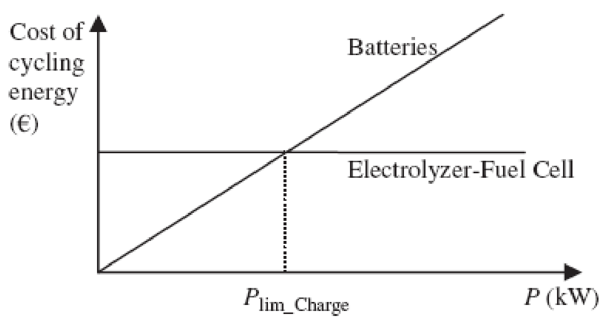


Figure 17: Cost of cycling energy [25]

Figure 17 shows the cost of cycling energy of the batteries and the electrolyzers as a function of the spare energy P_{charge}. It can be observed that, for low values of P_{charge} ($\leq P_{lim\_charge}$ on the graph), it is cheaper to use the spare energy produced to charge the batteries as much as possible. If there is still more energy, then the spare energy should also be used to produce hydrogen in the electrolyzer.
From a certain power, P_{lim_charge}, it becomes cheaper to use the electrolyzer. This power is simply obtained by equating $C_{cycling\_bat}$ to $C_{cycling\_Ely\_FC}$:

$$P_{\text{lim\_charge}} = \frac{\dfrac{C_{Ely}}{Life_{Ely}} + C_{O\&M\_Ely} + \dfrac{C_{FC}}{Life_{FC}} + C_{O\&M\_FC}}{\dfrac{1000 C_{bat} \eta_{Ely} \eta_{FC}}{C_N N_{bat\_p} U_{DC} N_{cycles\_eq} \eta_{global\_bat}}}$$

The strategy to optimize the charge process is as follows:

- If $P_{charge} \leq P_{lim\_charge}$, then the batteries are charged as much as possible, and, if there is still spare energy, it is used to produce H_2 in the electrolyzer.
- If $P_{charge} > P_{lim\_charge}$, then the hydrogen is produced in the electrolyzer at full power, and, if there is still spare energy, it is used to charge the batteries.
- If the electrolyzer has a minimum power, P_{min_Ely}, then $P_{lim\_charge} = max\,(P_{lim\_charge}, P_{min\_Ely})$.

a. Discharge process

In the case of lack of energy for one hour, the energy is obtained either from the batteries, the CHP unit, or from the fuel cells, depending on the associated costs of each technique.

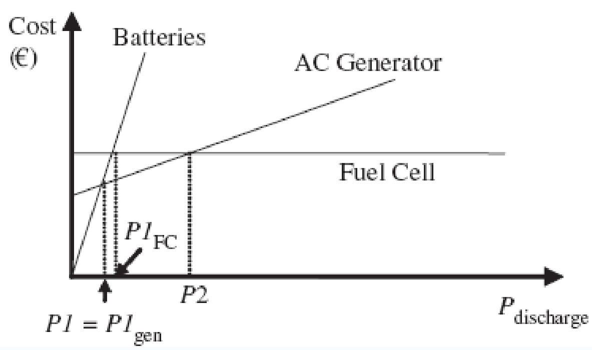


Figure 18: Costs of supplying energy in the discharge process [15]

Figure 18 shows the cost of supplying energy as a function of the deficit power. It appears that, for powers between 0 and a certain value P1, supplying the required power through the batteries is the optimal solution. From the value P1, it may become more economical to supply the power with another component. This value of P1 is the minimum of the two values resulting from the intersection of the cost function of supplying energy with batteries and the cost function of supplying energy with the CHP and the fuel cells (see graph).

We call $P1_{gen}$ the power at which the cost of supplying energy with batteries equals the cost of supplying energy with the CHP unit, and $P1_{FC}$ is the power at which the cost of supplying energy with batteries equals the cost of supplying energy with the fuel cells.

If the value of $P1_{gen}$ (resp. $P1_{FC}$) is negative, this means that it is always cheaper to supply energy with the batteries than with the generator (resp. the fuel cell). It may also be possible that both P1gen and $P1_{FC}$ have negative values, which means that the use of the batteries is always the optimal solution.

A value P2, at which the energy produced by the component supplying power from P1 is not the cheapest anymore, may also exist.

Consequently, the strategy that optimizes the discharge process is:

- If $P_{discharge}$<P1, then the energy is supplied by the batteries.
- If P1≤$P_{discharge}$≤P2, then the energy is supplied by the component with the lowest value of P1 (either the CHP unit or the fuel cell).
- If $P_{discharge}$>P2 then the energy is provided by the component with the highest value of P1.
- Once the component to supply the required energy is selected, it must be determined whether it is able to provide all the energy required. If it is not the case, the remaining power is provided by the component that can produce it at the lowest possible cost.
- If the second component necessary to supply the energy is not available, the third one is used to supply the remaining energy.

7. The HARI project and the hydrogen economy

As defined before, "Hydrogen Economy" represents an energy systems relying exclusively on the primary resource of renewables and hydrogen for energy storage.
The HARI project has highlighted a very important point: the efficiency of passing through the cycle from electricity to hydrogen and back to electricity is very poor, around 16%. The efficiency of the overall electrical and hydrogen energy system at West Beacon farm is 44%. This difference can be explained by the fact that, wherever possible, the power generated by the renewables is used directly as electricity in the loads, or stored briefly as electricity in the battery. The option of converting the electricity produced to hydrogen for storage before reconverting it back to electricity when needed must be only considered as a last resort. Wherever possible, electricity must remain as electricity in the system until it reaches the end-point appliance. Therefore, hydrogen should not be used for storage of electricity, except in particular situation where there is no alternative (e.g. in remote, off grid applications). Instead hydrogen should provide fuel and constitute, via electrolysis, a balancing mechanism between the supply and demand on the utility grid.

In the ultimate hydrogen economy scheme, the only primary resource available is renewable energy, even for transportation. In this scenario, the installed capacity of renewable energy resource is largely enough to feed the electricity network alone. But this necessary installed capacity increases substantially when it is question to feed the whole energy system (comprising transportation and others). At West Beacon Farm, though not eliminated all periods of supply shortfall are substantially reduced in frequency and duration. The need to store electricity is therefore limited and the energy that was converted to hydrogen can most of the time be used as fuel without being reconverted back to electricity (see next figure). Electrolysis as fuel production becomes then a load management tool for a more efficient use of renewable energy.

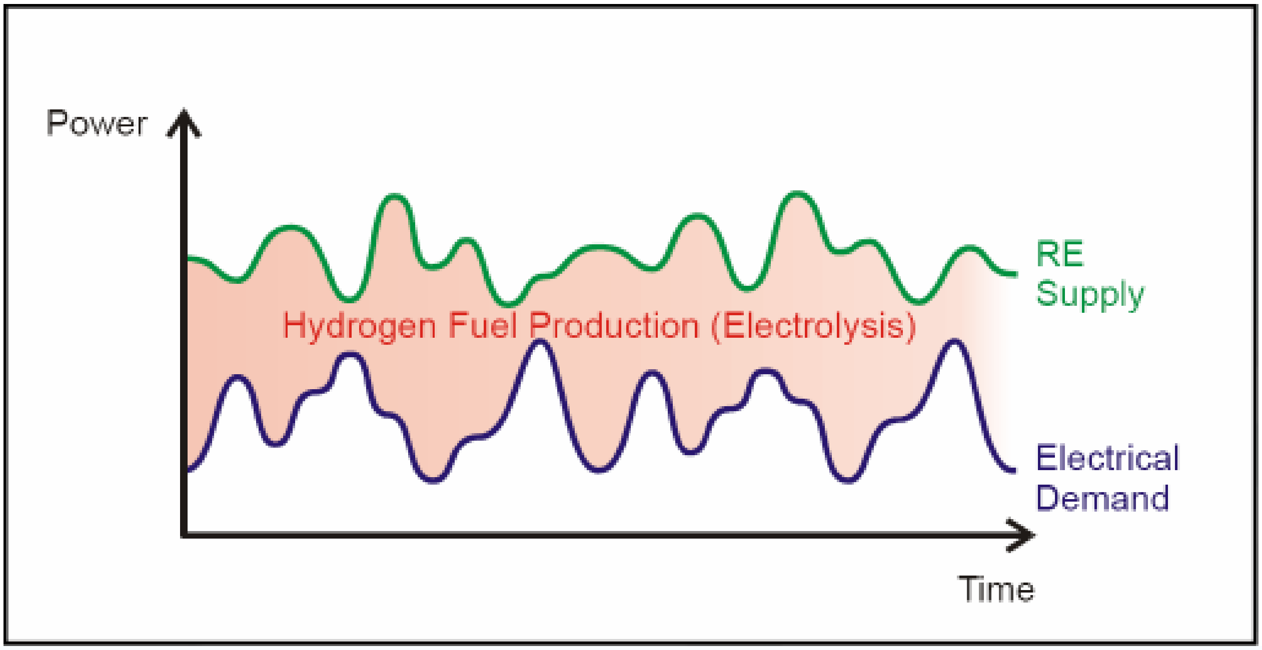


Figure 19: The Hydrogen Economy model [2]

Even if such a scenario is still a long way off and this technology requires many years of development, it is already evident that a hydrogen distribution grid is not intended to replace the current electrical distribution grid. Indeed the electricity grid, whose majority of the electrical infrastructure is already in place (even if some reinforcement will be required), is an efficient method of transporting energy. Moreover, no extensive hydrogen pipeline network exists and the existing natural gas network would need considerable modifications to be used with hydrogen. While electricity is an excellent means for the spatial displacement of energy, hydrogen is a good means of achieving its temporal displacement. The advantages and complementarities of these two energy vectors should therefore be exploited appropriately in the future energy system. Actually, hydrogen pipelines seem only adapted where a very large-scale storage of hydrogen is needed.

8. Conclusion: knowledge gained so far and further plans

Energy storage based on converting electricity to hydrogen gas and back to electricity is a possible answer to the problem of intermittency within stand-alone renewable energy systems. The hydrogen energy storage system installed at West Beacon Farm as part of the HARI project has been designed to provide a long-term energy storage in order to cope with the difficultly to match energy supply and demand on the site using exclusively renewables as primary energy resource. At times of excess renewable energy, the electrolyzer is used as a controllable load by which the excess energy is converted into hydrogen. When there is insufficient renewable energy to meet the demand, fuel cells are used to produce electricity. As there are no standing losses in the hydrogen storage tank, it can be used as a long-term inter-seasonal store of energy. This hydrogen system was successfully integrated into an existing renewable energy system and software models of the overall system have been developed and verified against real-world operation data.

However, some problems still need to be investigated and future improvements on the system are expected in the long-term. For example, the lifetime of the electrolyzer could be significantly limited because of the repetition of on/off switching cycles due to the intermittency of the renewables production and the operational limits of the electrolyzer. Some batteries are therefore still required to provide short-term storage but it is planned to develop an electrolyzer adapted to the dynamic supply from intermittent power sources in order to improve its efficiency, reliability and cost.

In order to create a real stand-alone renewable energy system, it is also planned to convert the existing wind turbines so that they can operate independently of the utility grid. Under normal circumstances, wind turbines need a grid connection to activate and control their induction generators but turbines at West Beacon farm need to run autonomously, which can be achieved using power electronics. After the modifications on the electrical mini-grid, the whole system can operate independently of the utility grid. This tested concept could then be widely applied to stand-alone energy systems.

The HARI project has also provided some useful information on the safety aspect. Indeed, safety has a crucial importance in this project since a major incident would have disastrous consequences for the reputation of this emerging technology at this critical time. Moreover, this technology being planned to be used in a domestic environment, safety issues become even more relevant. The use of hazardous materials like hydrogen or potassium hydroxide (use in the electrolyzer and very corrosive to the skin and the eyes) has been closely investigated. Full chemical resistant overalls, hoods, boots and gloves are obviously required, and it appeared that specific alkali-resistant breathing masks would be necessary because some symptoms of throat irritation, intense headaches and tiredness have occurred amongst some members of the project team.

But the major issue is the efficiency of the overall system. On this point, the HARI project clearly highlights the limitations of the concept of “hydrogen economy” and of using hydrogen for energy storage. The cycle going from electricity to hydrogen and back to electricity again is largely wasteful (because of significant losses in the electrolyzer and fuel cells) with an efficiency around 16% and must therefore be used only as a last resort. Using the electricity directly (without passing through the hydrogen energy system) wherever possible, the efficiency of the electrical and hydrogen system reaches 44%. It is therefore important that only the excess energy goes through the store. Wherever possible, energy produced from renewables must remain as electricity and be used directly but sometimes converting this energy to hydrogen may be inevitable. Once converted to hydrogen, energy should only be used as fuel for transportation and remote or portable power generation.

Improving the system design, the energy management and the control strategy for the installation may provide the solution. Indeed, the system is currently designed for a maximum robustness and reliability but it can be largely improved on the efficiency point of view. The new DC bus based electrical network which includes detailed measurements of energy flows around the system should improve this efficiency. Thermal management will also be necessary in the optimisation of the system, as by-product heat can be captured and used to reduce the heat losses or for cooling requirements.

The electricity grid will obviously remain the main method of transmission and distribution, since a hydrogen pipeline network seems quite unrealistic. It is then possible to exploit the strengths and complementarities of electricity, which is an excellent means for the spatial displacement of energy, and hydrogen, which is a good means for its temporal displacement.
Of course, even if these results are not reassuring, the HARI project doesn't suggest that the hydrogen economy is not a practical solution for the future energy system, but it warns that searching for a practical large-scale, long-term energy store will be very challenging and expensive. In a world where the primary energy resources are only renewables (no fossil fuel available), the installed capacity of renewables will have to be much greater than normally considered for the generation of grid electricity, having also to fulfil the requirements of portable power and all forms of transport.

Rupert Gammon, Bryte Energy director, says: "The HARI project has provided us with an unrivalled opportunity to gain knowledge through the direct experience of designing, installing and operating a complete, zero-carbon energy system on a day-to-day, real-world basis. It has given us unique insights into matters such as the powering of electrolyzers with intermittent and dynamic supplies and in discovering what strategies will and will not work in the implementation of a future hydrogen economy". In a long-term future, whole national and international energy networks may operate on this hybrid (electricity and hydrogen) principle even if integrating so many elements presents many technical challenges. That's why the HARI project provides vital experience to initiate the creation of such sustainable energy systems for the future. The ultimate goal of the project is to build software models that could be very helpful in the design of similar hydrogen and renewables systems.

