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REVIEW PAPER

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HYDROGEN ENERGY: TERCEIRA ISLAND DEMONSTRATION FACILITY

The present paper gives a general perspective of the efforts going on at Terceira Island in Azores, Portugal, concerning the implementation of an Hydrogen Economy demonstration campus. The major motivation for such a geographical location choice was the abundance of renewable resources like wind, sea waves and geothermal enthalpy, which are of fundamental importance for the demonstration of renewable hydrogen economy sustainability. Three main campus will be implemented: one at Cume Hill, where the majority of renewable hydrogen production will take place using the wind as the primary energy source, a second one at Angra do Heroismo Industrial park, where a cogen electrical - heat power station will be installed, mainly to feed a Municipal Solid Waste processing plant and a third one, the Praia da Vitoria Hydrogenopolis, where several final consumer demonstrators will be installed both for public awareness and intensive study of economic sustainability and optimization. Some of these units are already under construction, particularly the renewable hydrogen generation facilities.

Key words: hydrogen economy; Azores; hydrogen energy; Terceira island Hydrogenopolis; sustainable energy; Terceira hydrogen facilities; renewable hydrogen (H2RE); wind energy; marine wave energy; geothermal energy; hydrogen power; hydrogen production.

In a global world, where energy is a major factor for development, it is clear that we must make sure to have sustainable access to it. If no one doubts about the advantages of our present technological society and economy, it is also clear that a large portion of mankind does not have access to it and that in the economically developed countries such development did carried together several drawbacks that one shall avoid for the sake of a future healthy planet and sustainability for future generations.

Our present energy model is based on fossil fuels, which copes for some 81 % of global energy consumption, together with some 6 % contribution from renewable (mainly hydroelectric), 6 % from nuclear and 7 % from biomass (mainly wood in the less developed countries). Three sorts of major drawbacks can be readily identified in the present energy system.

i) It causes environmental degradation (greenhouse gas emissions, acid rains, marine oil spills, the always present non-zero risk of nuclear accidents, very long lived and extremely poisoning nuclear wastes).

ii) It relies on a limited, non-renewable, stock of earth produced / deposited fossil fuels that are being depleted at a rate that will make them economically un-exploitable in just a few more decades.

iii) It causes economical and social instability either due to a sustainable mean climb of the energy cost, as the result of an increasing demand, not followed by a similar availability in the offer side, or due to fear of losing control and access to the fossil resources, since almost all major reserves (or their near future remnants) are now mainly concentrated in very specific geographical areas outside the major consumption centres.

Clearly, an alternative to such an energy system must be found and implemented. The optimum alternative would be one that can solve simultaneously all the above mentioned drawbacks. Fortunately it exists and can be realised. It is the Renewable Hydrogen Society and Economy.

The Renewable Hydrogen Society and Economy can be defined as the one whose dominant fuel, for final consumption, will be the renewable hydrogen – – H_2RE (the one solely generated through renewable resources, particularly renewable electricity and sea water), but where other renewable fuels (like second generation biofuels) will coexist simultaneously. It can

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be proved (Alves, 2003) that although biomass second generation derived fuels can, and will, be produced in the future as alternative renewable fuels, our planet will not be able to produce enough biomass for energy purposes due to a lack of land space availability and direct concurrence with the feeding agriculture and water resources. At the best, with biomass one will be able to achieve 20 to 25 % of our present global energy needs. The remnant 80 to 75 %, that is the majority of it, can be fulfilled by the H_2RE.

The Hydrogen Economy start up, according to the present paradigm, is often seen as a complement to Renewable Energy (RE) and a way to store it. Although this can be a good demo approach of one of the major roles for hydrogen in the future, it is hardly feasible in a larger scale because of economical reasons. The hydrogen production when associated with common RE facilities (as a way to store the RE excess that can not be absorbed by the electric grid and that will be used later, during periods of insufficient RE availability, to produce and deliver electricity on demand to the grid) has such an economy that the overall payback period is often much larger than the expected lifespan of the installed equipment (Alves, 2003). This system is reproduced for illustration in Fig. 1. This makes the present paradigm of hydrogen production/uses a good one for demo applications and public awareness, but it is an unsustainable one for large scale reproduction since it is not economically viable, except, perhaps, in some particular situations of remote access.

The present vision and effort, although tailored for the Terceira island case, introduces a new paradigm that, in our opinion, can be used elsewhere. In this new Hydrogen Economy paradigm, the hydrogen will be produced through RE devices that will be particularly adapted to work solely and exclusively for hydrogen production. A significant increase on hydrogen production ratio is expected for the same available RE, implying, thus, a much smaller cost per unit mass of hydrogen produced.

Our effort concerns the full process of hydrogen production in a "Well to Wheel" like approach, starting at the primary RE conversion, used for hydrogen generation, but proceeding through its storage and delivery, down to its final use and consumption. This corresponds to a vision of a new emerging global Industry devoted to hydrogen production (Fig. 2 illustrates such a new paradigm).

We strongly believe that the renewable hydrogen (H_2RE) process as we envision it is the only one solution that can be fully sustainable in the long term future.

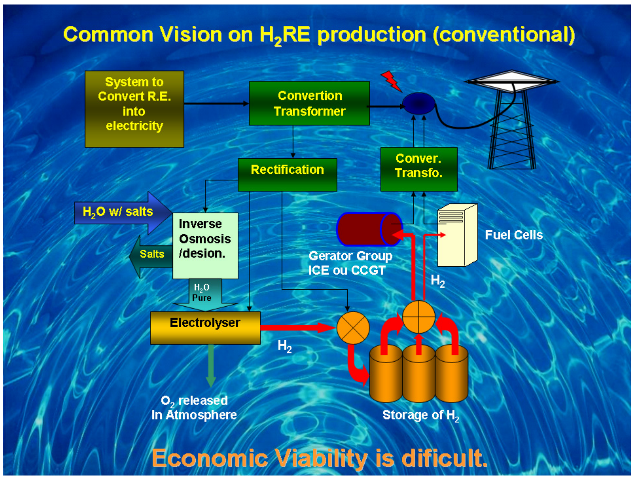

Fig. 1. Present hydrogen production paradigm.

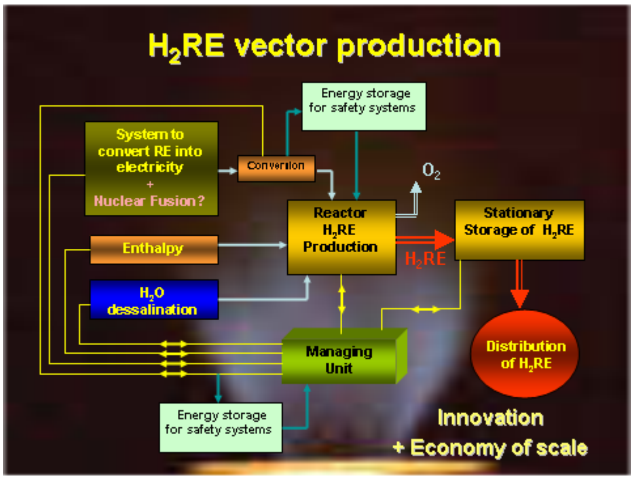

Fig. 2. A new industry devoted to the exclusive hydrogen production is expected to take place according to our vision and paradigm approach.

ENERGY CONSUMPTION PATTERNS IN AZORES

In order to define a feasible way for the Hydrogen Society and Economy start up in Terceira Island and in Azores, one should first address the present patterns of local energy production/imports and consumption to understand how the already existing solutions can be morphed with the new H_2RE ones.

The whole Azores Region had 241,735 inhabitants in 2004, of which 131,609 in São Miguel island and 55,833 in Terceira island, while the remaining 54,293 inhabitants were dispersed in the other 7 islands. In Terceira, we can further consider that, 20,252 inhabitants are in Praia da Vitoria and 35,581 in Angra do Heroismo.

As almost everywhere, the Azorean society and economy depends entirely on fossil fuels imports, coming from Portugal mainland in the present case. A similar situation occurs with the other Portuguese Archipelago of Madeira. Its electrical energy system is composed of as much micro-grids as the number of islands since they are far enough from each other to make centralised electricity generation economically unfeasible. Such a reality had created a situation that promoted the early introduction of local renewable energy units. It started with mini-hydroelectric power plants and progressed more recently to wind and geothermal power units. The Public Electrical Company EDA, has, at present, the full control of local electricity production and delivery to the final users. Figures 3 and 4 depict both fossil fuel and electrical micro-grid dependencies.

In Fig. 5 it is summarised the energy fluxes for the reference year of 2004. Some 285,000 tons of oil equivalent (or 3420 GW $h_{equivalent}$) were imported to the Azores. This amounted to some 97 % of the global energy consumption in that year. The renewable energy resources used (mini-hydroelectric, wind and geothermal units) all together represented only some 3 % of the total or 100 GW $h_{equivalent}$ (or about 14 % of the full electric demand). Of the whole energy available for consumption, 80 % was used as fuel and 20 % as electricity (from which 86 % were of thermoelectric fossil origin).