C. Simulation with TRNSYS

1. Definitions

a. What is TRNSYS

TRNSYS is a TRaNsient SYstems Simulation program with a modular structure. TRNSYS allows the user to specify the components that constitute a specific system and the manner in which they are connected. The program can recognize the system organisation and simulate its operation. The TRNSYS library includes many of the components commonly used in thermal and electrical energy systems, as well as component routines to manage the integration of weather data or other time-dependent forcing functions and output of simulation results. The modular nature of TRNSYS gives the program a large flexibility, and makes it possible to add mathematical models not included in the standard TRNSYS library.
TRNSYS (original version in 1975) has become a reference program for researchers and engineers around the world thanks to its great capacities for the detailed analysis of any system whose behaviour is dependent on the passage of time. TRNSYS is particularly suited for the analysis of solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration or fuel cells.
(Source: TRNSYS website http://sel.me.wisc.edu/trnsys)

b. What is HYDROGEMS

HYDROGEMS is a series of HYDROGen Energy ModelS designed for the simulation of integrated renewable and hydrogen energy systems. The HYDROGEMS library includes component subroutines for PV arrays, wind energy conversion systems (WECS), diesel engine generator systems (DEGS), advanced alkaline water electrolysis, high-pressure hydrogen gas storage, metal hydride (MH) storage, proton exchange membrane fuel cells (PEMFC), alkaline fuel cells (AFC), compressors, power conditioning equipment, and logical control functions. Seven years of modeling and simulation work on stand-alone power systems undertaken at the Institute for Energy Technology have been necessary to develop HYDROGEMS. The models have been tested and verified against numerous renewable and hydrogen installations around the world.
The compatibility between HYDROGEMS and TRNSYS makes it possible to integrate the HYDROGEMS component models with the standard library of thermal and electrical components of TRNSYS. The major HYDROGEMS components (PV, WECS, electrolyzer, and fuel cells) are also available as external functions for EES, an engineering equation solver, which has built-in functions for thermodynamic and transport properties of many substances, including steam, air, air-water vapour mixtures, refrigerants, cryogenic fluids and hydrocarbons. This characteristic makes HYDROGEMS particularly useful for system design or redesign and the optimisation of control strategies for integrated renewable and hydrogen energy systems.
(Source: HYDROGEMS user guide, Institute for Energy Technology)

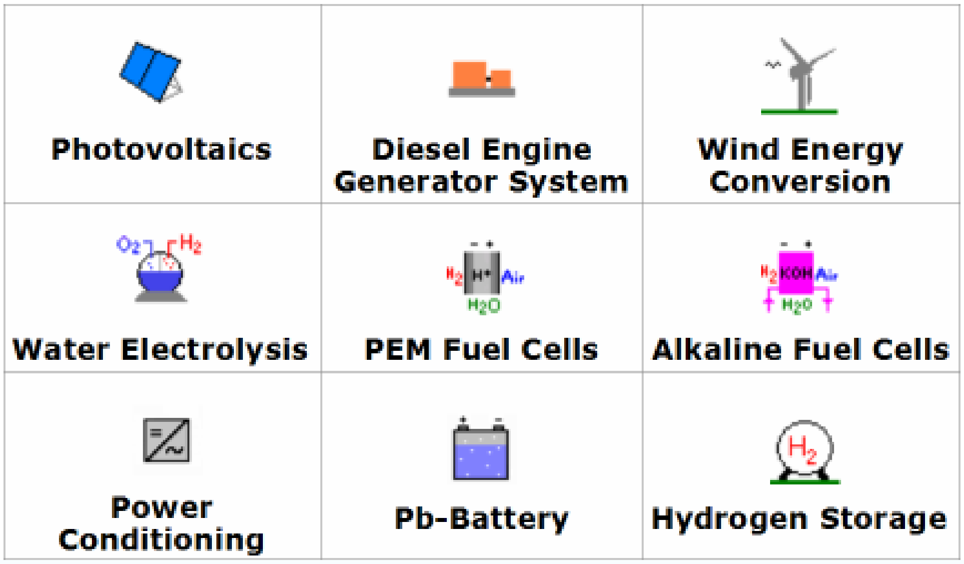


Figure 20: HYDROGEMS components [10]

A description of the mathematical models defining the different elements of the HYDROGEMS library can be found in the HYDROGEMS User Guide [10]. In this guide are described the parameters and inputs necessary for each model, as well as the outputs available after the simulation.

2. HARI model: control strategy based on the SOC of the hydrogen store

a. The Master Controller

As mentioned before, the HARI system control is based on the state of charge of the battery. However, such a control being very complex to simulate with TRNSYS since such a controller doesn't exist in TRNSYS library yet, an approximation of the system was developed basing the control strategy on the state of charge of the hydrogen store (see figure 21). This can be achieved using the Master Level Controller (type 105 in the library of TRNSYS) which is designed to control a stand-alone power system including wind turbines (or another source of renewable power), an electrolyzer, a fuel cell, a hydrogen storage device and diesel engine generator sets (or another auxiliary power source that consists of multiple units).

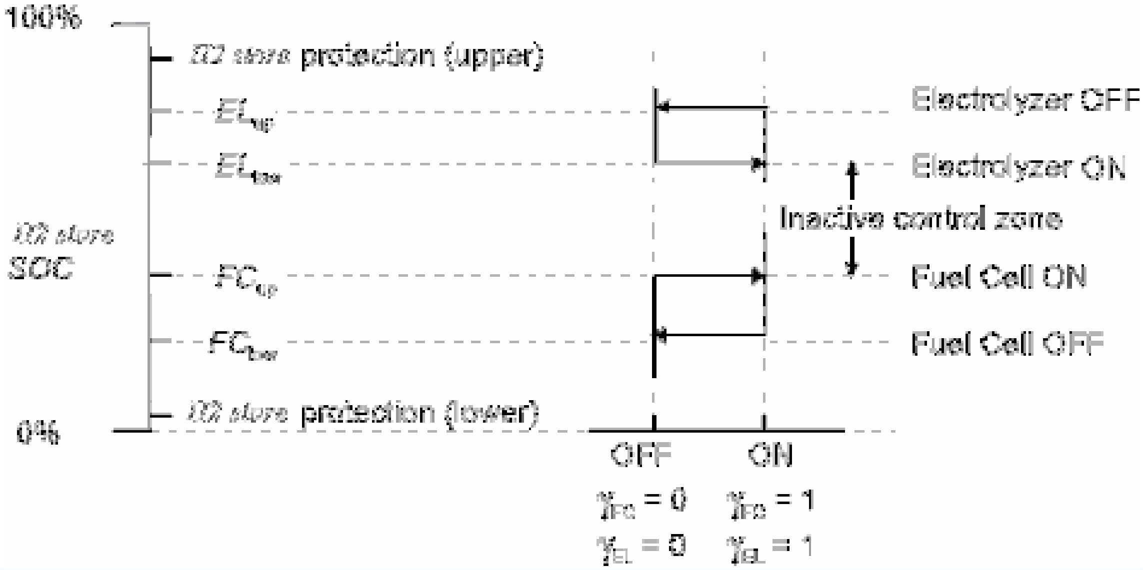


Figure 21: Control strategy based on the SOC of the hydrogen store

In this project, the parameters EL_{up}, EL_{low}, FC_{up}, and FC_{low} have been respectively fixed at 100, 90, 10 and 0%.

In this section is described the mathematical model of the Master Controller:

P_{WECS} (W) is the power generated by the wind turbine (or another renewable energy device)
$P_{DEGS,max}$ (W) is the rated power generated by one DEGS
$P_{DEGS,set}$ (W) is the power setpoint for each DEGS
N_{DEGS} is the number of DEGS operating at fixed power
$N_{DEGS,min}$ is the minimum number of DEGS operating at any time
$N_{DEGS,max}$ is the maximum number of DEGS operating at any time
$P_{FC,min}$ (W) is the minimum (idling) Power of the Fuel Cell
$P_{FC,max}$ (W) is the rated power of the Fuel Cell
$P_{FC,set}$ (W) is the power setpoint for the Fuel Cell
$P_{Ely,min}$ (W) is the minimum (idling) power of the Electrolyzer
$P_{Ely,max}$ (W) is the rated power of the Electrolyzer
$P_{Ely,set}$ (W) is the power setpoint for the Electrolyzer
P_{Load} (W) is the power to the load
P_{dump} (W) is the dumped power
P_{busbar} (W) is the power balance on the mini-grid bus bar
SOC is the State Of Charge of the energy storage
EL_{low} is the SOC for which the Electrolyzer is switched ON
EL_{up} is the SOC for which the Electrolyzer is switched OFF
FC_{low} is the SOC for which the Fuel Cell is switched OFF
FC_{up} is the SOC for which the Fuel Cell is switched ON

The decisions of the controller are based on the mini-grid busbar power balance, assuming that the minimum number of DEGS is operating and that the fuel cell and electrolyzer are idling:

$$P_{busbar} = P_{WECS} + N_{DEGS,min}\, P_{DEGS,max} + P_{FC,min} - P_{Load} - P_{Ely,min}$$

EXCESS POWER ($P_{BUSBAR} > 0$)

1. Electrolyzer status

- If the electrolyzer is currently OFF (Idling):
  - If SOC < EL_{low}, switch ON:
  - Operate with $P_{ely,set} = P_{WECS} + N_{DEGS,min}\, P_{DEGS,max} + P_{FC,min} - P_{Load}$
  - Else, remain OFF (Idling)
- Else (electrolyzer is currently ON):
  - If SOC > EL_{up}, switch OFF (Idling)
  - Else, keep operating and $P_{ely,set} = P_{WECS} + N_{DEGS,min}\, P_{DEGS,max} + P_{FC,min} - P_{Load}$
- Constraints on $P_{Ely,set}$: If $P_{Ely,set} > P_{Ely,max}$ then $P_{Ely,set} = P_{Ely,max}$

2. Dump

- If PEly,max was reached: $P_{dump} = P_{WECS} + N_{DEGS,min}\, P_{DEGS,max} + P_{FC,min} - P_{Load} – P_{Ely,set}$

POWER DEFICIT ($P_{BUSBAR} < 0$)

1. Switch off fuel cell if necessary, based on the H2 storage tank level

- Switch Fuel cell to idling mode if the fuel cell is currently ON and SOC < FClow
- Keep idling if the fuel cell is currently OFF and SOC ≤ FCup

2. DEGS, Electrolyzer and Dump

- If the fuel cell is currently OFF (idling):
  - Find NDEGS, the minimum number of operating DEGS that generates a power excess, assuming the electrolyzer is idling. N_{DEGS} is the minimum value for which ($P_{WECS} + N\, P_{DEGS,max} + P_{FC,min} - P_{Load} – P_{Ely,min}$) ≥ 0
  - Electrolyzer operates at $P_{Ely,set} = P_{WECS} + N\, P_{DEGS,max} + P_{FC,min} - P_{Load}$
  - No dumped power: $P_{dump} = 0$
- Else (the fuel cell is currently ON):
  - Find N_{DEGS}, the minimum number of operating DEGS that generates a power excess, assuming the electrolyzer is idling and the fuel cell is at maximum power. N_{DEGS} is the minimum value for which ($P_{WECS} + N\, P_{DEGS,max} + P_{FC,max} - P_{Load} – P_{Ely,min}$) ≥ 0
  - Assume electrolyzer is idling
  - Set Fuel cell power: $P_{FC,set} = P_{Load} + P_{Ely,min} - P_{WECS} - N\ _{PDEGS,max}$
  - If $P_{FC,set} < P_{FC,min}$ then impose $P_{FC,set} = P_{FC,min}$
  - Set Electrolyzer power to use all power that would be dumped:

  $P_{Ely,set} = P_{WECS} + N\, P_{DEGS,max} + P_{FC,max} - P_{Load}$

Of course this model is far from being ideal. One can see from these equations that the fuel cells can run on partial load in this system, which is not the case in the real HARI system where fuel cells run only at fuel power. Moreover, it is assumed that the “diesel generators” can only operate at their rated power $P_{DEGS,max}$ or be switched off, which will not be the case in any stand-alone power system. However, it should give a good first approximation of the actual system. Moreover, the problem concerning the diesel generators operating at partial power can be partially solved by increasing $N_{DEGS,max}$ while decreasing $P_{DEGS,max}$ as much as possible in order to improve the resolution of the calculations. For this model of the HARI system, $N_{DEGS,max}$ has been set up at 150 while $P_{DEGS,max}$ is fixed at 0.1kW to ensure that 15kW of generators are available.

The main difference between the control strategy in TRNSYS and HOMER is that HOMER cannot base its control strategy on the SOC of the hydrogen tank. The set points presented on figure 21 don't exist in HOMER. In HOMER, the electrolyzer operates whenever the surplus electricity exceeds its minimum load point and there is headroom in the hydrogen storage tank. The fuel cell operation is governed by need, fuel supply, schedule, and its cost relative to the other dispatchable power sources. All these differences make difficult the comparison between HOMER and TRNSYS

b. HARI system modelling

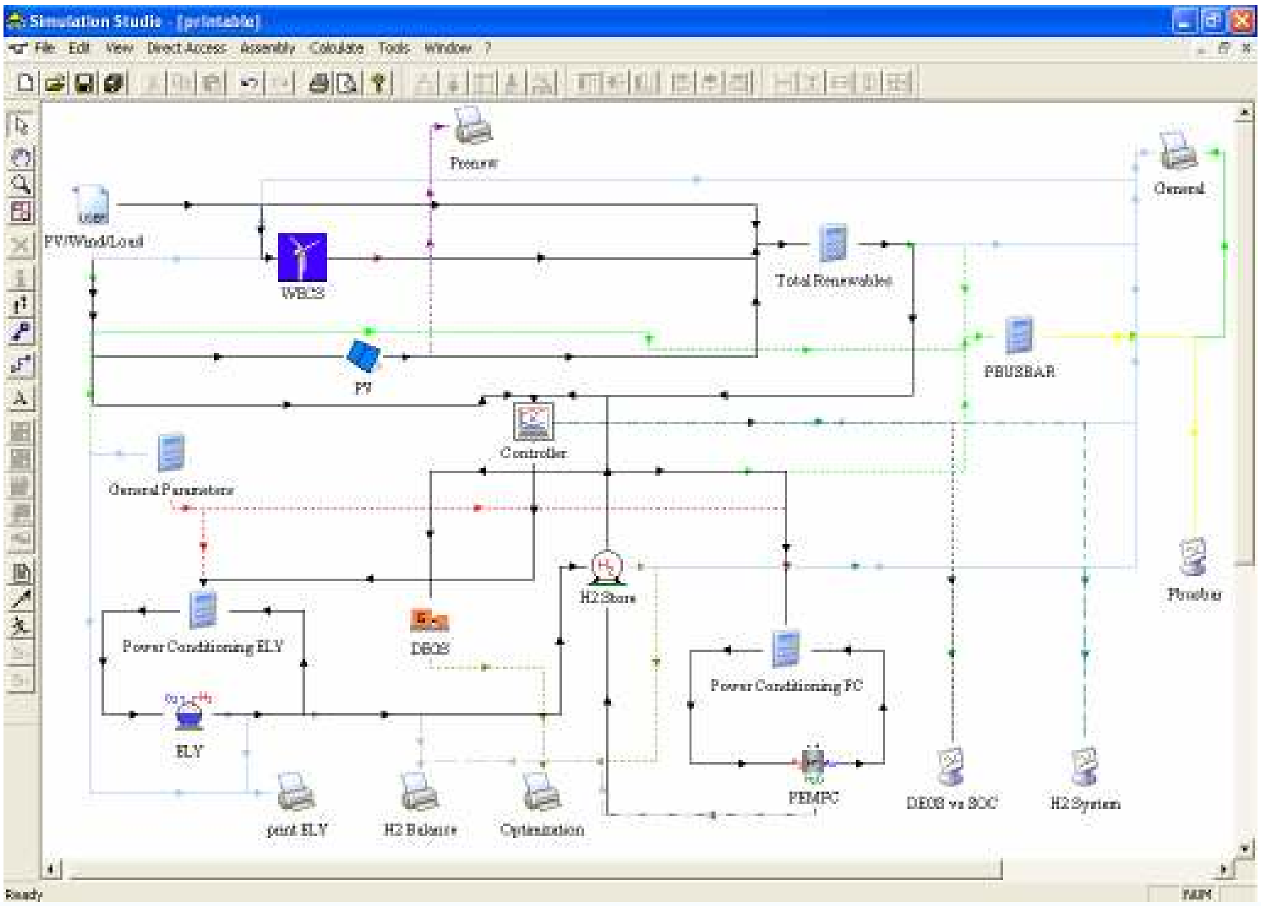


Figure 22: HARI modeling with TRNSYS, including printers and plotters

Figure 22 represents the whole modelling of the HARI system, comprising the system components, as well as the printers and plotters used for the analysis. Figure 23 represents only the HARI system components and will be easier to present in this report.