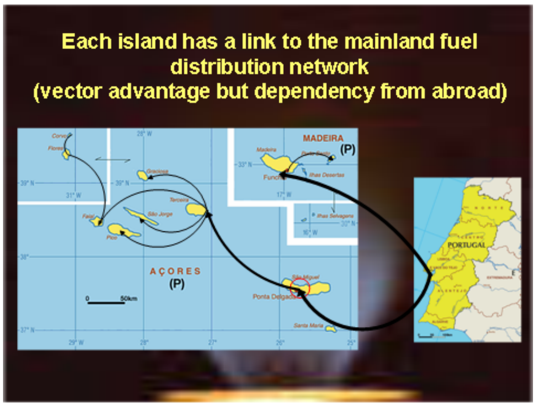

Fig. 3. Fossil fuel import dependency from Portugal mainland.

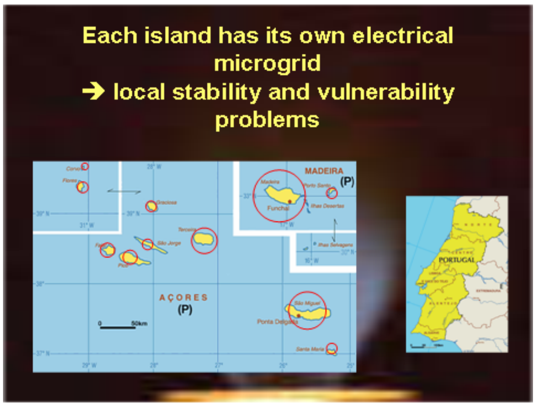

Fig. 4. Azores Islands electrical micro-grid dependency.

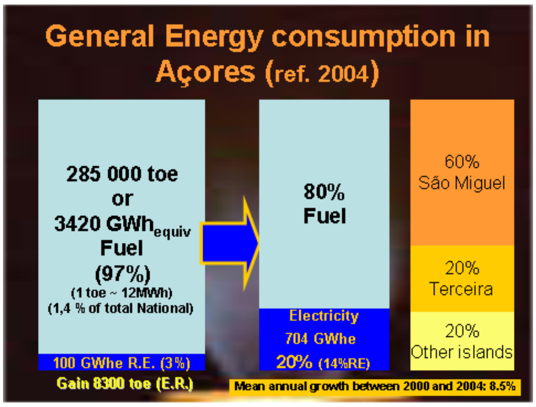

Fig. 5. Global energy consumption in Azores Region for the reference year of 2004. Some 285000toe have been imported in 2004 and just 3 % of the global energy consumed was of local renewable production (corresponding to 14 % of the overall electric sector alone).

The São Miguel island represents more than half of the whole consumption (60 % in 2004), while Terceira absorbs one fifth of the whole archipelago (20 %).

Such Figures allow us to determine that in Terceira the *per capita* consumption was, in 2004, 285000 *toe* (0.20/55833) = 1.02 *toe* (or about 12240 kW $h_{equivalent}$ per inhabitant). In São Miguel we find 1.30 *toe* per inhabitant and for the other islands some 1.05 *toe*.

AVAILABLE RENEWABLE ENERGY RESOURCES IN AZORES

In order to define a strategy for the progressive and sustained introduction of H_2RE in Terceira Island, a close knowledge of the available and accessible RE resources is required. A complete characterisation of the several RE resources was produced for the different islands.

For Terceira, the best promising RE resources appears to be, by order of abundance, wind, ocean waves, geothermal and biomass.

Concerning the wind resource, several wind vector time series were analysed for several island locations, together with a NCAR (National Centre of Atmospheric Research of USA) database of 40 years for the whole North Atlantic. A good description of the different synoptic situations flowing across the Azores archipelago was achieved. In Fig. 6 it is illustrated the mean wind speed calculated from the NCAR observations for the whole North Atlantic during, for example, the year 1994 and at 50 m height. Clearly, a good average number for the mean wind speed at the Azores area is around 10m/s.

Together with this synoptic analysis, several *in situ* wind vector time series were collected.

Here for illustration two different sites in Terceira were selected. One at "Cume" hill ("Serra do Cume") and another near the Praia da Vitoria city coast line. These were selected because they are representative of the wind at the places chosen for the installation of the hydrogen generation facilities. In Fig. 7 two frequency distributions, at 30 m height, for the wind speed (red) and wind available energy (black), at Cume hill, are represented. Case a) concerns the one year period comprised between 06-05-2003 and 06-05-2004, while case b) concerns the one year period between 06-05-2004 and 06-05-2005.

Similarly, but for the coastal area site near Praia da Vitoria, called "Ponta do Facho", in Fig. 8 the two frequency distributions, at 10 m height, for the wind speed (red) and for the wind available energy (black), are represented. The one year period comprised between 08-08-2003 and 08-08-2004, is represented.

The analysis of these time series and frequentcy distributions can be summarised in tables 1, 2 and 3.

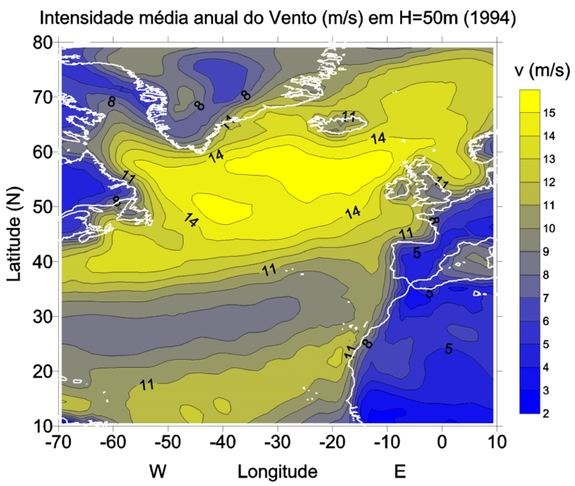

Fig. 6. Annual mean wind intensity at 50 m height for the North Atlantic an relative to 1994.

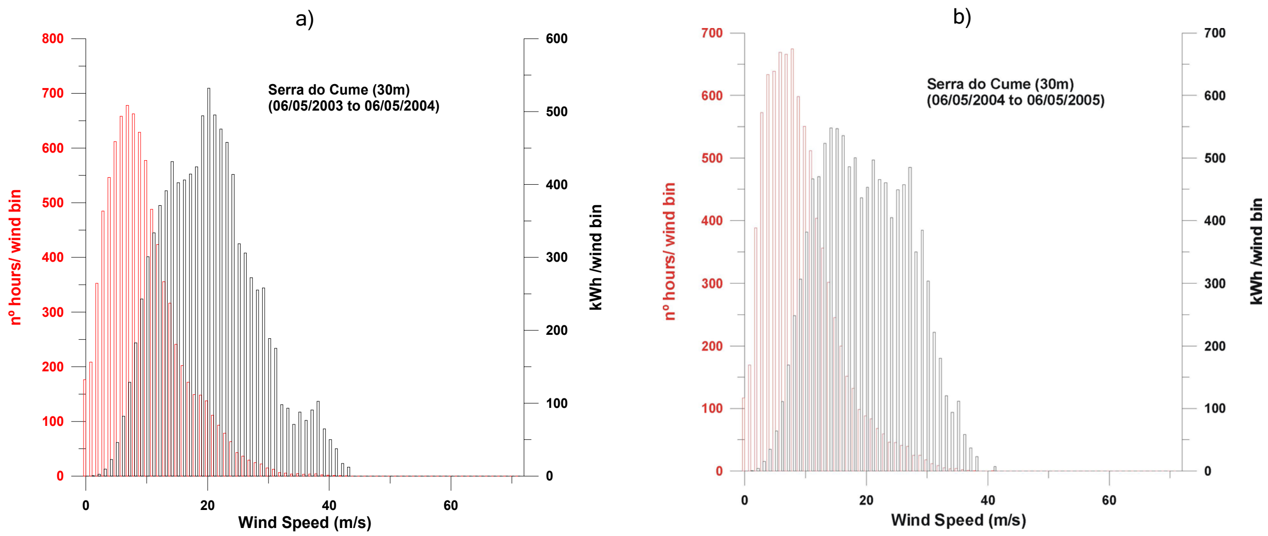

Fig. 7. Frequency distributions of the wind velocity at 30 m height per wind bin (red) and of the available wind energy per wind bin (black) at the "Cume hill" ("Serra do Cume") in Terceira Island. Case a) concerns the one year period comprised between 06-05-2003 and 06-05-2004, while case b) concerns the following one year period until 06-05-2005.

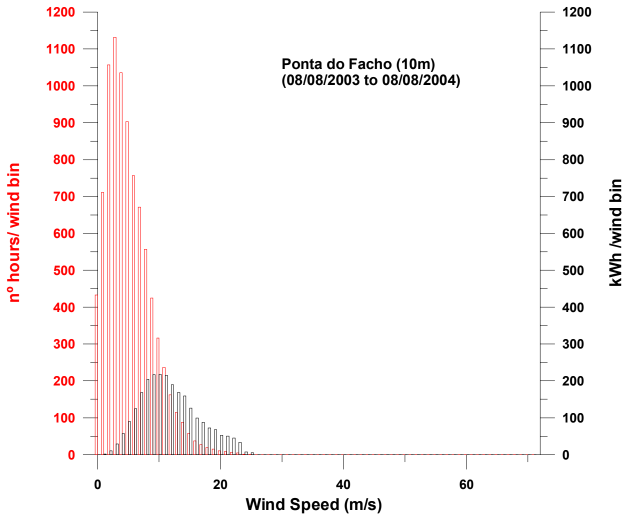

Fig. 8. Frequency distributions of the wind velocity at 10 m height per wind bin (red) and of the available wind energy per wind bin (black) at the coast, in Ponta do Facho, close to Praia da Vitoria city. The one year period comprised between 08-08-2003 and 08-08-2004 is reported.

Table 1. Summary of observed parameters for the three time series chosen for illustration

Parameter	Cume Hill		Ponta Facho
	Year 1	Year 2	Year 1
No. of hours measured	8783.7	8654.2	8783.8
No. of valid days measured	366	360.6	366
Total wind energy density available per year (kWh / m^2)	12851.3	11413.0	2497.4
Max nominal energy density accessible per year (kWh / m^2)	1844.6	1844.6	1844.6

Table 2. Summary of the energy distribution (%) per wind class and for the 3 cases chosen

Wind class	Cume Hill		Facho Hill
	Year 1	Year 2	Year 1
0-10 m/s (0-36 km/h)	7.4	8.4	36.1
10-20 m/s (36-72 km/h)	41.2	42.9	56.1
20-30 m/s (72-108 km/h)	39.3	38.6	7.7
30-40 m/s (108-144 km/h)	10.9	10.1	0
40-50 m/s (144-180 km/h)	1.2	0.06	0

Table 3. Monthly mean wind speed (m/s) for the 3 yearly time series chosen

Month	Cume Hill		Facho Hill
	Year 1	Year 2	Year 1
1 (Jan)	15.4	11.9	7.6
2 (Feb)	11.9	8.8	7.4
3 (Mar)	12.1	16.7	6.8
4 (Apr)	10.4	10.0	6.9
5 (May)	7.8	8.8	4.8
6 (Jun)	9.3	8.6	4.0
7 (Jul)	6.5	6.4	4.0
8 (Aug)	7.9	8.5	4.5
9 (Sep)	8.8	6.8	5.1
10 (Oct)	8.5	9.8	4.8
11 (Nov)	10.7	10.9	5.7
12 (Dec)	12.2	9.8	7.1
Annual (30 m)	10.1	9.8	-
Annual (10 m)	9.7	9.2	5.7

According to the data in Table 1, it is clear that there is about 5 times more available energy at Cume Hill that at Ponta do Facho. At a nominal wind speed of 10m/s and choosing a wind turbine with an overall efficiency of η = 0.35, the nominal power density for that turbine will be $p = 0.5\eta\rho_{air}v^3$ = 0.21 kW m^{-2}. So, for example (Table 1), at Cume Hill in year one, the mean available energy density was 12851.3 kW h m^{-2}, but with η = 0.35 and if the wind turbine was working all the time at its rated nominal power, then it would have been producing a maximum energy of 0.21 kW m^{-2}×8783.7 h = 1844.6 kW h m^{-2}, that is 14.4 % of the available energy in year one would have been converted.

From Table 2, at Cume Hill, we can see that most of the wind energy is comprised in the wind intervals of 10-20 m/s (41.2 % of the energy in year 1) and 20-30 m/s (39.3 % of the whole available energy in year 1), well above the chosen nominal 10 m/s. Wind turbines with higher nominal wind speeds shall be used to take advantage of the available energy.

In Table 3 it is clear that winter months at Cume Hill are very promising for future hydrogen production, with mean wind speeds at 30 m height varying between some 9 m/s (February of year 2) and 17 m/s (March of year 2). The annual mean values at 50 m height will be above 10 m/s in both cases.

Concerning the ocean waves resource, the analysis was performed in two different ways: i) using WaveWatch numerical prediction wave-action model for wave field generation using NCAR wind data and ii) using local Primitive Equation models, calibrated with *in situ* data from directional wave buoys, for wave energy estimation at particular sites in Azores. As an example of case i), Fig. 9a shows the significant wave height field generated for the North Atlantic and Fig. 9b is a zoom for the Azores area. Clearly, with this, one can predict not only the expected available energy, but also where it will be available. As an example of case ii), Fig. 10 shows an ocean wave field simulation for the Praia da Vitoria harbour zone (Fig. 10b), where some of the scheduled hydrogen facilities will be installed. This model has been used for helping decision to where the wave converter devices should be installed. Lately, this same model can be running continuously, allowing thus to evaluate all the time the available wave energy.

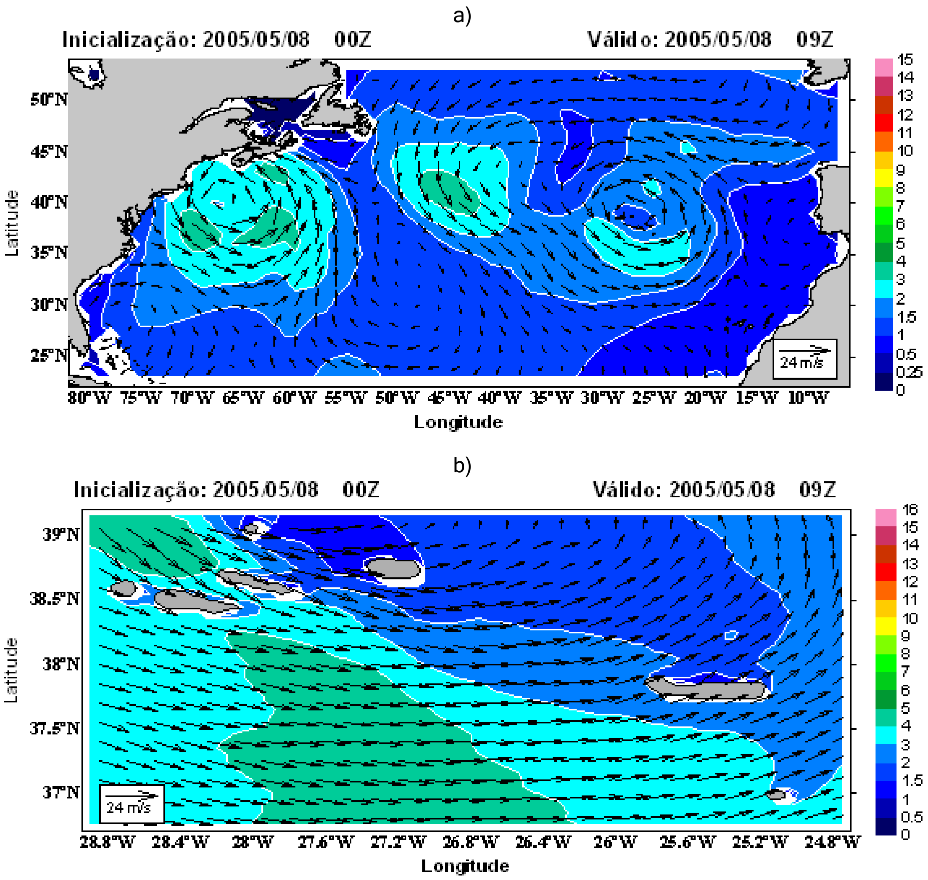

Fig. 9. Case a) shows the significant wave height, H_s, in meters, for the North Atlantic at example day 08-05-2005. Case b) shows the same field as in a), but after zooming for the Azores region, with Terceira Island around 27.2° W and 38.7° N.

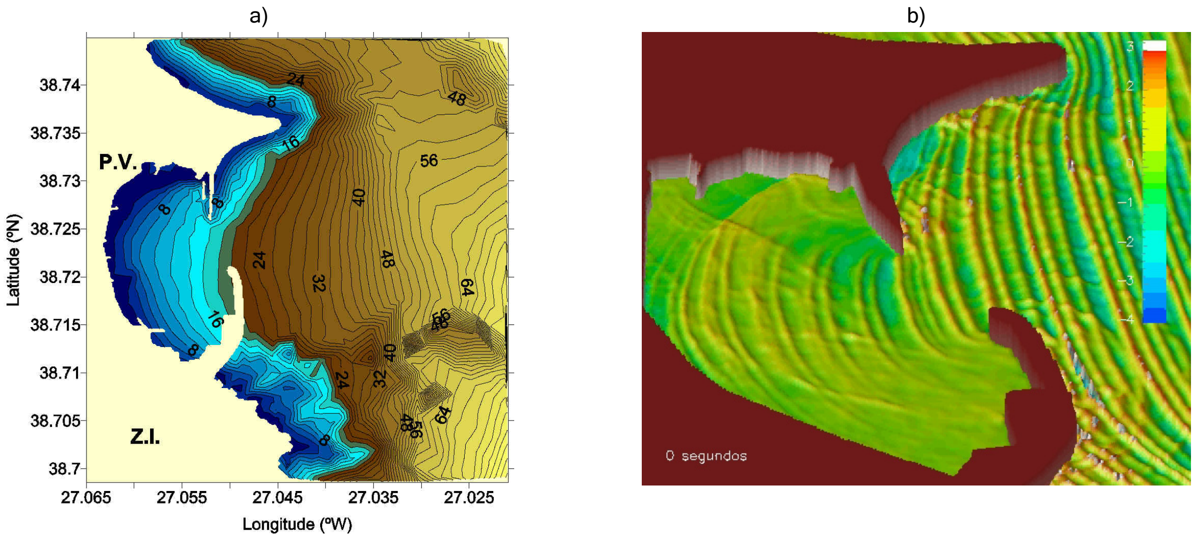

Fig. 10. Ocean wave field simulation and wave propagation for the Praia da Vitoria harbour zone (case b), together with the bottom topography (depth in meters), for the same area (case a). Depending on the outside harbour wave direction, he waves can get inside the port.