The TRNSYS system includes a data file (wind speed, solar radiation and load data every hour), the two 25kW Carter wind turbines, 6kW of PV arrays, a Master Controller, the hydrogen system (an electrolyzer of 38kW, 22.8m^3 of hydrogen storage facility, 7kW of fuel cells and the corresponding power conditioning devices), 15 kW of diesel engines (running with Liquid Petroleum Gas) and different calculators required for the modeling of the system. The main difference between the real HARI system and this model is (except the absence of the battery bank and the control strategy associated) that this model includes only one fuel cell of 7kW instead of two fuel cells of 2 and 5kW. This is simply due to the fact that the Master Controller used in TRNSYS is designed to control only one fuel cell at the time.

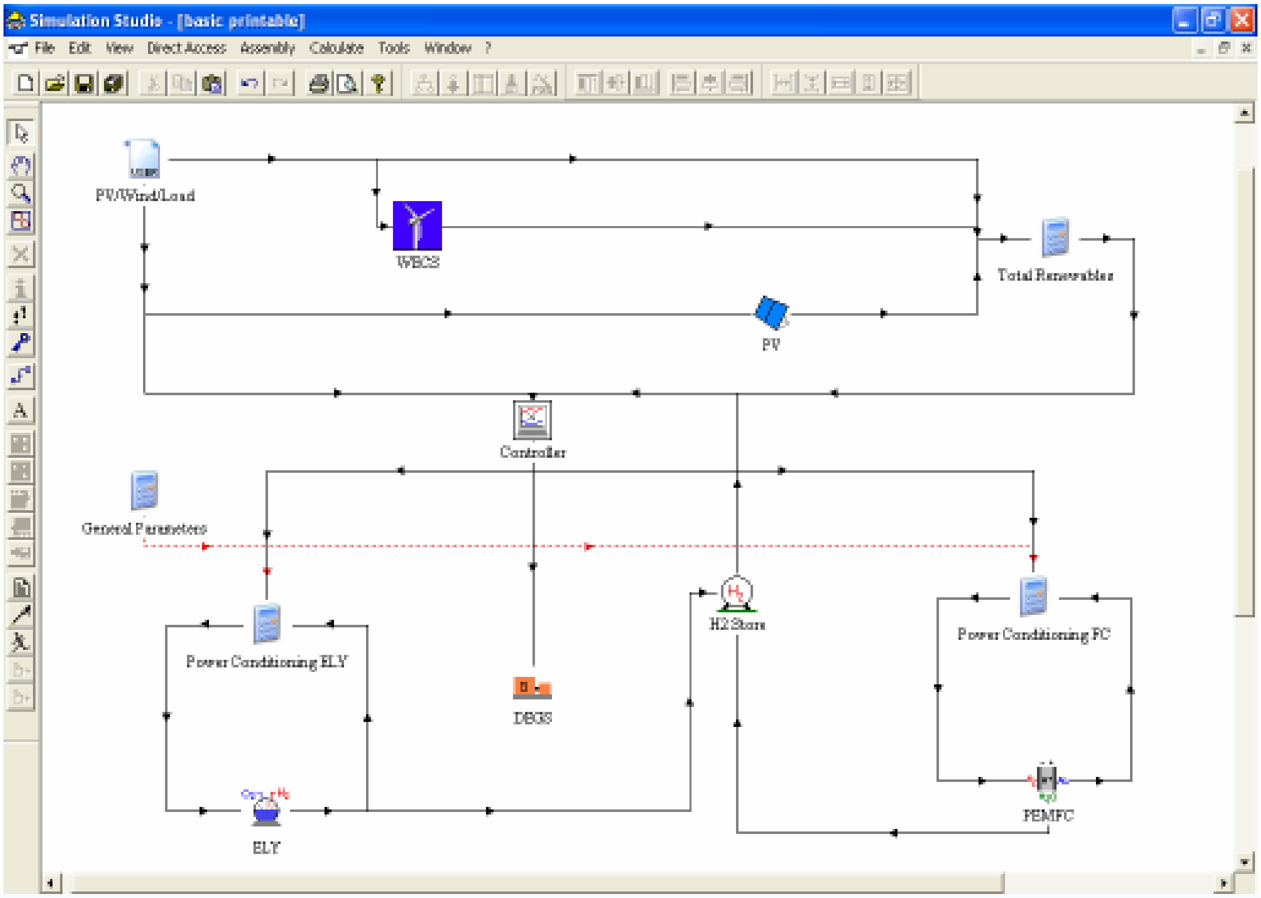


Figure 23: HARI modeling with TRNSYS

Most of the parameters necessary to build this model were provided by Rupert Gammon, like the power curve and characteristics of the Carter wind turbines or some features of the PV arrays and the electrolyzer. However, a few parameters were still missing for confidentiality or availability reasons. Some default values have then been used once their impact on the simulation results have been tested, notably for the PV arrays or the fuel cells. For the electrolyzer, an Engineering Equation Solver (EES) executable has been created by Øystein Ulleberg during the workshop at IFE in Norway. This executable (see figure 24) allows to obtain the external parameters required by TRNSYS (figure 25) for an alkaline electrolyzer similar to the one of the HARI system.

All the load and resource (solar and wind) data used in this model are the ones used and defined in the HOMER simulation. These input data will be presented in details in the next section dedicated to HOMER.

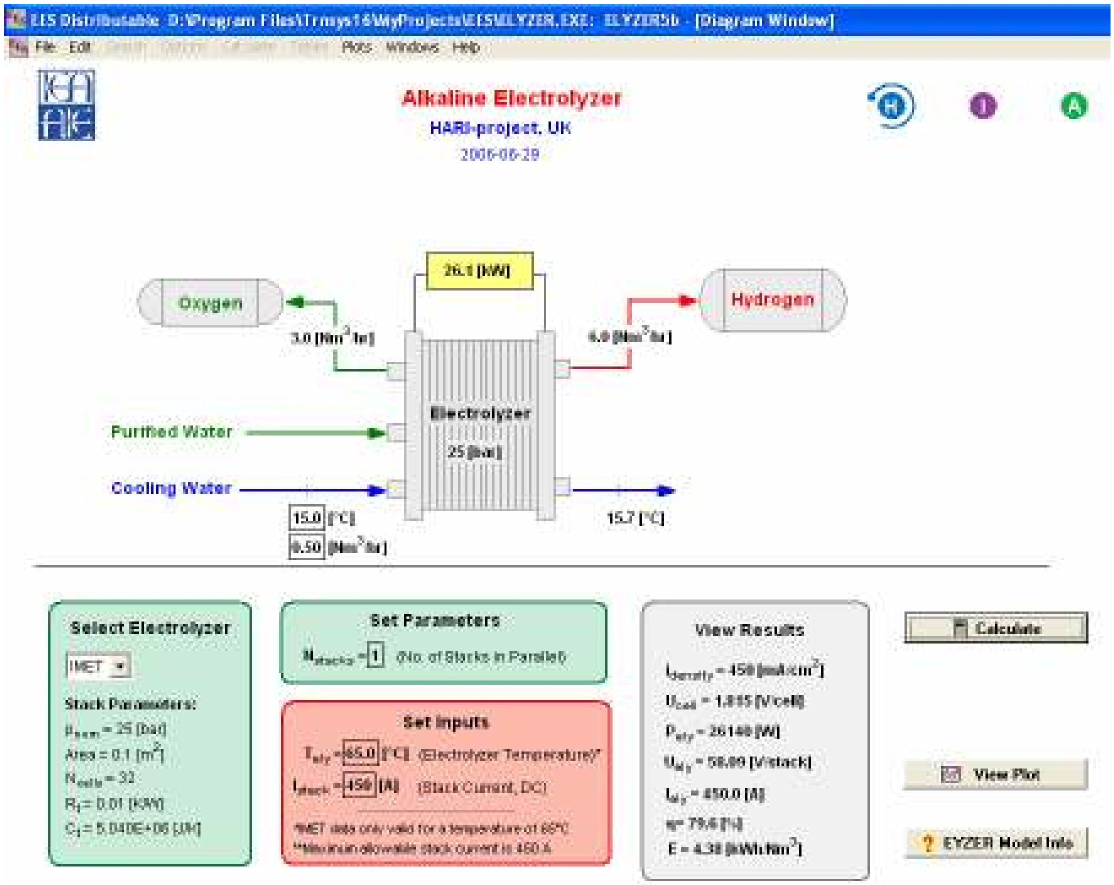


Figure 24: Alkaline electrolyzer model (EES executable developed by Øystein Ulleberg)

	Description	IMET [25 bar, 25 kW
Row 1	Pnom	25
Row 2	Area	0.1
Row 3	Ncells	32
Row 4	tau_t	14
Row 5	R_t	0.01
Row 6	r1	0.00002
Row 7	r2	0
Row 8	s1	0.25
Row 9	t1	0.015
Row 10	t2	0
Row 11	t3	0
Row 12	a1	200
Row 13	a2	0.98
Row 14	h1	7
Row 15	h2	0.02

Figure 25: Parameters of the electrolyzer required by TRNSYS

D. Simulation with HOMER and combined modelling

1. What is HOMER

The Hybrid Optimization Model for Electric Renewables (HOMER) software is a computer model that simplifies the design of both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation applications. HOMER performs three tasks: simulation, optimization and sensitivity analysis. This package allows to evaluate the economic and technical feasibility of a large number of technology options and to take into account the variations in technology costs and energy resource availability. HOMER's library includes both conventional and renewable energy technologies: PV array, wind turbine, run-of-river hydro-turbine, various generators, electrolyzer, battery bank or hydrogen storage tank.

In its simulation process, HOMER models the performance of a particular system configuration each hour of the year in order to determine its technical feasibility and life-cycle cost. To achieve this, HOMER simulates the operation of the system by making energy balance calculations for each of the 8,760 hours of the year. For each hour, the electric and thermal demands in the hour are compared to the energy that the system can supply in that hour, and calculates the flows of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides for each hour how to operate the generators and whether to charge or discharge the batteries.

In its optimization process, HOMER simulates all the different possible system configurations, discards the infeasible ones that do not satisfy the defined constraints, displays a list of the feasible ones by ranking them according to their life-cycle cost and finds the one that satisfies the technical constraints at the lowest cost. The optimization process is particularly useful to determine the optimal size and quantity of each component of the system.

In order to limit the input complexity and to allow fast enough computation to make the optimization process practical, HOMER's simulation logic is less detailed than other modelling tools like TRNSYS for example.
(Source: http://www.nrel.gov/homer)

2. Control strategy in HOMER

Systems containing a battery bank and one or more generators require a dispatch strategy that defines the rules governing the charge of the battery. But the choice of the control strategy is definitively the weak point of HOMER. It offers only two control strategies, cycle charging and load following. The optimal strategy depends on the sizes of the generators and battery, the price of fuel, the O&M costs of the components or the amount of renewable power in the system.

Under the load following strategy, whenever it is needed the generators produce just enough power to meet the demand. Load following is generally preferable in systems with a lot of renewable power, when the available power sometimes exceeds the load, like it is the case in the HARI project.

Under the cycle charging strategy, whenever a generator is needed, it operates at full capacity and the surplus power is used to charge the battery. A set point state of charge can also be applied: the generators will not stop charging the battery until it reaches the specified state of charge. Cycle charging tends to be optimal in systems with little renewable power.

Each hour, HOMER looks at the available generators and chooses to operate the one that can produce the required amount of power and operating reserve most cheaply. The cost per kWh of a generator involves fuel, O&M, and replacement costs. It is also important to know that HOMER considers a generator "available" only if there is sufficient fuel for it to operate at full power for one hour. This point becomes particularly relevant in the case of fuel cell consuming stored hydrogen produced by an electrolyzer, since it might be a meaningful constraint quite often when the quantity of stored hydrogen is insufficient to allow the fuel cell to operate at full power.

Another simulation program, Hybrid2 developed by NREL and the University of Massachusetts, performs a more accurate simulation and offers more possibilities to control the system than HOMER, but it does not provide any optimization or sensitivity analysis. It may therefore be interesting to use HOMER to design an approximately optimal system, and then use Hybrid2 to refine the system design and investigate its performance in more details. It is that idea that has been applied in this project by using HOMER in the first place before using TRNSYS (instead of Hybrid2) for a more accurate simulation.

3. HARI system modelling

Figure 26 represents the model of the HARI system with HOMER. But as it was explained in the last part concerning the TRNSYS simulation, the model developed with TRNSYS is slightly different than the real HARI system in order to make it simpler and adapted to the control strategy available in TRNSYS library: there is no battery bank and only one fuel cell of 7kW instead of two fuel cells of 2 and 5kW.
One of the objectives of this project being to compare the results of the simulations with HOMER and TRNSYS, it is therefore important to build a model in HOMER copying the TRNSYS one. Figure 27 represents a copy of the TRNSYS model developed with HOMER.

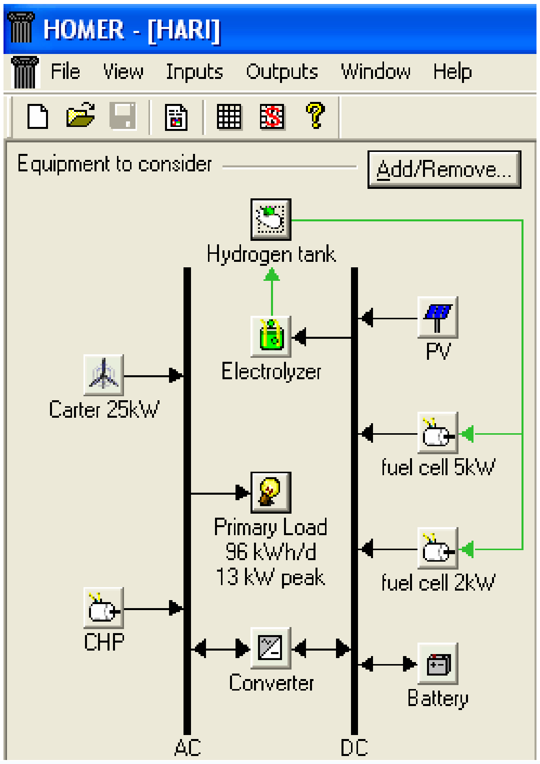


Figure 26: Model of the HARI system with HOMER

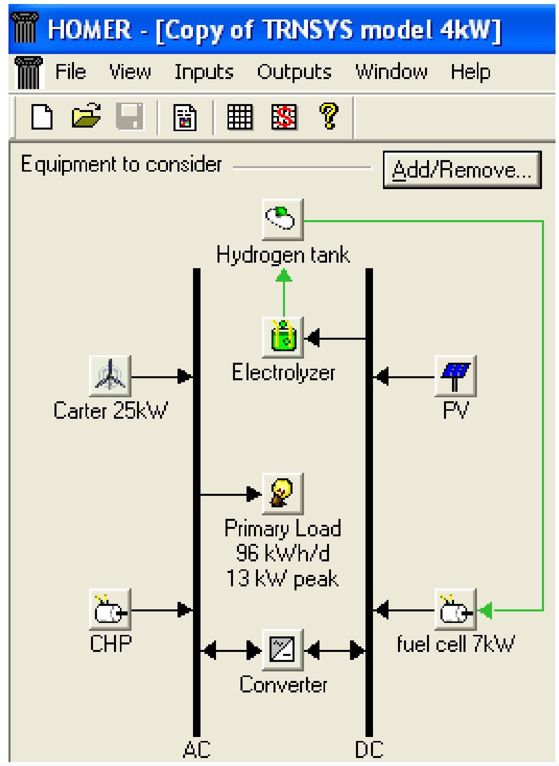


Figure 27: Copy of the TRNSYS model with HOMER

4. Load and resource data

To simulate a system for one year, HOMER and TRNSYS require some hourly load, solar and wind data of the site. This data allows HOMER to calculate the energy needed and the resource available for every time-step of the simulation.