By repeating this kind of ocean wave analysis, all major details of ocean wave propagation, including the formation conditions for inside harbour resonant waves and wave converter behaviour were described.

Geothermal energy is another resource whose exploration had been shown to be viable in Terceira Island. However, EDA S.A., through its parent company GeoTerceira, is the only company in Azores that acquired the rights for exclusive exploration of geothermal energy up to the year 2050. The production of hydrogen *via* geothermal energy is thus dependent on the time schedule of GeoTerceira. Only after the installation of the first geothermal power station by GeoTerceira one can start hydrogen production in that way. Since GeoTerceira programmed to install its first 12 MWe unit after 2010, hydrogen production with this resource must wait until that time. According to the geothermal prospective wells already done in Terceira Island, there is a potential for some 20 to 30 MWe.

Biomass is another resource that is available in Terceira. Since there is an intensive local cattle industry over the island, mainly cow and swine, the quantity of dung and manure available makes biogas production economically viable. Gasification from Municipal Solid Waste (MSW) and forest waste is also an important local renewable resource where an overall potential of about 20 $MW_{equivalent}$ can be achieved.

RENEWABLE ELECTRICITY AND HYDROGEN FACILITIES SCHEDULED FOR TERCEIRA

General description. Terceira Hydrogenopolis

The renewable electricity and hydrogen facilities of Terceira will be spread through three major production Campus: i) The “Serra do Cume” hill Campus, ii) The “Industrial Park of Angra do Heroismo” Campus and iii) the “Praia da Vitoria Hydrogen Complex and Hydrogenopolis” Campus. As it is schematised in Fig. 11, the “Serra do Cume” Campus will be mainly devoted to the large scale generation of hydrogen, using wind energy as its primary renewable energy resource and to stationary storage of hydrogen and oxygen. From here, the two gases will be delivered by pipeline to the “Industrial Park of Angra do Heroísmo”, which is placed some 3 km away from the hydrogen production field. At this Industrial Park we will install and hydrogen - electrical power station that will deliver renewable electricity on demand and CoGen hot water and/or steam on demand to our MSW gasification plant that will be installed by 2010 at this same location. A biogas unit for methane generation will be installed also close to this MSW facility.

The future geothermal field and power station will be placed some 10 km away from this Industrial Park.

Part of the hydrogen stored at the “Serra do Cume” campus will also be consumed at the Praia da Vitoria site. In this case, since the distance is about 12 km, the hydrogen will be transported by proper road container in a first stage and by pipeline later on. At the Praia da Vitoria Hydrogenopolis Campus, there will be also a hydrogen and oxygen generation unit (through wind and ocean wave resources) with local stationary storage. This Hydrogenopolis will include several demo/research subunits: i) a hydrogen – electric power station, ii) a Hydrogen vehicle filling station, with an associated maintenance and research laboratory, iii) a Technological demo park, PTEC, with several hydrogen consumption devices, devoted to public awareness and promotion, iv) a R&D laboratory devoted to support all the required research and testing for the whole project campus (including graduate and post-graduate courses in direct connection with the Azores University), v) an ensemble of demo domestic like buildings, fed by a local hydrogen and methane network (these buildings will be used mainly to lodge visitors of the campus and technical personnel and students), vi) the hydrogen - electric power station will also deliver electricity to the local harbour industries, while the CoGen warm water will be used either in these industries and, or, vii) at Tourist facilities (salt water ocean swimming pools) for pleasure and visitor awareness.

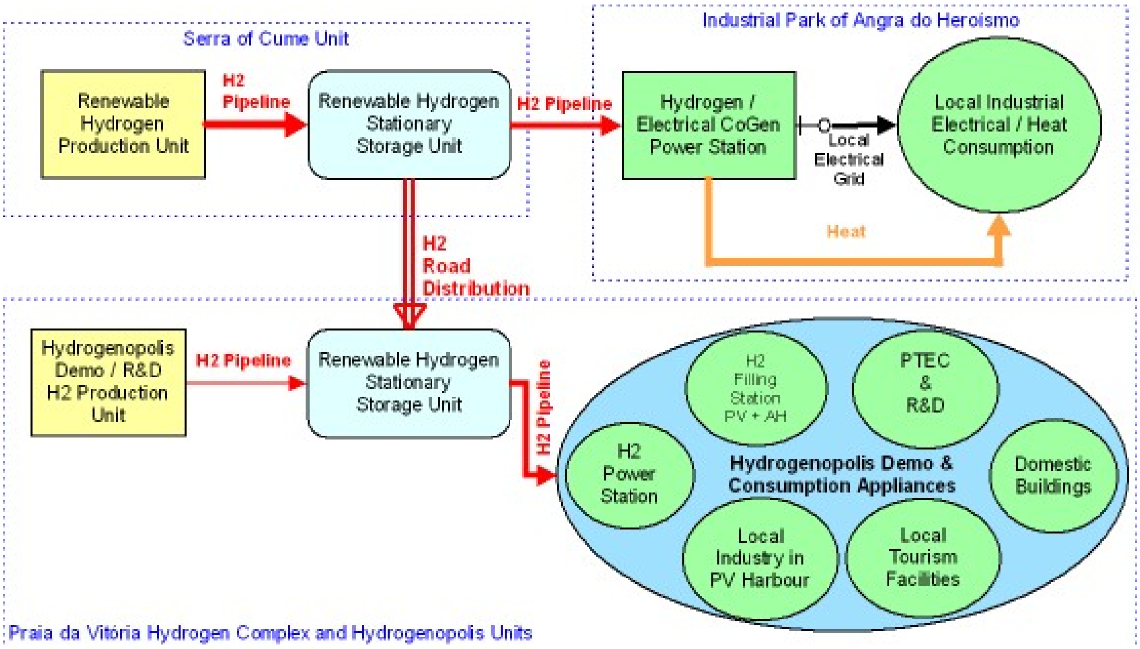

Fig. 11. Global Flow Diagram of the Renewable Hydrogen and Electricity at Terceira Hydrogenopolis site facilities.

Hydrogen production centres

As mentioned above, there will be mainly two hydrogen production centres: one at Cume Hill, for a larger scale production and another at Praia da Vitoria Campus mainly for local use, demonstration purposes and research.

At Cume Hill the hydrogen and oxygen will be produced through water electrolysis of locally collected rain water (Fig. 12). Such water will be de-ionised previously for electrolysis use. Wind turbines will be installed for electricity generation for electrolyser servicing and control operation. Hydrogen and oxygen will be compressed and stored in local stationary containers. At start up, the electricity required for proper compressor work will be delivered from locally installed biodiesel electrical generators. Later on, it can be delivered either by our hydrogen-electrical power station, to be installed at the Industrial Park of Angra do Heroismo, or by our biodiesel generators in case of any emergency. In this way, our hydrogen-oxygen generation and storage campus will be completely autonomous from the local electrical grid owned by EDA, whose electricity is generated via non-renewable fuel oil.

The expected average production at Cume Hill will be 2000 Nm^3 H_2/h and half of that in oxygen.

At the Praia da Vitoria Hydrogenopolis production campus the strategy of hydrogen and oxygen generation and storage will be the same, except that quantities will be smaller than at Serra do Cume Hill and the renewable energy source will be more diversified, since not only the wind resource will be used, but also the ocean waves will be employed. In Fig. 13 one can see that the ocean wave production strategy is similar to the wind one. In this coastal campus, desalinated sea water will also be used (together with the rain collected one).

The minimum expected production at Praia da Vitoria Hydrogenopolis will be 400 Nm^3 H_2/h and half of that in oxygen.

The wind and ocean wave hydrogen-oxygen generation and storage strategy have also in common the fact that they will operate completely independent from the existing electrical grid or from fossil fuels. Both the wind and ocean wave generators (in both production campus) will be completely devoted to the solely task of hydrogen-oxygen generation.

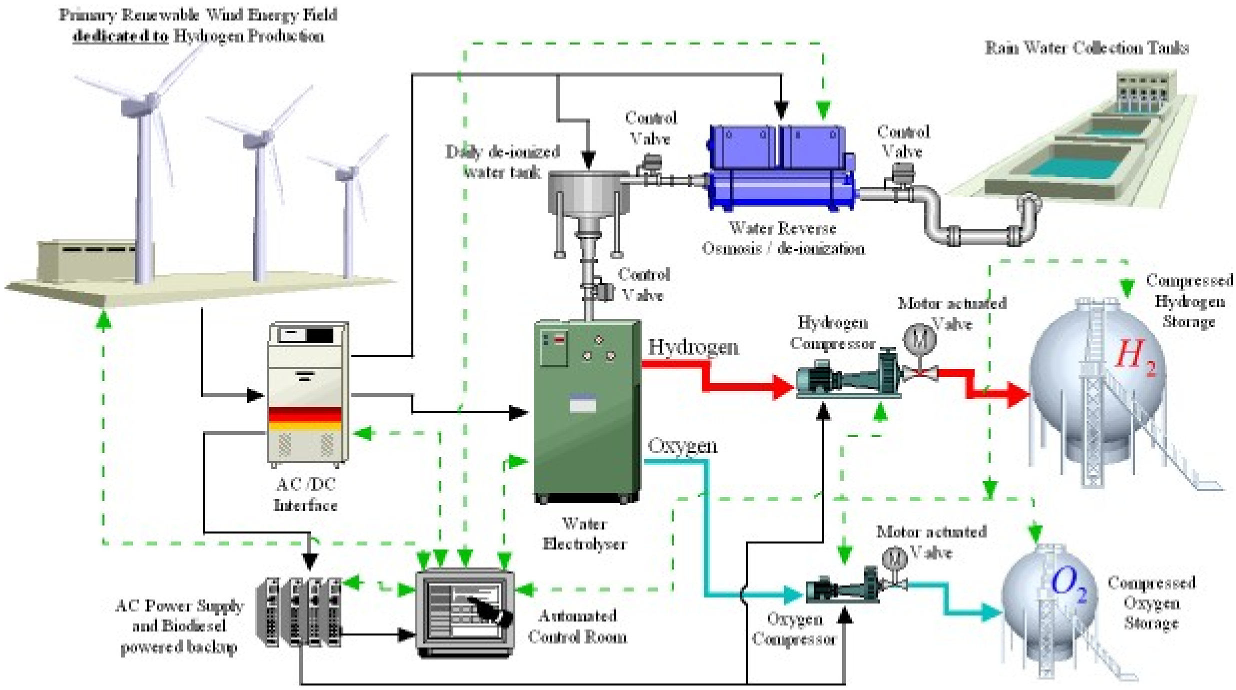

Fig. 12. Global Flow Diagram for hydrogen production from wind energy. Components Design for the Terceira Hydrogenopolis.

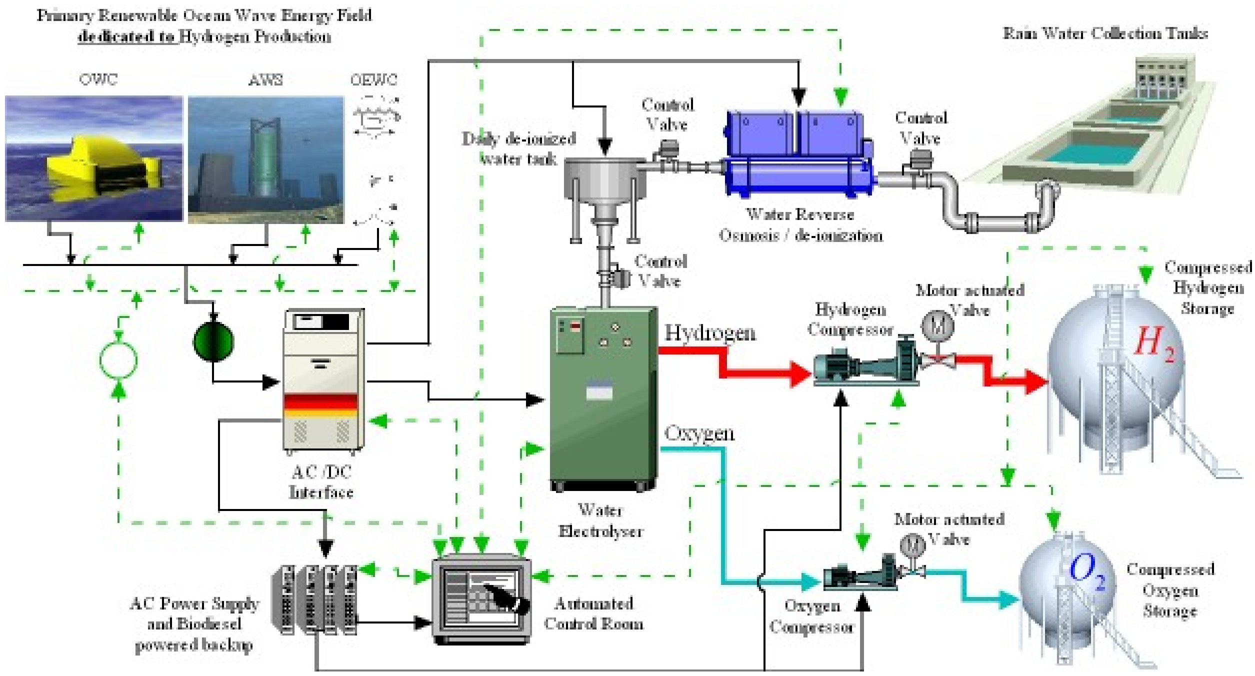

Fig. 13. Global Flow Diagram for hydrogen production from ocean wave energy. Components Design for the Terceira Hydrogenopolis.

With an expected mean hourly production of 2000 Nm^3H_2/h at "Serra do Cume" campus, the mean daily energy accumulated in hydrogen will be 2000 $Nm^3H_2/h \times 3$ kW h/Nm^3 $H_2 \times 24$ h = 144000 kW h. Considering a production rate of 1 Nm^3H_2 and 0.5 Nm^3O_2 per 5 kW he, than the mean daily RE (from wind) required will be: 2000 $Nm^3H_2/h \times 5$kW h/$Nm^3H_2 \times 24$ h = = 240000 kW h. If wind power is converted to electricity with a conventional load factor of 0.4, than the installed mean nominal wind power shall be 240000 kW h/(0.4×24 h) = 25.0 MW.

A similar calculation for the Praia da Vitoria Hydrogenopolis hydrogen production campus will give an accumulated mean daily energy in hydrogen of 400 $Nm^3H_2/h \times 3$ kW h/$Nm^3H_2 \times 24$ h = 28800 kW h, will require a mean daily RE production (from wind + ocean waves) of 400 Nm^3H_2/h×5 kW h/Nm^3H_2×24 h = 48 MWh, and an installed mean nominal wind + wave power of 48000 kWh/(0.4×24h) = 5.0 MW.

In what concerns hydrogen and oxygen storage, a minimum of 7 full consumption days must be ensured at stationary storage. At "Serra do Cume" a capacity for 2000 Nm^3H_2/h×24 h×7 days = 336000 Nm^3H_2 ⇔ 336000 Nm^3H_2×0.0899 kg m^{-3} H_2 = 30.206 t H_2 must be installed. If hydrogen is stored at 350 bar and its temperature is kept identical to the surrounding environment, then a volume of about 336000 Nm^3H_2×1.236/350 bar = 1187 m^3 at 350 bar is needed (with 1.236 the hydrogen compression factor at the chosen storage pressure).

Similarly, for the Praia da Vitoria Hydrogenopolis storage we get 400 Nm^3H_2/h×24h×7 days = = 67200 Nm^3H_2 ⇔ 67200 Nm^3H_2×0.0899 kg m^{-3} H_2 = = 6.04 t H_2 for the storage capacity and a volume of 67200 Nm^3H_2×1.236/350 bar = 237 m^3 at 350 bar.

Hydrogen/electricity power stations

Most of the hydrogen and oxygen generated and stored at the "Serra do Cume" campus will be delivered to an electrical power station that will be built inside the Industrial Park of Angra do Heroismo. This power station will deliver H_2RE electricity and CoGen hot water and, or, steam to the MSW processing plant and to some other local industries. No uses of the local electrical grid will be made, in order to make sure that a 100 % clean energy will be delivered. Fig. 14 shows a draft plan of such strategy.

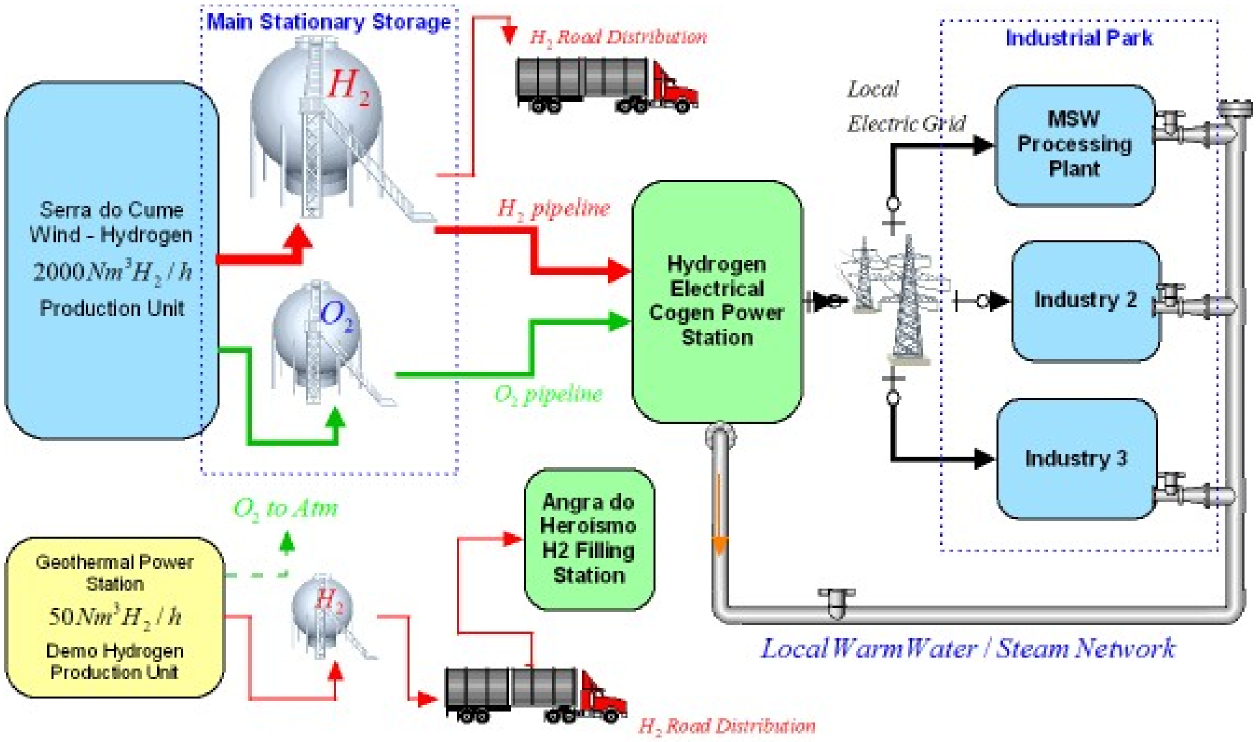

Fig. 14. Global Flow Diagram for Serra do Cume and Local Industrial Appliances using Renewable Hydrogen and Electricity at Angra do Heroismo Industrial Park.