– The primary load used for both HOMER and TRNSYS simulations has been created using a generic remote load existing in HOMER sample files and scaling it to 4kW, the average load at West Beacon Farm. As presented on figure 28, this load can be summarized by an hourly load data, an hourly and daily noise, as well as an annual average and an annual peak power. An hourly-based time series for the whole year is synthesized by HOMER from these specific values.

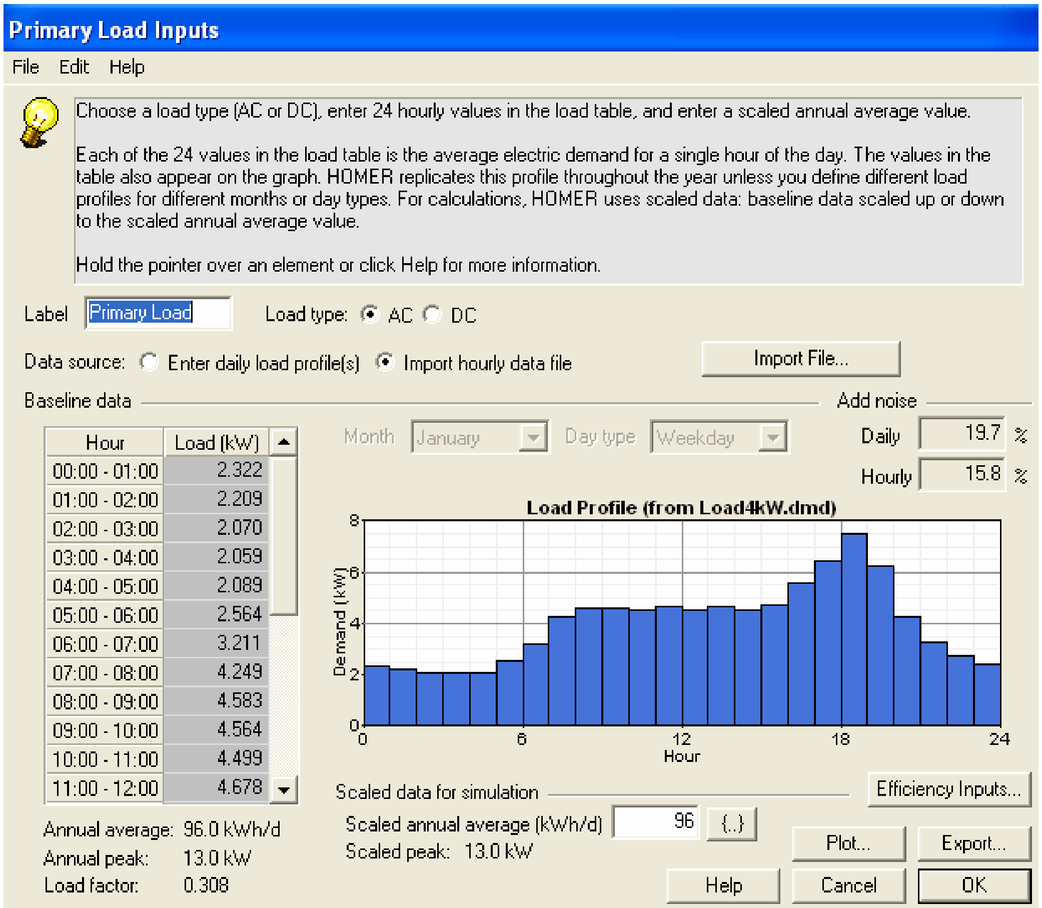


Figure 28: Load data for HOMER and TRNSYS simulations

– The solar data used in both simulations is also generated through HOMER. Once the geographical coordinates (longitude and latitude) of the site have been entered, it is possible to obtain the solar data of the area via Internet by registering freely to the NASA website. The coordinates of Loughborough can simply be determined using *Google Earth*: 52°46'N, 1°16'W. From monthly average, HOMER synthesizes an hourly-based time series of solar data - the format required by both simulations.

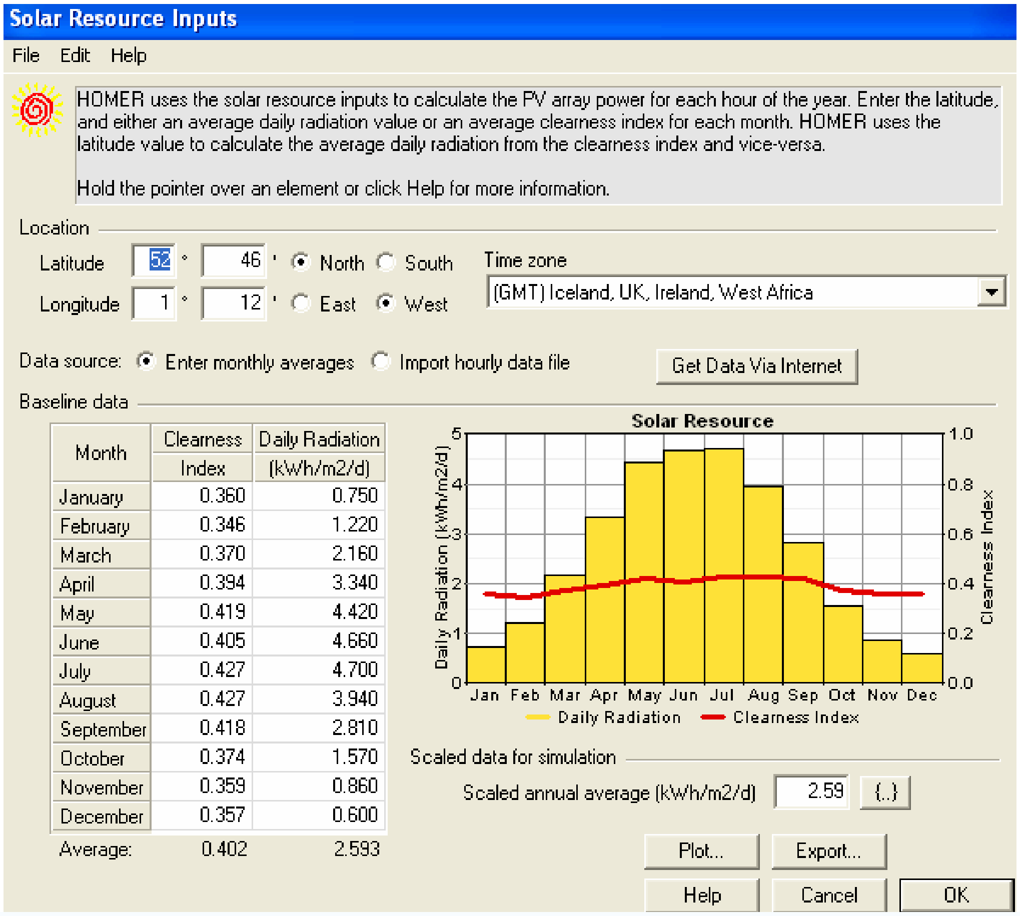


Figure 29: Solar data for HOMER and TRNSYS simulations

– The wind data used for this project are *Reanalysis data* that are totally freely available on Internet through the NCEP website at http://nomad3.ncep.noaa.gov/cgi-bin/pdisp_6p_r2.sh?ctlfile=wind.ctl&povlp=ovlp&ptype=ts&dir=.

The Reanalysis Project is a joint project between the National Centre for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR). This project provides long-term wind data collected since 1948. The original objective of the Reanalysis project was to provide valuable long-term information about the weather in order to correlate current measurements and to improve the forecasting of the climate evolution, even if techniques have largely changed during the last 60 years. This project uses a global data assimilation system, along with observations from the land, sea (from ships and marine buoys), aircraft, satellite and other data to produce global fields of various meteorological parameters. The quality of the data is controlled and assimilated by the data assimilation system which has been kept unchanged over the project period. To increase the reliability of the wind data, the reanalysis also uses delayed observations and the database is periodically updated as new processing and modeling techniques become available.

The reanalysis project is particularly useful when we want to evaluate the wind resource on a particular site. Wind data are collected every 6 hours, so four times a day.

Using the algorithm created during the group project of my *MSc in Energy Systems and the Environment* at the University of Strathclyde (http://www.esru.strath.ac.uk/EandE/Web_sites/05-06/wind_resource/index.html for more information), it is possible to obtain the wind speed at the site every 6 hours.

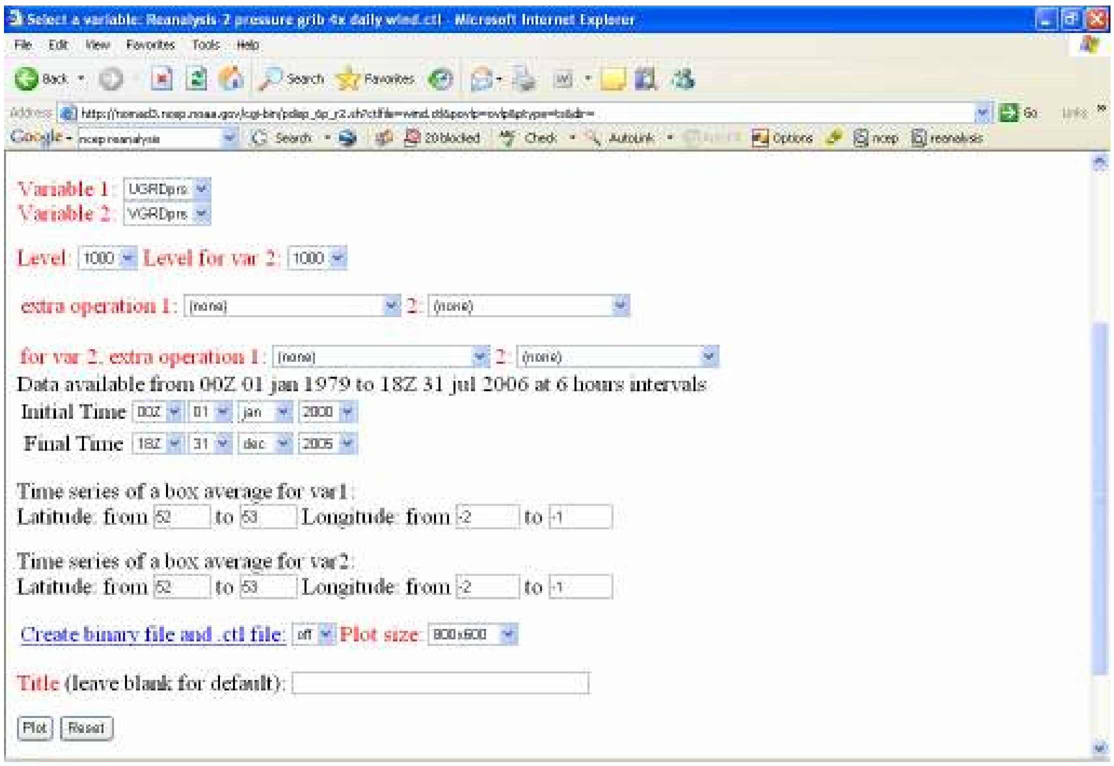


Figure 30: The NCEP reanalysis data download page

For the present project, the monthly average wind speeds of the last 6 years of reanalysis data have been considered to estimate the wind resource at WBF.

	2000	2001	2002	2003	2004	2005	Average
January	9.68427	9.01661	10.22065	10.99371	10.56403	13.39250	**10.65**
February	11.01295	7.29170	12.54598	8.55875	10.13446	9.30027	**9.81**
March	8.81403	7.57306	8.16581	7.81556	8.79847	8.46476	**8.27**
April	5.94433	7.49342	7.89058	7.95183	6.79125	7.26458	**7.22**
May	6.28960	6.07677	8.29363	7.99073	5.20847	7.96968	**6.97**
June	6.20450	6.24542	7.25550	6.03117	7.30950	5.86375	**6.48**
July	4.67790	5.71532	5.67056	6.47427	5.98806	5.64218	**5.69**
August	5.37403	5.58685	4.63234	5.40323	6.55734	6.37621	**5.66**
September	6.54500	8.35142	5.87083	5.25825	10.02817	7.28033	**7.22**
October	8.82597	9.45685	8.16661	8.95992	9.63621	7.97403	**8.84**
November	9.57317	8.80425	8.62792	9.19508	8.52742	9.19517	**8.99**
December	9.57597	9.60065	8.87960	9.48194	8.97056	8.81806	**9.22**

Table 2: Reanalysis data used to define the wind resource at WBF

(Reanalysis data provided by the NOAA-CIRES ESRL/PSD Climate Diagnostics branch, Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov)

The data are collected at an altitude of 110m, and the altitude of the site being about 50m (determined with Google Earth), the anemometer height must be defined as 60m.
As for the solar data, HOMER synthesizes an hourly-based time series of wind speeds from the reanalysis monthly average.

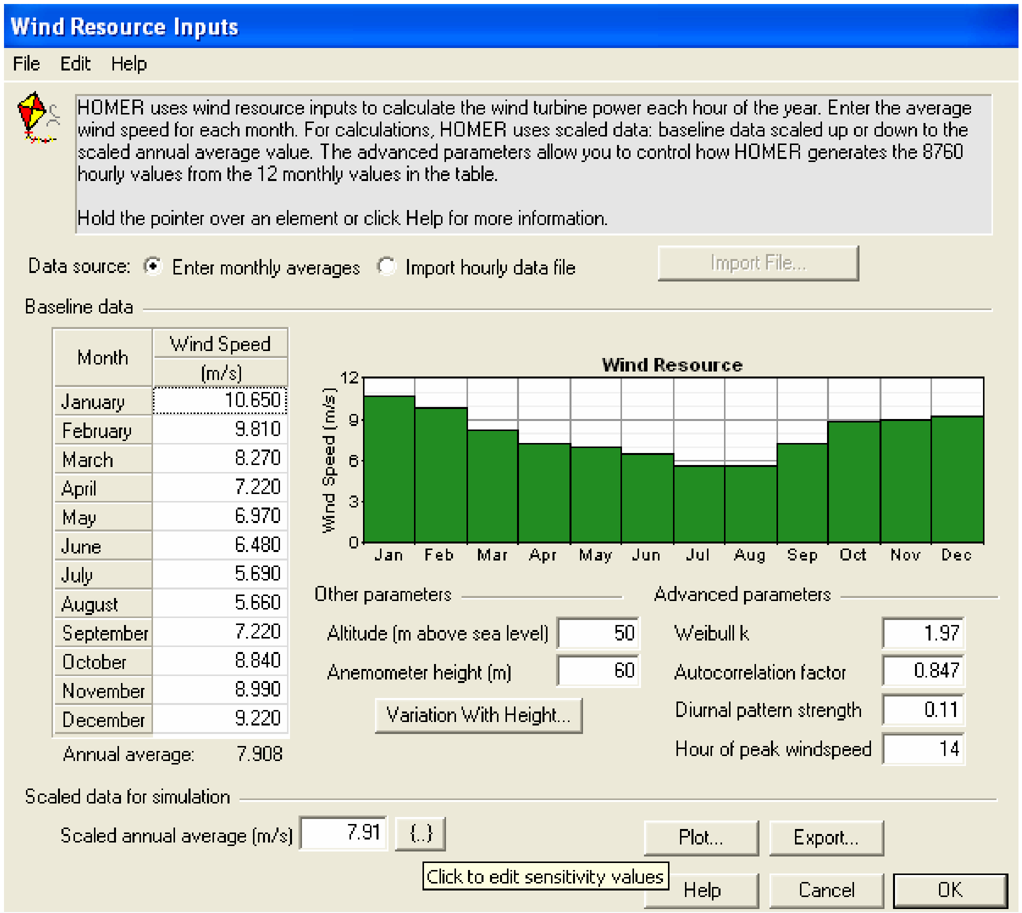


Figure 31: Wind data for HOMER and TRNSYS simulations

5. Simulation of the HARI system by HOMER and TRNSYS

HOMER and TRNSYS follow two totally different philosophies. While HOMER requires very few details about the components and bases its calculations on economic considerations, TRNSYS allows to detail the characteristics of each component of the system, as well as the characteristics of the control strategy. It can therefore be expected that the two models will give significantly different results.

Comparing the energy production or consumption of each component over the year of simulation seems to be the most convenient way to compare the models. The state of charge of the hydrogen store and the energy balance in the system can also be compared. This can be achieved by using directly the outputs of the simulations after processing them for comparison in an Excel sheet.

	TRNSYS		HOMER		Difference between TRNSYS and HOMER
		in %		*in %*	*in %*
Annual electrical energy production (in kWh)					
PV arrays	6287	*3.7*	6263	*3.8*	**+0**
Wind turbines	150363	*89.4*	149612	*91.0*	**+0**
CHP	125	*0.1*	1774	*1.1*	**+1324**
FC	11410	*6.8*	6771	*4.1*	**-41**
Total production	168185		164420		**-2**
Annual electric loads served (in kWh)					
AC load served	35040	*23.2*	35040	*55.9*	**=**
Electrolyzer load served	115707	*76.8*	27634	*44.1*	**-76**
Total load served	150747		62674		**-58**
Average SOC of the H2 storage (in %)	0.96		0.97		**+1**
Energy balance	17438		101746		

Table 3: Comparison of HOMER and TRNSYS simulations for the HARI system

These results perfectly illustrate the difference between TRNSYS and HOMER.
Except for the AC load that is of course identical for both simulations and the energy production of the PV arrays and the wind turbines that are similar because the weather data and the power curve of the turbine are identical, one can observe on table 3 that the operation of the fuel cell, CHP unit and electrolyzer are totally incomparable. HOMER uses less often the fuel cell than TRNSYS (-41%) but uses considerably more the CHP unit than TRNSYS (+1,324%). The same phenomena can be observed with the electrolyzer since HOMER uses it 76% less than TRNSYS.

Figure 32 shows a fairly similar SOC of the hydrogen tank in both simulations whereas figure 33 illustrates all the difference between the two programs by revealing that the energy balances in the systems are absolutely incomparable. We can clearly conclude here that it is impossible to compare both programs using these results.

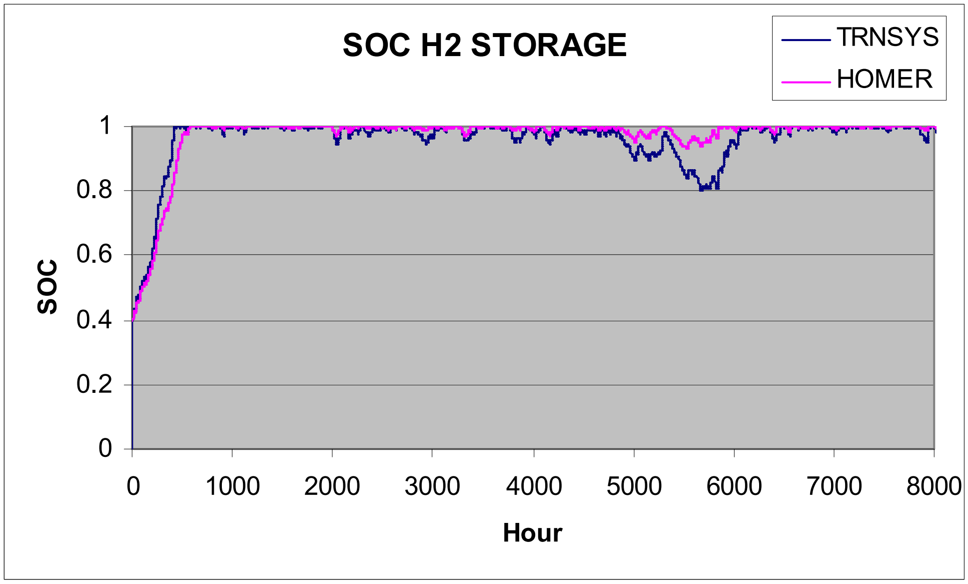


Figure 32: SOC of the hydrogen store simulated by HOMER and TRNSYS

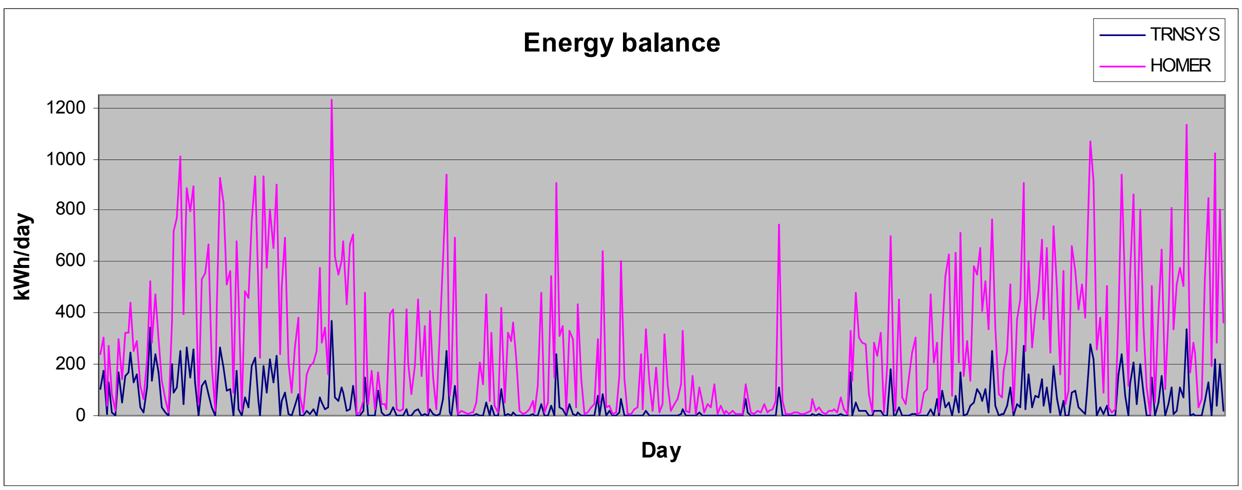


Figure 33: Energy balance simulated by TRNSYS and HOMER

E. Methodology for the optimization process

1. Optimization process

a. Methodology

As mentioned before in this report, HOMER is an optimization program based on energy cost calculations while TRNSYS is not an optimization tool but allows to model in much more details a system and its control strategy. It may therefore be interesting to use the advantages of both programs to optimize the size of the system. The basic idea is to use HOMER first to design an approximately optimal system and have a general idea of the optimal size of each component, and then to use TRNSYS to refine the system design and investigate its performance in more details.

Of course, as observed in the previous part concerning the comparison of results of both simulations, even if the weather data, the load data and the size of the components are identical, the control strategies of both models are different and TRNSYS requires much more detailed characteristics of the components. The results are therefore expected to be different, as well as the optimal size of each model. But it is important to keep in mind that HOMER is just used here to have a general idea of the optimal system amongst the feasible systems considered by HOMER. Once this first optimal system is found, the new sizes are entered in TRNSYS to be refined and adapted to the TRNSYS model.

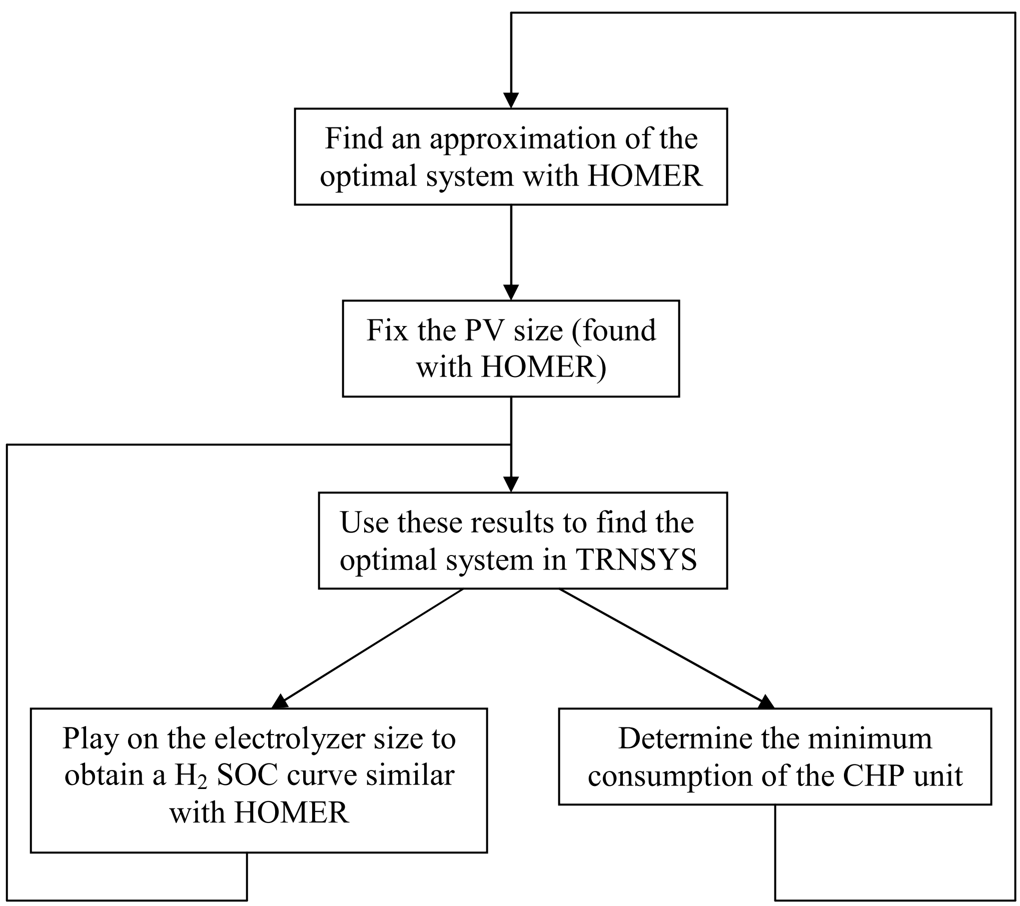


Figure 34: Methodology for the optimization process

b. HOMER optimal system

The optimal system proposed by HOMER and represented on figure 35 has been obtained step by step, first investigating a large range of values, then reducing the range progressively until these results. It includes 12kW of PV arrays, 2 wind turbines, 1kW of CHP, a 10kW fuel cell, a 6kW electrolyzer and 46kg of stored hydrogen, corresponding to 511Nm^3 of hydrogen.

To obtain this optimal system, a few assumptions and restrictions have been made. Firstly, the two 25kW Carter wind turbines have not been modified, and the number of wind turbines in the system has been fixed at 2. Moreover, willing to keep all the different components within the system, the minimum power of each component is limited at 1kW. Finally, in order to favour the use of renewables over the use of the CHP unit, the CHP size has been limited to 1kW to match its energy production with the one suggested by the simulation with TRNSYS (see table 5). This last point perfectly illustrates the necessity to use both programs in parallel and not independently one after the other.

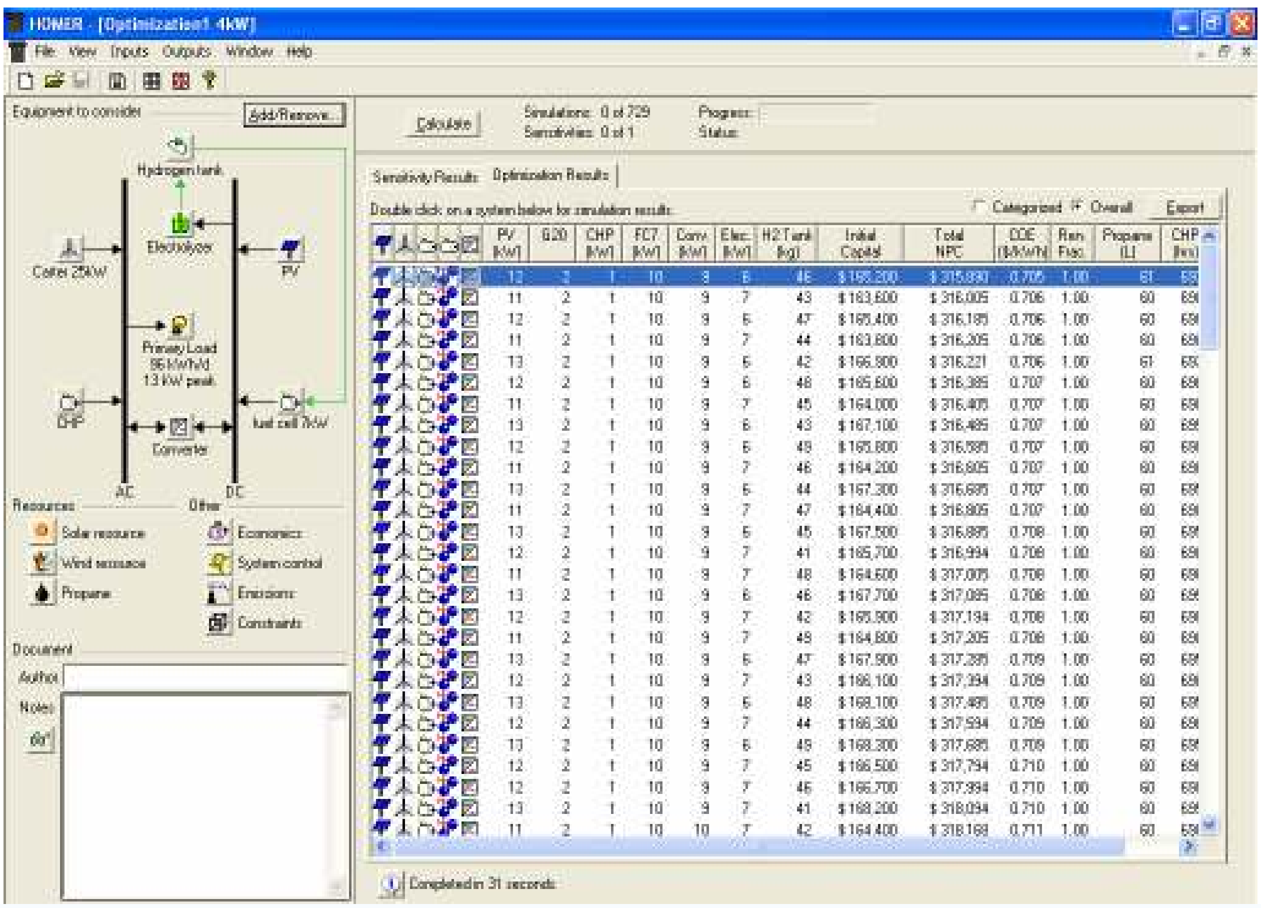


Figure 35: Optimal system found by HOMER

It is also important to notice that this optimal system has been obtained with particular capital, replacement, operation and maintenance costs for each component. HOMER basing its optimization process on costs calculations, it is obvious that changes in these costs would generate different results and therefore a different optimal system. However, these costs seem quite logical and in accordance with the prices of the market.

c. TRNSYS optimal system

The optimal system obtained with TRNSYS includes 12kW of PV arrays, 2 wind turbines, 3kW of CHP, a 9kW fuel cell, a 9kW electrolyzer and 3.9m^3 of H_2 stored at 137bar, corresponding to about 488Nm^3 of hydrogen.