The electricity and water distribution to the local consortium industries will be achieved through specifically built and dedicated lines.

At least, half of the hydrogen/oxygen production at "Serra do Cume" campus will be used at the Industrial Park power station. Most of the electricity will be produced via a Hydrogen-Oxygen Boiler and steam turbine CoGen system. The basic system is depicted at Fig. 15. A Rankine Reheat-Regenerative Cycle will be used. The heat source is from hydrogen-oxygen boiler. CoGen process steam and condenser coolant water will be used to access the non-electrical converted system heat.

The Hydrogen and oxygen will be delivered from the "Serra do Cume" campus *via* a pipeline link to the local buffer storage close to the power station. This pipeline link shall accomplish with normal rules for this kind of infrastructures, namely in seismic zones as it is the Azorean case (see G. Birgisson Esq. and W. Lavarco Esq., 2004 for some related aspects).

Produced electricity will be delivered to the final user industries *via* a local owned electrical grid. Similarly, a hot water and, or, steam owned pipeline system will be used to deliver it to the associated industries.

A global hydrogen-electrical efficiency conversion rate of 40 % is expected at this steam turbine power station. A global 50 % efficiency of CoGen heat recovery is expected, contributing to an overall system efficiency of 90 % (electrical + thermal).

Together with the Rankine Reheat-Regenerative Cycle other smaller scale approaches for electricity production *via* hydrogen consumption will be employed. In Fig 16 it is shown a set of Hydrogen Internal Combustion Engines. These ICEs are prepared to generate electricity with an efficiency of about 35 % and produce CoGen warm water with an efficiency of about 45 %.

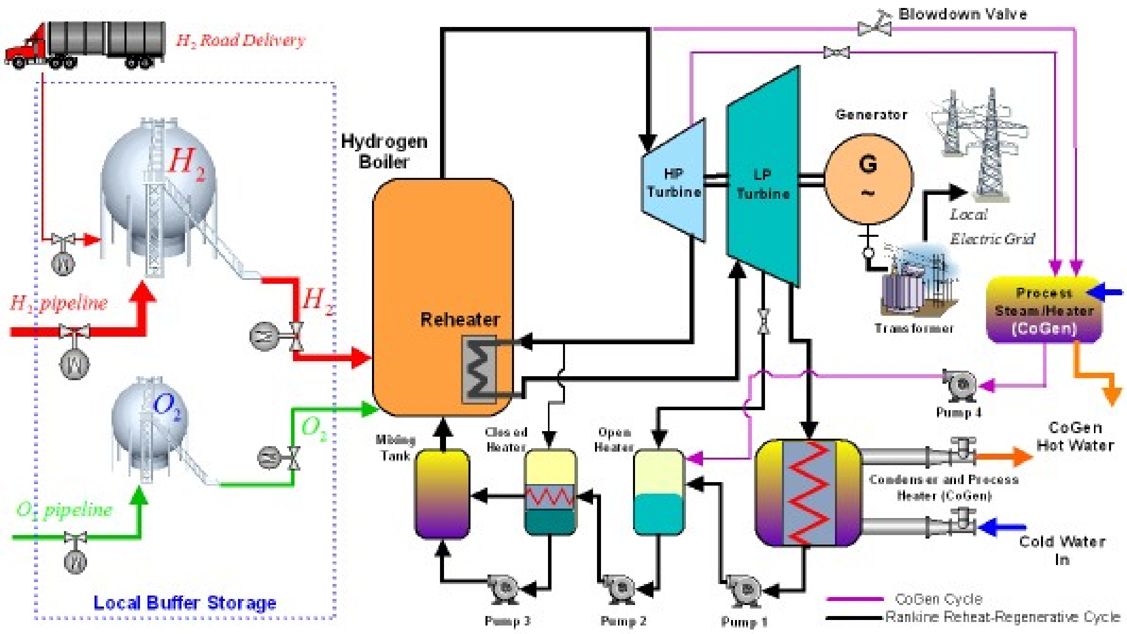

Fig. 15. Global Flow Diagram for the Hydrogen Electrical Steam-Turbine-CoGen Power Station running on Renewable Hydrogen at Terceira Hydrogenopolis.

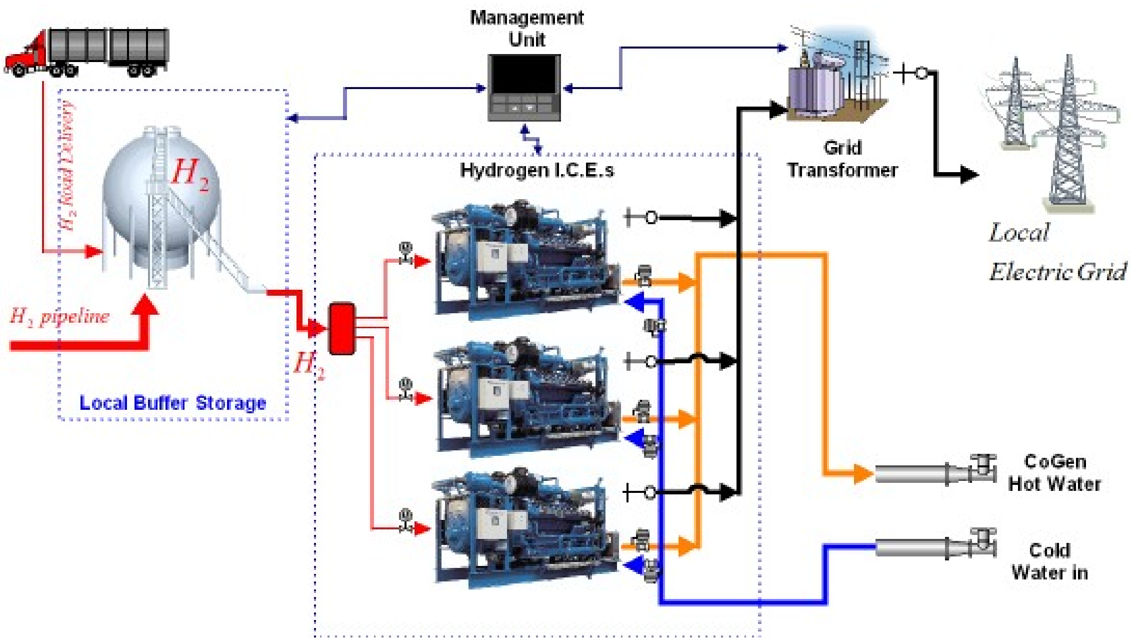

Fig. 16. Global Flow Diagram for the Hydrogen Electrical ICE-CoGen Power Station, running on Renewable Hydrogen at Terceira Hydrogenopolis.

Another approach will be also implemented, as shown in Fig. 17. A set of Hydrogen Fuel Cells will be used with expected mean hydrogen to electrical efficiency of about 60 %. Some 30 % of CoGen low enthalpy warm water will be also available for other uses.

At the Industrial Park of Angra do Heroismo, the envisaged electrical power to be installed is 1.5 MWe for the Rankine Reheat-Regenerative Cycle, 300 kWe for the ICE systems and 100 kWe for the Fuel Cell system, with a total electric installed power of 1.9 MWe. This will correspond to about 80 % usage of the hydrogen generated at the "Serra do Cume" campus. The remaining 20 % will be available for road truck delivery to the Praia da Vitoria Hydrogenopolis campus. In fact, with the mean daily production rate of 48000 Nm^3H_2/day at "Serra do Cume", 144000 kW h/day will be available. If this power is continuously consumed (24 h/day), than 144000 kW h day^{-1}/24 h = 6.0 MW will be available. With a mean hydrogen to electrical efficiency of 40 % and 50 % of thermal efficiency, we can get 6.0 MW×0.4 = = 2.4 MWe and 6.0 MW×0.5 = 3.0 MWt. An overall hydrogen to useful power efficiency of 100(2.4 MWe + + 3.0 MWt)/6.0 $MW_{equivalent}$ = 90 % can be achieved. A nominal (conventional) overall efficiency from wind to useful power of 100(2.4 MWe + 3.0 MWt)/25.0 $MW_{equivalent}$ = 21.6 % will result.

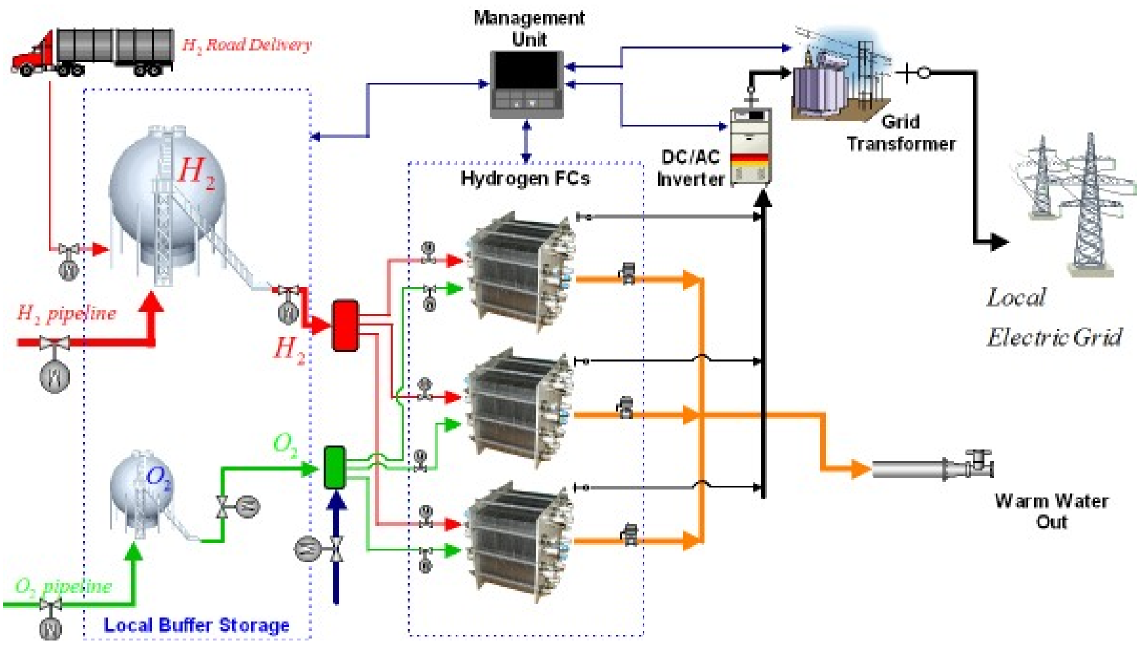

Fig. 17. Global Flow Diagram for the Hydrogen Electrical Fuel Cell Power Station, running on Renewable Hydrogen at Terceira Hydrogenopolis.

Praia da Vitoria Hydrogenopolis Demonstrators

General description

Praia da Vitoria Hydrogenopolis will comprise several demo/research units that are schematised in Fig. 18.

It will include:

i) a hydrogen generation unit, dimensioned for a minimum of 400 Nm^3H_2/h, with local stationary storage facility for up to 7 full generation days and an external reception unit for the road transported hydrogen,

ii) a hydrogen vehicle filling station, with an associated maintenance and research laboratory,

iii) a technological demonstration park (PTEC) with several hydrogen consumption devices, devoted to public awareness and promotion,

iv) a R&D laboratory devoted to support all the required research and testing for the whole project campus (this unit will be closely articulated with the graduate and post-graduate courses at the Azores University, that will have its own facilities included in the Hydrogenopolis),

v) an ensemble of domestic like buildings demonstrators, fed by a local hydrogen and methane network (these buildings will be used mainly to lodge visitors of the campus and technical personnel and students),

vi) an hydrogen-electric power station that will deliver electricity to the Hydrogenopolis and to the local harbour industries and CoGen warm water that will be used either in these industries and, or, at tourist facilities and

vii) a tourist facility using the hydrogen CoGen water to heat ocean (salt water) swimming pools for pleasure and visitor awareness.

A local electrical grid and warm water network will be built for distribution inside the Hydrogenopolis and to the associated industrial partners.

The hydrogen generation unit at the Hydrogenopolis will be dimensioned to produce a minimum of 400 Nm^3H_2/h, together with the local stationary storage facility for up to 7 full generation days. Such configuration is similar to the one shown in Fig. 12, for the wind primary energy case and in Fig. 13, for the ocean wave case.

These different units will have access to the hydrogen produced both at “Serra do Cume” campus and at the Praia da Vitoria Hydrogenopolis. About 80 % of the total produced in “Serra do Cume” will be used at the Angra do Heroismo Industrial Park, while the remaining 20 % will be transported to Praia da Vitoria Hydrogenopolis (see Table 4).

The amount of hydrogen accessed by each unit defined in Fig. 18 is different, according with the expected consumption. Table 5 resumes the amounts that will be available to each one of it. Note that 62 % out of 19200 Nm^3H_2/day (11904 Nm^3H_2/day, or 1070.2 kg H_2/day) will be used at the Hydrogenopolis Power Station. With an electrical efficiency of 35 %, some 12500 kW h_e will be delivered daily, while some 19640 kW h_t will be available as hot water, with thermal efficiency up to 55 %. Around 13 % of the 19200 Nm^3H_2/day will be available for hythane generation. For the Filling Station a total of 12 % (or 2304 Nm^3H_2/day) plus a local generation of about 556 Nm^3H_2/day will be available for vehicle refuelling. Also note that it is expected that the Touristic Facilities and the participating Local Harbour Industry will consume electricity and CoGen hot water from the Hydrogen Power Station, instead of using hydrogen directly.

Concerning the hydrogen power station it will be similar to the one at “Serra do Cume” campus, but with a smaller generation capacity. It will include the same three major methods of electrical generation: Hydrogen Steam Turbine, ICE and Fuel Cells. This power station will also be used intensively for demo and research purposes. For example, it will also include a Biogas generation unit with methane purification to explore ways of using hydrogen and methane blends. This research is intended to evaluate opportunities and optimise strategies for a joint use of Hydrogen and Natural Gas (a blend mixing usually known as hythane).

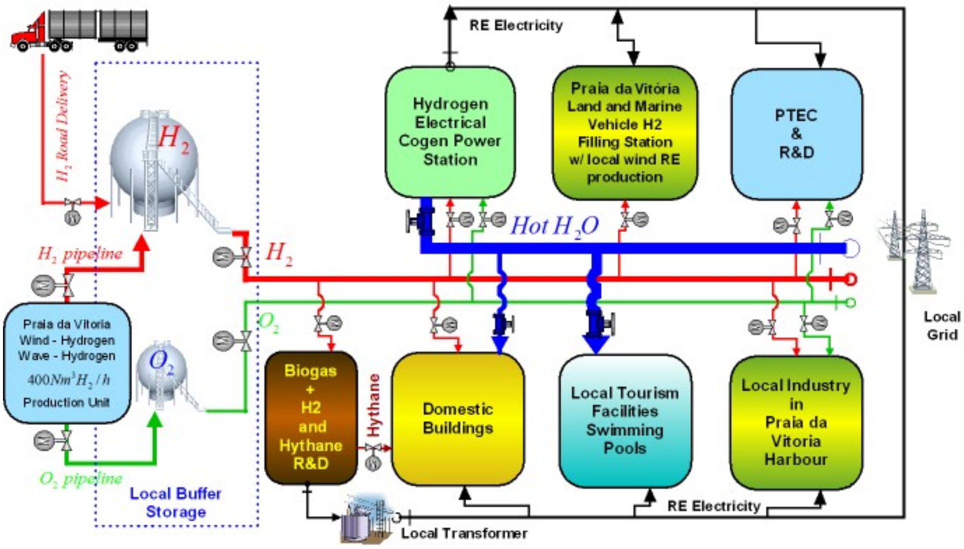

Fig. 18. Praia da Vitoria Hydrogenopolis and its demo / research units.

Table 4. Hydrogen production at “Serra do Cume” and at Praia da Vitoria Hydrogenopolis

Serra do Cume Campus production:	2000	Nm^3H_2/h local production
	1600	Nm^3H_2/h Consumption at the Industrial Park of Angra do Heroismo
	400	Nm^3H_2/h Transported for consumption at Praia da Vitoria Hydrogenopolis
Hydrogenopolis hydrogen availability:	400	Nm^3H_2/h local production
	400	Nm^3H_2/h Transported from Serra do Cume
Total:	800	Nm^3H_2/h available at Praia da Vitoria Hydrogenopolis
	19200	Nm^3H_2/day = 1726,08 kg H_2/day at Praia da Vitoria Hydrogenopolis

Table 5. Hydrogen, electricity and hot water share of the different units at Praia da Vitoria Hydrogenopolis

Praia da Vitoria Hydrogenopolis uses	H_2 %	Nm^3 H_2/day	kg H_2/day	Electric share %	Thermal share %	Energy kW h_e/day	Energy kW h_t/day
Hydrogenopolis Power Station	62	11904	1070.2	Efficiency 35 %	Efficiency 55 %	12499.2	19641.6
Mixing with biogas methane (hythane)	13	2496	224.4	2	0	250.0	0.0
Hydrogen Filling Station	12	2304+ +(556 local gen)	207.1+ +(50 local gen)	3	0	375.0	0.0
Residential Uses	10	1920	172.6	3	5	375.0	982.1
Touristic Facilities	0	0	0	7	85	874.9	16695.4
Local Harbour Industry	0	0	0	65	8	8124.5	1571.3
Research & maintenance	2	384	34.5	15	1	1874.9	196.4
Technological Park - PTEC	1	192	17.3	5	1	625.0	196.4

Biogas and hythane generation unit

The main Biogas generation unit will be installed at the Angra do Heroismo Industrial campus.

In Fig. 19 it is presented a design layout for this unit. The feeding material for the Biogas generator will be composed mainly of pig and cow manure (about 70 % all together), chicken dung (20 %) and other organic matter (10 %).