This optimal sizing has been obtained step by step by modifying gradually the size of the different elements with the objectives to minimize their size for cost interests, to reduce as far as possible the use of the diesel generators, and in a second time to maximize the average SOC of the H_2 storage. Like in HOMER optimization process, the number of 25kW Carter wind turbines has been fixed at 2. Finally, the PV size has been fixed to 12kW, as found by HOMER.

d. Summary

The following table shows a summary of the optimal system proposed by HOMER and TRNSYS with the size of the different elements of the system. The two systems are fairly similar except for the electrolyzer which is bigger in TRNSYS.

	HOMER optimal system	**TRNSYS optimal system**
PV arrays (in kW)	12	12
Number of wind turbines	2	2
CHP (in kW)	1	3
Converter (in kW)	9	-
Fuel cell (in kW)	10	9
Electrolyzer (in kW)	6	9
H_2 storage (in Nm^3)	511	488

Table 4: Summary of HOMER and TRNSYS optimal systems

2. Operation of the optimal systems found by HOMER and TRNSYS

It is possible to compare the optimal systems proposed by HOMER and TRNSYS exactly in the same way than described in section *D.5*.

	TRNSYS		HOMER		Difference between TRNSYS and HOMER
		in %		*in %*	*in %*
Annual electrical energy production (in kWh)					
PV arrays	12519	*7.2*	12525	*7.4*	**+0**
Wind turbines	150363	*86.0*	149612	*88.2*	**+0**
CHP	18	*0.0*	21	*0.0*	**+21**
FC	12012	*6.9*	7512	*4.4*	**-37**
Total production	174911		169670		**-3**
Annual electric loads served (in kWh)					
AC load served	35040	*41.8*	35040	*59.8*	**=**
Electrolyzer load served	48884	*58.2*	23583	*40.2*	**-52**
Total load served	83924		58623		**-30**
Average SOC of the H2 storage (in %)	0.8		0.8		**+0**
Energy balance	90987		111047		

Table 5: Operation of the optimal systems obtained with HOMER and TRNSYS

As it was the case in section *D.5*, the results presented in the table above are considerably different. It is first interesting to notice that even if HOMER has a smaller available CHP unit than TRNSYS, both use it to produce about the same quantity of energy (18 and 21 kWh). The production of the fuel cell is way lower in HOMER (-37%), as well as the electrolyzer consumption (-52%), which explains why the total energy balance is larger in HOMER.

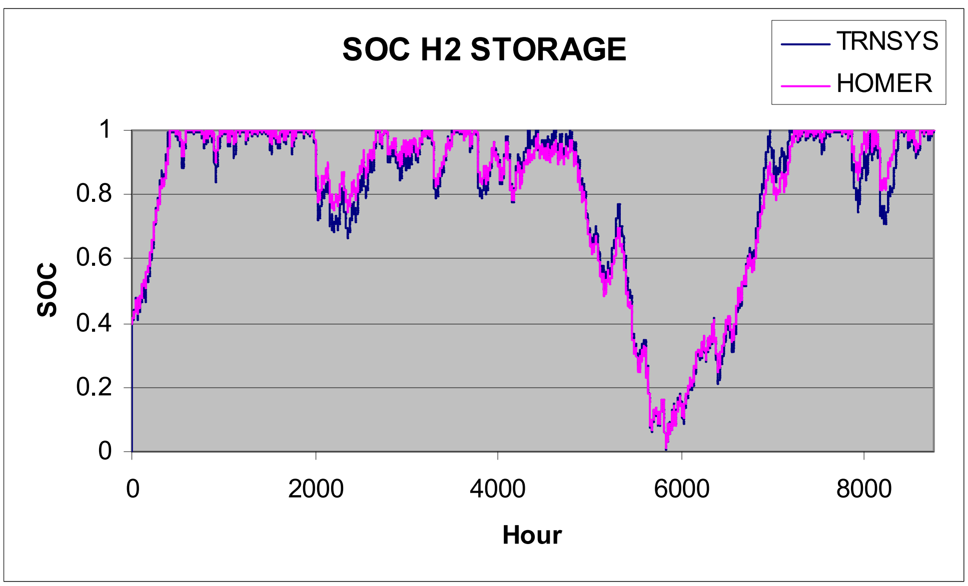
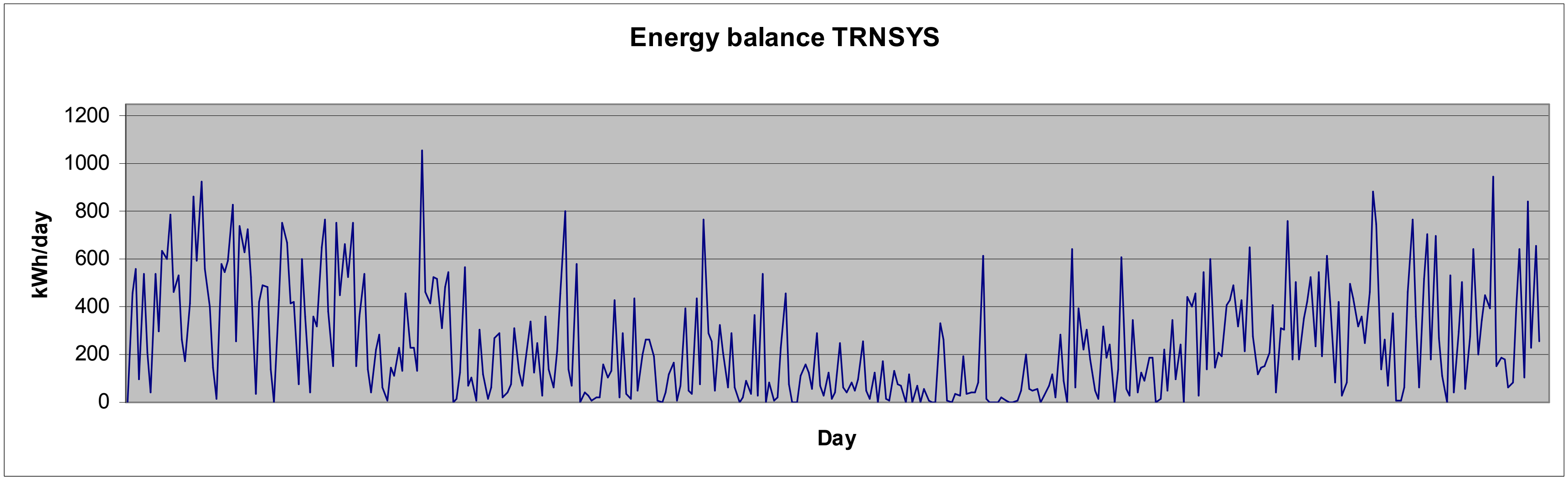
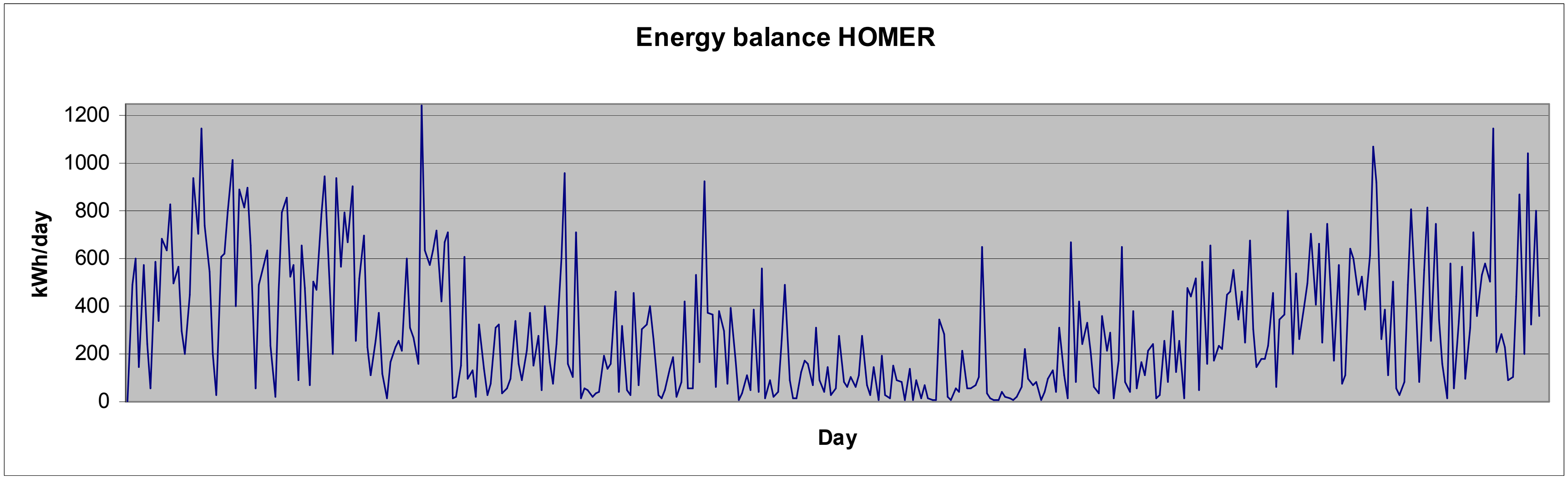


Figure 36: SOC of the H2 store for the optimal systems found by HOMER and TRNSYS

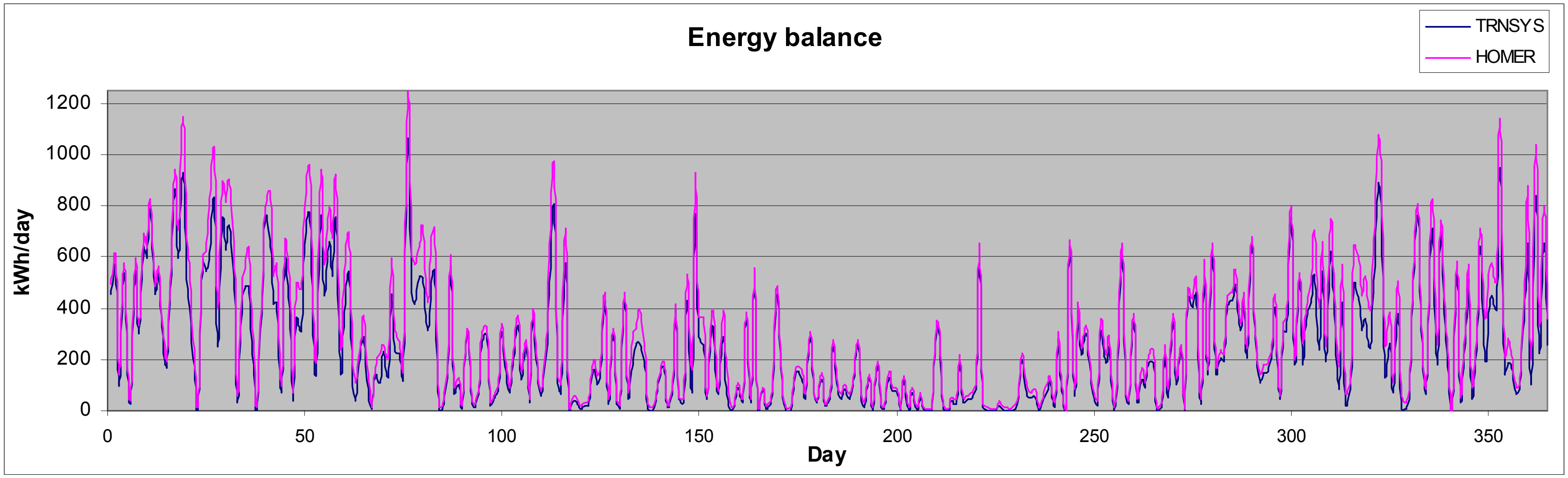
Figure 36 presents an important point of this comparison between the two models. The curves presented here are nearly identical, which means that the SOC of the hydrogen storage over the year is closely resembling in both simulations with very similar fluctuations. We clearly observe the same basic shape with a high level during winter and spring despite a few drops, a major drop between the hours 4000 and 6000 and finally a quick increase after the summer period. These fluctuations can simply be explained by the intermittent renewable resource that is largely inferior during summer than during the rest of the year (the solar resource is superior but cannot compensate the drop of wind speeds, see section *D.4*). Whereas the hydrogen level is kept high until hour 4000 thanks to the large amount of renewable power, the fuel cell is intensively used during the summer period to compensate the lack of renewable power which causes the drop of the hydrogen level. After this period, the renewable power available increases back and the hydrogen level can progressively reach higher values.


Energy balance TRNSYS
1200
1000
800
600
400
200
0
kWh/day
Day

(a)


Energy balance HOMER
1200
1000
800
600
400
200
0
kWh/day
Day

(b)



(c)

Figure 37 (a), (b) and (c): Energy balance in the optimal systems found by HOMER and TRNSYS

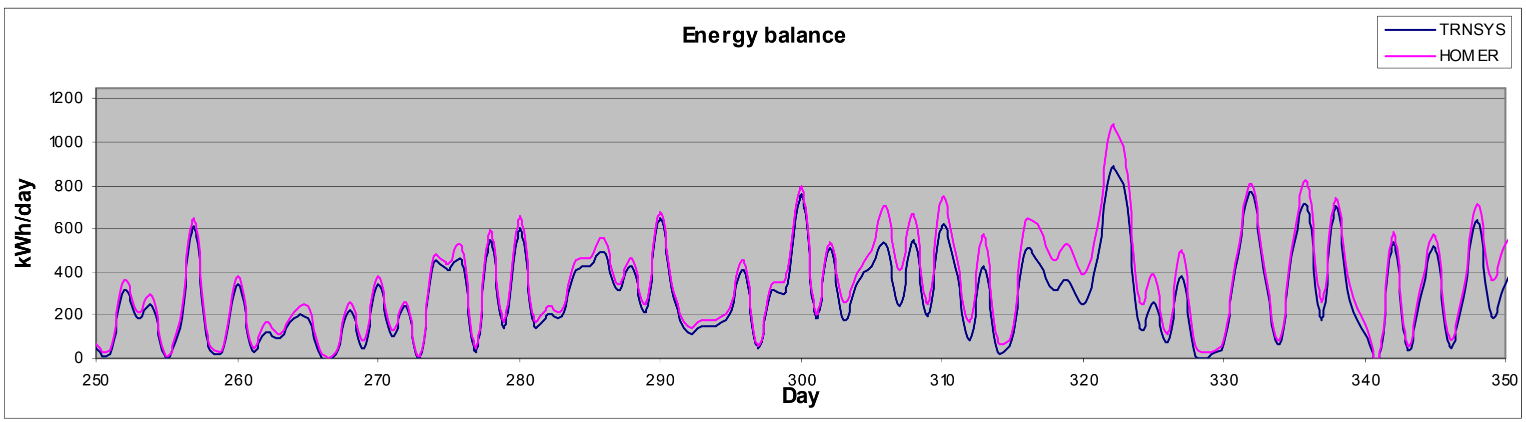


Figure 37 (d): Zoom of figure 36 (c) between days 250 and 350

Another very interesting aspect of this comparison is the energy balance in the system represented on figure 37 (four graphs above). Here one can see that the energy balance in the system follows the same trend in both optimal systems by HOMER and TRNSYS with exactly the same fluctuations. This impression is confirmed by figure 38 that presents the correlation between energy balances in both optimal systems. The R^2 value which is very close to 1 *(R^2 = 0.9787)* indicates that the correlation between the two energy balances is nearly perfect.

Figure 38 also indicates that the energy balance (= *energy production - energy consumption*) is about 15% superior in HOMER which can be simply explained by the results in table 5: even if it produces about 4,500kWh less with the fuel cells, HOMER consumes considerably less energy through it electrolyzer (about 30,000kWh less). This difference explains the larger energy balance in HOMER.
However, the very high level of correlation between the two curves proves that HOMER and TRNSYS globally operate in the same way, though not in the same proportion. This is an important output of this analysis.

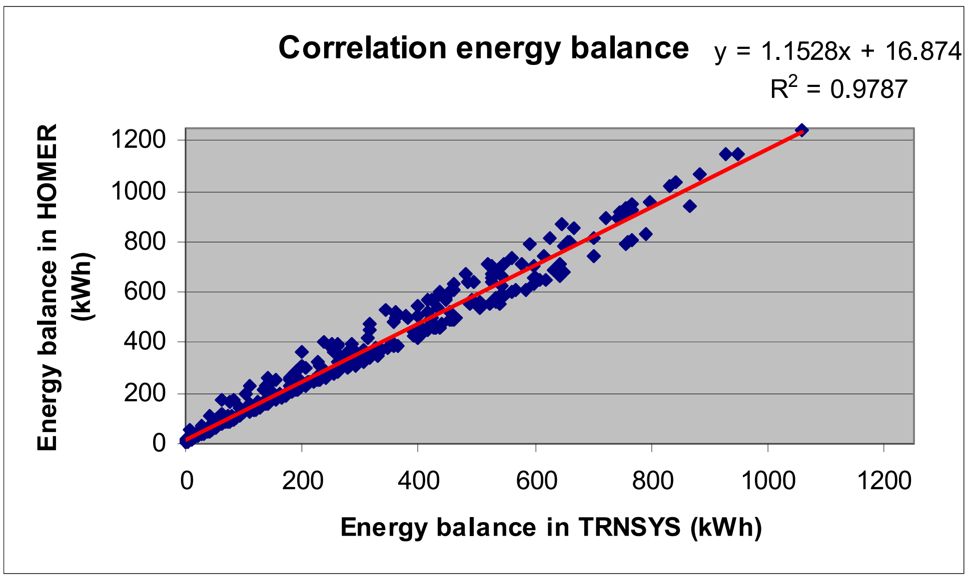


Figure 38: Correlation between the energy balances in the optimal systems found by HOMER and TRNSYS

3. Conclusion on the HARI optimal system

The optimal system for the HARI system calculated by TRNSYS for these particular load and weather data includes 12kW of PV arrays, 2 wind turbines, 3kW of CHP, a 9kW fuel cell, a 9kW electrolyzer and 3.9m^3 of H_2 stored at 137bar. This new system is globally way smaller than the actual system, notably for the electrolyzer and the hydrogen storage. This optimal system has been build with the major objective to reduce the size of the components and to reduce the use of the CHP unit. Of course, all thermal advantages of the CHP have not been taken into consideration in this study, since it was only considered as a diesel generator running on LPG. The CHP in the actual system has without any doubt many advantages but it was only seen as a fossil fuel consumer to eliminate in this study.

	Original size in kW	Optimal size in kW	Difference in %
PV arrays	6	12	+100
Wind turbines	50	50	=
CHP	15	3	-80
FC	7	9	+29
Electrolyzer	38	9	-76
H_2 storage (in m^3)	22.8	3.9	-83

Table 6: Comparison between the actual and optimal HARI systems

It is particularly interesting to notice that the use of the CHP unit has been substantially decreased between the original and the optimal system, passing from 125kWh to 18kWh over the year of simulation. This reduction has been compensated by an increase of the size of the fuel cell and the PV arrays.
The second major advantage of this optimal system is the significant reduction of the size of the hydrogen storage which was bulky and seemed largely oversized. Of course, if a hydrogen vehicle or a CHP unit running on hydrogen are introduced in the system (as it is planned in the future at WBF), it could be useful (and necessary) to have a bigger quantity of hydrogen available on the site. A bigger hydrogen store would then be necessary.

To conclude, the results presented in this part seem to indicate that the TRNSYS model is reliable to predict the operation of the system through its energy balance and the SOC of its hydrogen store over the year. The methodology developed here that uses complementarily the strengths of HOMER and TRNSYS to estimate the optimal size of the system that satisfies the load requirements seems to give satisfactory and reliable results.

4. Relocation of the model in Glasgow

Now that TRNSYS has been tested on the HARI site in Loughborough, it is interesting to evaluate the impact of changes in the weather input data on the simulation results.
In the next part Loughborough weather data will be replaced by Glasgow weather data in order to determine the effects of such changes on the results of the simulations and on the optimal system size suggested by the optimization process.

a. Glasgow weather data

Since the objective of this part is to determine the impact of weather changes on the simulation, the load data used here is of course exactly the same than the one used for the simulation at WBF presented in section *D.4*. Solar data presented on figure 39 have been obtained from the NASA website after entering the coordinates of Glasgow (55°51'N, 4°15'W) and wind data on figure 40 are issued from the Reanalysis data available in table 7.

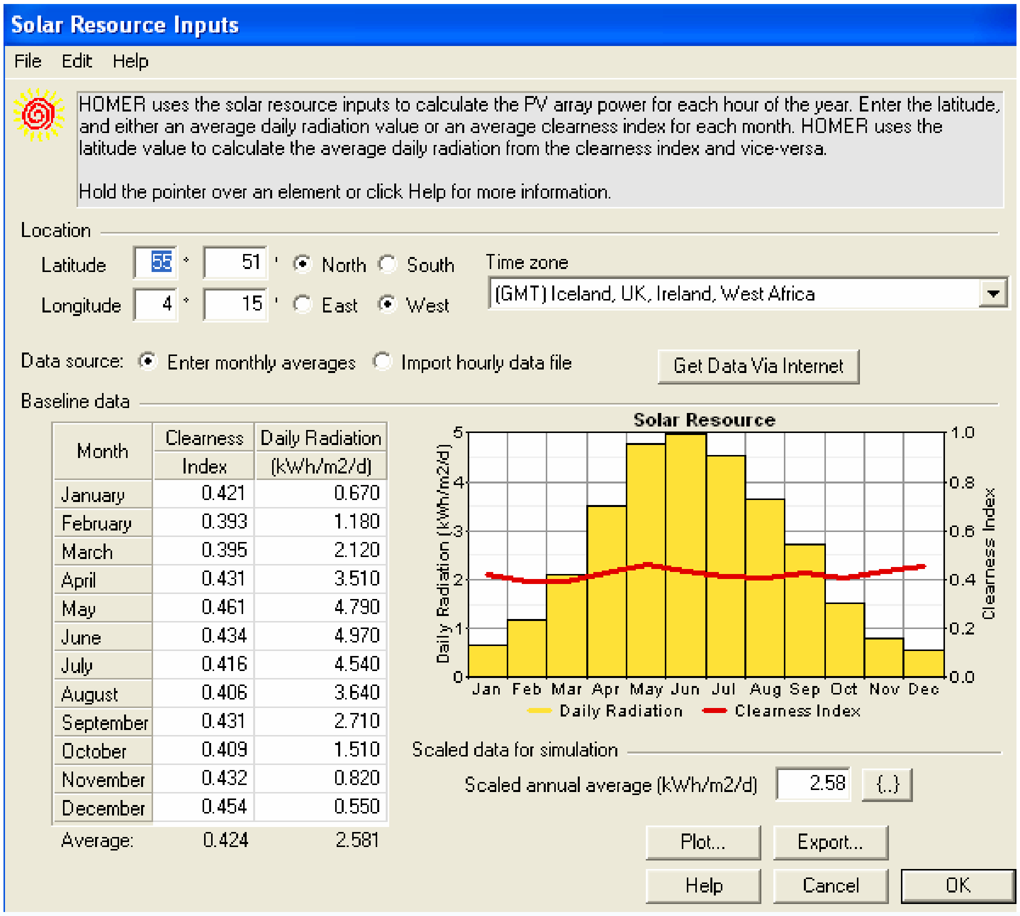


Figure 39: Glasgow solar data for HOMER and TRNSYS simulations

	2000	2001	2002	2003	2004	2005	Average
January	11.39863	9.01645	12.35258	11.51661	10.53363	14.26097	**11.51**
February	12.53750	8.58536	12.55705	10.32714	9.81768	10.26223	**10.68**
March	9.14194	7.98863	9.92242	8.30863	9.56363	9.59903	**9.09**
April	6.97642	7.46442	7.52408	7.50858	8.86058	9.07367	**7.9**
May	5.44395	5.06911	7.96153	8.45839	6.46331	7.60548	**6.83**
June	6.68900	7.04100	8.82942	7.76983	8.48083	6.41675	**7.54**
July	4.54694	6.93226	5.33290	7.23694	7.30661	5.92363	**6.21**
August	5.13911	6.22742	5.40089	6.40161	6.99016	7.45298	**6.27**
September	6.81817	8.45683	5.86125	7.24858	10.51650	9.10633	**8**
October	9.07097	10.85113	8.27468	8.89218	8.73895	10.03363	**9.31**
November	9.15842	10.16017	10.39667	10.39792	9.90908	10.82950	**10.14**
December	9.10073	9.54952	8.19403	9.73121	11.87500	9.67548	**9.69**

Table 7: Reanalysis data used to define the wind resource in Glasgow

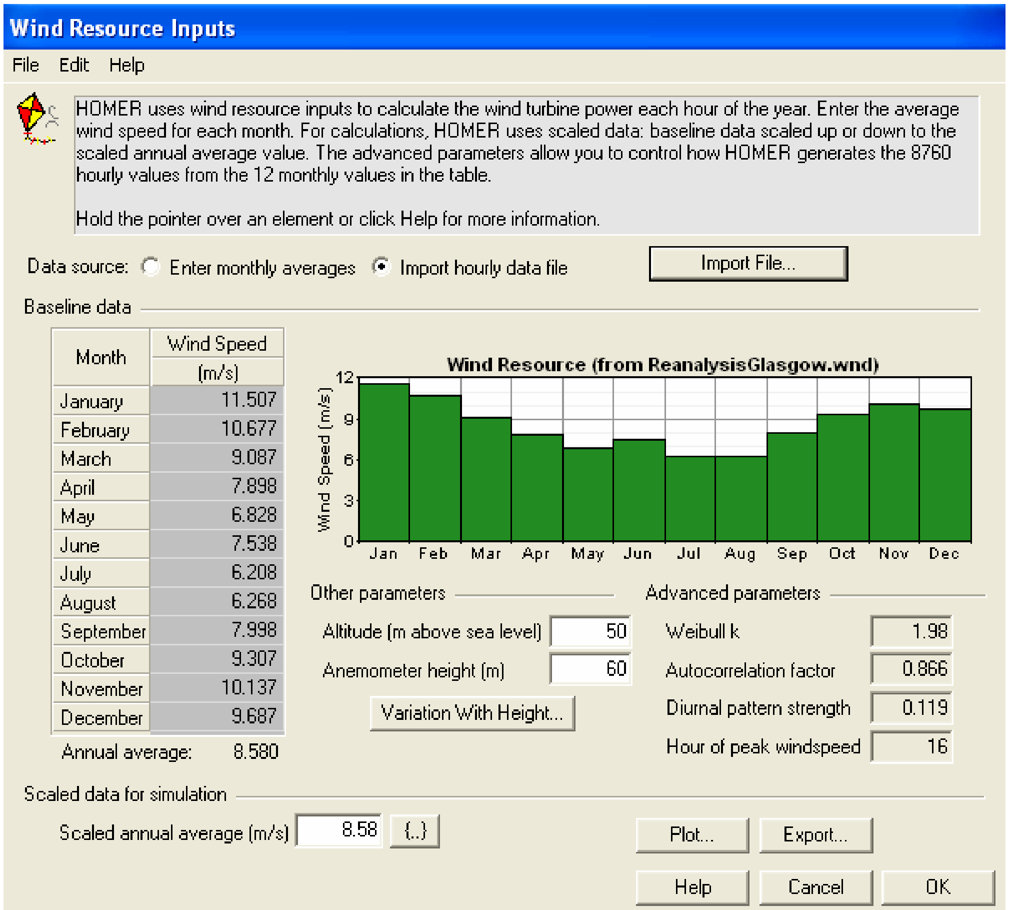


Figure 40: Glasgow wind data for HOMER and TRNSYS simulations

When comparing these data with the ones of Loughborough, it is noticeable that the solar resource is similar at both sites (though slightly higher in Loughborough) whereas the wind resource is around 10% higher in Glasgow, which should have an impact on the optimal size of the system.

b. Optimal system in Glasgow

The methodology used here is exactly the same than the one used in Loughborough for the optimisation of the HARI system. The size of PV arrays has been determined by HOMER whereas the size of the CHP unit has not been modified. Then, the size of the fuel cell, the electrolyzer and the hydrogen store have been optimised with TRNSYS.

	HOMER optimal system	TRNSYS optimal system
PV arrays (in kW)	10	10
Number of wind turbines	2	2
CHP (in kW)	1	3
Converter (in kW)	9	-
Fuel cell (in kW)	10	9
Electrolyzer (in kW)	5	7.5
H_2 storage (in Nm^3)	388 (35kg)	376 (3m^3 at 137b)

Table 8: Summary of HOMER and TRNSYS optimal systems in Glasgow

As it was the case in Loughborough, one can observe that the major difference between these two solutions is the size of the electrolyzer, this one being bigger in TRNSYS. Otherwise, the fuel cell and the hydrogen tank have still similar sizes.

	TRNSYS		HOMER		Difference between TRNSYS and HOMER
		in %		*in %*	*in %*
Annual electrical energy production (in kWh)					
PV arrays	11059	*5.6*	11041	*5.7*	**+0**
Wind turbines	176134	*88.7*	175254	*90.9*	**+0**
CHP	14	*0.0*	17	*0.0*	**+23**
FC	11431	*5.8*	6543	*3.4*	**-43**
Total production	198638		192855		**-3**
Annual electric loads served (in kWh)					
AC load served	35040	*43.8*	35040	*63.2*	**=**
Electrolyzer load served	44897	*56.2*	20391	*36.8*	**-55**
Total load served	79937		55431		**-31**
Average SOC of the H2 storage (in %)	0.81		0.83		**+2**
Energy balance	118701		137424		

Table 9: Comparison of the optimal systems in Glasgow obtained with HOMER and TRNSYS

The results presented in table 9 and in the figures 41, 42 and 43 perfectly confirm the results obtained at Loughborough. The use by HOMER of the fuel cell and the electrolyzer is smaller than in TRNSYS, with respectively -43 and -55%. The SOC of the hydrogen tank is still very similar in both simulations and the correlation between the two energy balances is still excellent (R^2=0.9865). One can also see that the energy balance is still substantially higher in HOMER (about +12%) for the same reasons than mentioned in the previous part.

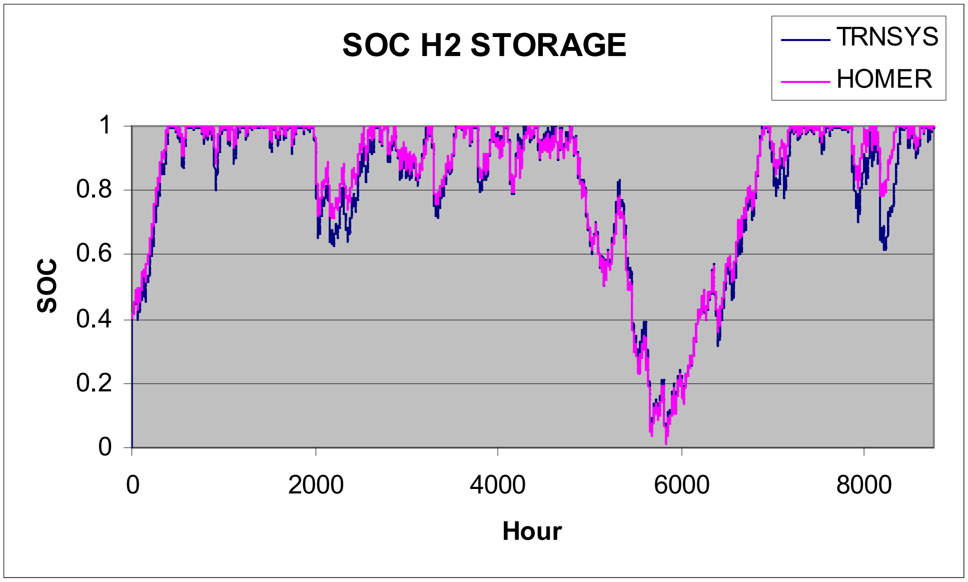


Figure 41: SOC of the H2 store in the optimal systems found by HOMER and TRNSYS in Glasgow

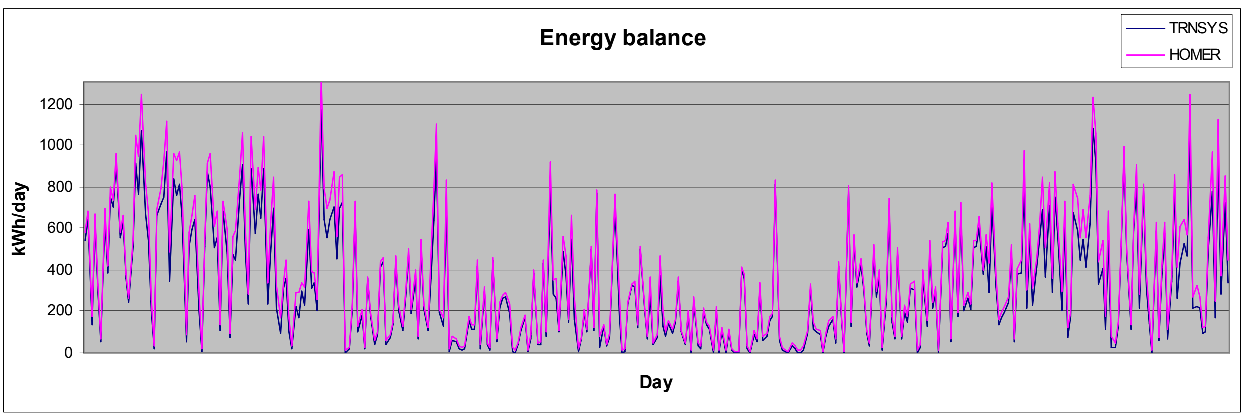


Figure 42: Energy balance in the optimal systems found by HOMER and TRNSYS in Glasgow

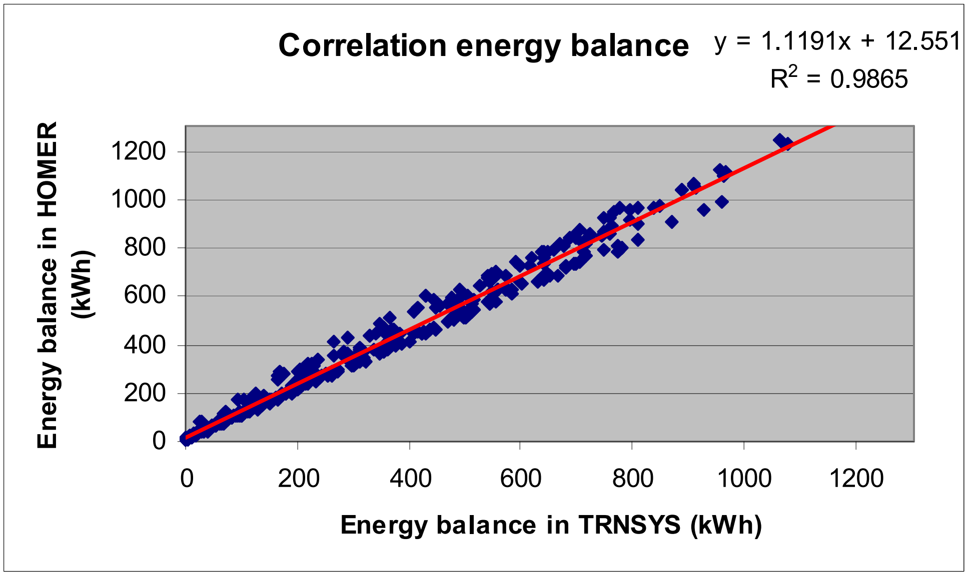


Figure 43: Correlation between the energy balance in the optimal systems found by HOMER and TRNSYS in Glasgow

c. Impact of the weather changes on the optimal system size

The real interest of transposing the models in Glasgow is to compare the optimal systems proposed by TRNSYS in the two places.

	TRNSYS optimal in Loughborough	**TRNSYS optimal in Glasgow**
PV arrays (in kW)	12	10
Number of wind turbines	2	2
CHP (in kW)	3	3
Fuel cell (in kW)	9	9
Electrolyzer (in kW)	9	7.5
H_2 storage (in m^3) at 137b	3.9	3

Table 10: Comparison of the optimal systems found by TRNSYS in Loughborough and Glasgow

Logically, since the wind speeds are higher in Glasgow, the system requires less solar power to provide the necessary amount of renewable energy. The loss of PV power is easily compensated by the extra wind power.

Since the CHP unit and the fuel cell are identical on both sites, the major differences between the optimal systems in Loughborough and Glasgow are the sizes of the electrolyzer and the hydrogen storage necessary, which are both smaller in Glasgow by respectively 17 and 23 %.

	WBF-Loughborough		Glasgow		Difference
		in %		*in %*	*in %*
Annual electrical energy production (in kWh)					
PV arrays	12519	*7.2*	11059	*5.6*	**-12**
Wind turbines	150363	*86.0*	176134	*88.7*	**+17**
CHP	18	*0.0*	14	*0.0*	**-21**
FC	12012	*6.9*	11431	*5.8*	**-5**
Total production	174911		198638		**+14**
Annual electric loads served (in kWh)					
AC load served	35040	*41.8*	35040	*43.8*	**=**
Electrolyzer load served	48884	*58.2*	44897	*56.2*	**-8**
Total load served	83924		79937		**-5**
Average SOC of the H2 storage (in %)	0.8		0.81		**+1**
Energy balance	90987		118701		**+30**

Table 11: Comparison of performances of the optimal systems in Loughborough and Glasgow

To go in more details, table 11 shows that the loss of PV power is actually more than compensated by the extra wind resource in Glasgow. The renewable energy production is therefore much bigger in Glasgow. And since the electrolyzer load served is smaller in Glasgow, this explains the big difference in the total energy balance of the system.
Finally it appears obviously on figure 44 that the SOC of the hydrogen storage over the year really resemble each other at WBF and in Glasgow.

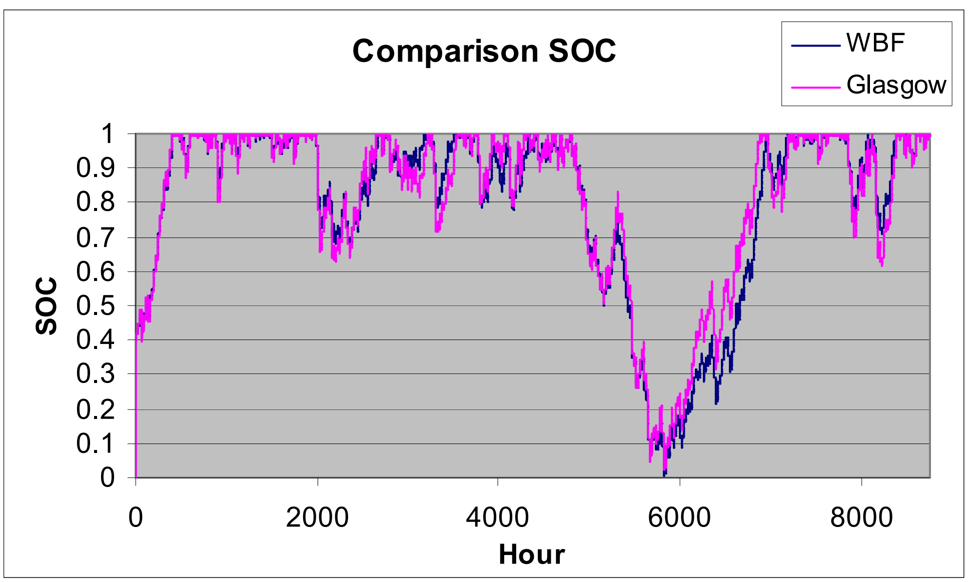


Figure 44: Comparison of the SOC of the H2 store in Loughborough and Glasgow

To conclude, this part shows fairly logically that having a bigger wind resource allows to reduce the size of the majority of the elements of the power system: the PV arrays, the electrolyzer and the hydrogen tank. Having a maximum renewable resource constitutes therefore a great advantage for the implantation of such stand-alone energy systems.

F. Conclusion

Because storing energy from renewables using a hydrogen system is still an expensive and immature technology, developing computer programs that can model such hybrid systems is absolutely essential for the future of this technology.
In this context, this project aimed at simulating the HARI system with the TRaNsient SYstems Simulation program TRNSYS. The first objective was of course to assess the ability of TRNSYS to simulate any stand-alone power system without major difficulties. Once the model developed, TRNSYS has been used in parallel with HOMER (another modeling and optimization program) to determine the optimal size of the system to satisfy the load requirements at West Beacon Farm. Finally, Loughborough wind and solar data have been replaced by Glasgow data in order to assess the impact of weather changes on the optimal configuration of the system.

The main findings from this project was that there were some limitations in the capabilities of the tools studied. However, despite these limitations the use of modelling programs seems to be an efficient and reliable way to determine the optimal size of a renewable-hydrogen system and its performances. A particular methodology, which uses the TRNSYS and HOMER modelling tools in parallel has been established.

The specific conclusions are as follows.

- Developing a model of the HARI system with TRNSYS was not a simple task. The study highlighted an important weakness of the current version of TRNSYS. There is only one controller available in TRNSYS library to control the system. Even if this controller can provide interesting results in many cases, it is absolutely essential in the future to be able to choose a control strategy amongst others. Selecting the most appropriate strategy must be part of the whole system optimization process since, as shown in this study, a change in the control strategy can have major effects on the operation of the system.

- The limitations on the controller available in TRNSYS library obliged to adapt and transform the HARI system, and notably to change significantly its control strategy. The actual HARI system is controlled through the state of charge of its battery. However, the only controller currently available in TRNSYS controls the system through the state of charge of the hydrogen store, and can only control one fuel cell at the time. The original HARI system has therefore been transformed to satisfy these new specifications. These limitations on the control strategy in TRNSYS appear clearly as an important drawback of the program at the moment. Nevertheless, controlling such a system through the state of charge of the hydrogen store is also a feasible solution that was worth testing.

- Weather and load data were not directly obtained from measurement at WBF because of the difficulty to obtain the necessary data in the format required by HOMER and TRNSYS for one whole year. While the load data has been obtained from a sample remote load distribution scaled at 4kW, the raw solar data of the site comes from the NASA website and the raw wind data is reanalysis data generated by the NCEP reanalysis program. HOMER is then able to generate from these raw data hourly-based data compatible with the format required by both programs. Of course these data cannot be as accurate as direct measurements but this collection method allows to test the model at any site on Earth without requiring any measurement campaign. The necessary data can be easily collected and used immediately, which represents an enormous advantage.

- HOMER and TRNSYS simulate totally differently the real HARI system. The production or consumption of each component, as well as the hydrogen SOC over the year or the energy balance in the system are absolutely incomparable. It is therefore impossible to conclude on the performances of the actual HARI system with these results. However, it appears clearly that this is caused by the major differences in the control strategies in HOMER and TRNSYS. Whereas the system is ruled by some energy flow calculations in TRNSYS, HOMER bases its operation on costs calculations since it aims at producing the required energy most cheaply. simply selects each hour the available generators that can produce the required amount of power as cheaply as possible.

- A methodology using TRNSYS and HOMER in parallel has been established to optimize the size of the stand-alone power system. HOMER being an optimization tool based on costs considerations and TRNSYS being more detailed on the technical aspect (but it is not an optimization tool), it is interesting to use the strengths of both programs. In the methodology, HOMER is used first to design an approximately optimal system, and then TRNSYS is used to refine the system design and investigate its performance in more details.
This optimization process provides very interesting results. Indeed, while the sizes of the optimal system found by each program fairly resemble, the hydrogen SOC and the energy balance simulated by both models are very similar. Despite control strategies still different (which still explains the different operations of the different elements) and an energy balance about 15% superior in HOMER, the correlation is nearly perfect between both simulations, indicating some identical fluctuations of the energy balance.

- The HARI optimal system found by TRNSYS includes 12kW of PV arrays, 2 wind turbines, 3kW of CHP, a 9kW fuel cell, a 9kW electrolyzer and 3.9m^3 of H_2 stored at 137bar, which is considerably smaller than the system existing at the moment at WBF. The size of the hydrogen store has notably been reduced by 83% in comparison with the original HARI system. The use of the CHP unit has also been nearly eliminated in the new system, even if it is important to know that all thermal aspects have been neglected in this study.

- The virtual relocation of the HARI system in Glasgow also provides some interesting results. With a similar solar resource but a wind resource about 10% superior to Loughborough, the conditions in Glasgow allow to push even further the reduction of size of the optimal system, which highlights the importance of selecting carefully the appropriate data of the site.

To summarize, developing new controllers compatible with TRNSYS is absolutely necessary for a potential further use of TRNSYS to model and design stand-alone power systems. This should be one of the objectives of the Knowledge Transfer Partnership (KTP) I will undertake for the next two years at *SgurrEnergy*.

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