Biogas production is achieved by methanogenic bacteria. This is an anaerobic process that will take place at the Biogas Digester (see Fig. 19), whose capacity, in our case, will be 1500 m^3. Feeding material (up to 50 m^3/day) is received at a reception tank and flows into a pre-treatment tank where non-organic material is removed and sent to a disposal unit. A mixing tank will then homogenise organic matter and a heating unit, fed by CoGen water, will warm it up to 37 °C. The resulting material is then introduced in the Anaerobic Biogas Digester, which has a mean digestion retention time of 20 days. After gas treatment, the total methane generated will be about 2500 Nm^3/day. An availability of 8500 h/year is expected. A daily digester effluent of around 44 m^3/day will be sent to the local waste treatment unit.

The resulting methane will then be used for blending with hydrogen (hythane generation) in order to experiment and optimise its usage in different applications. Depending on the relative volume percentage of both gases composing hythane, the maximum available daily energy, from this unit, will remain between 2500 $Nm^3H_2\times3$ kW h/Nm^3 = 7500 kW h/day (pure hydrogen, see Table 5) and 2500 $Nm^3CH_4\times$ $\times10.6$ kW h/Nm^3 = 26500 kW h/day (pure methane).

A major application will be hythane combustion for electrical power and heat generation. For that, both an ICE and a gas turbine will be used. However, several other usages will be made, in particular, for residential consumption.

The Biogas unit will have, in average, a daily auto-consumption of about 50 kW×24 h = 1200 kW h (some 5 % of the total it can generate).

Maximum H_2S content per Nm^3 of biogas is 50 to 100 ml and will be removed from the main gas stream. So, local atmospheric emissions will not be a concern.

Hydrogen vehicles and filling station

Another major unit of Praia da Vitoria Hydrogenopolis is the hydrogen vehicle filling station. This unit is intended for hydrogen refuelling of a few vehicle types. The chosen vehicles will be subjected to performance analysis and comparison with other fuel type vehicles. For this, a maintenance and experimentation laboratory will be installed together with this unit.

Also, a demonstration and persistent marketing action will be undertaken through this unit, in close conjunction with the Technological Park (PTEC) activities.

Both land (cars, bus, scooters) and marine vessel examples will be undertaken.

The hydrogen for refuelling will be both generated locally (from water electrolysis using wind energy and up to 50 kg H_2/day) and, or, transported by road truck and, or, pipeline.

The hydrogen vehicle filling station will also have full access to the electrical grid, in order to ensure proper compressor work, to support filling hoses functioning and to deliver power to the vehicle maintenance laboratory. Such electrical grid will be fed by the Hydrogenopolis electrical power station.

An emergency backup power unit working on biodiesel will also be present.

In Fig. 20 it is shown the general design for the Hydrogen vehicle filling station.

According with Table 5, some 257 kg H_2/day, will be available to the hydrogen filling station (from which 50 kg H_2/day will be locally generated).

With this total of 257 kg H_2 /day, and assuming that each car will consume some 3 kg H_2 /day, that the bus will need some 40 kg H_2/day, one scooter will need 1 kg H_2/day and one marine vessel will require about 70 kg H_2/day, then we will be able of a daily refuelling of, for example, two Buses, one vessel, 30 cars and 17 scooters.

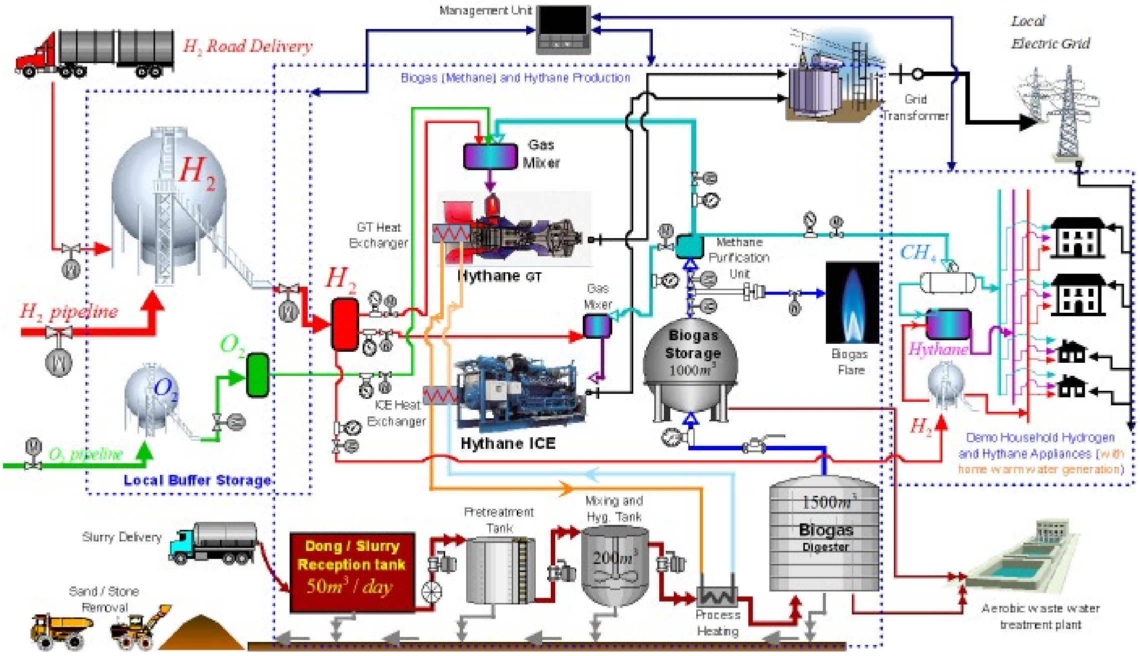

Fig. 19. Biogas production unit and hydrogen- methane blending for research and demonstration applications.

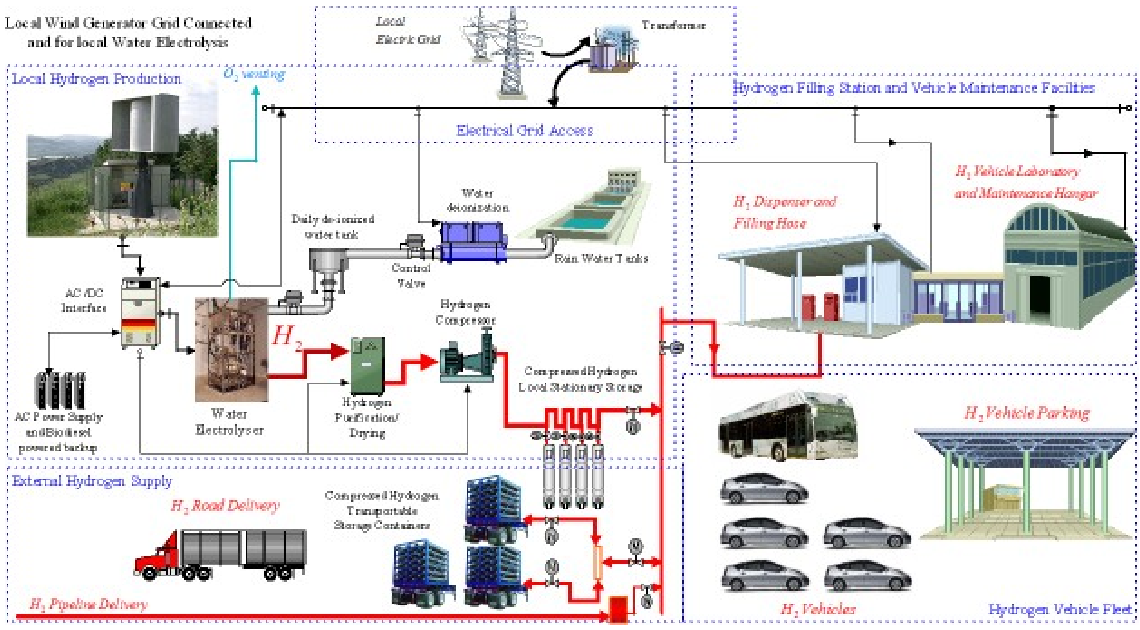

Fig. 20. Hydrogen vehicle filling station layout.

Residential uses of hydrogen

Another very important usage of hydrogen will be shown for residential consumption.

A similar philosophy and strategy to that of Natural Gas distribution network will be locally implemented at the Praia da Vitoria Hydrogenopolis. A few residential homes will be prepared for hydrogen gas and hydrogen generated electricity (from the local power station) consumption.

Four of these homes will be located inside the Hydrogenopolis field for demonstration and applied research purposes. Each of these homes will also have independent networks for hythane and methane. A relative performance operation can be achieved between the different gas choices. A few other homes can also be connected later on to the hydrogen network.

A strategy approach similar to the one already in used for propane, that is, closed condominiums, with a local propane storage close to the consumption point, will also be trialled.

The different gases for these experimenttal/demo houses will be delivered via pipeline or road truck. The local house distribution network will be tested and optimised for different material types and specifications, gas fluxes and pressures.

In each house several gas consumption equipments will be used. Some indoor examples are: i) a Space Heater, ii) a Stove/Oven, iii) a Water Heater, iv) an emergency electricity backup system using Fuel Cells and, or, a grid connected Power Supply Unit, or v) a Barbeque, as an outdoor example.

Similar to the Natural Gas or the propane strategies, the hydrogen gas consumption will be measured *via* a Hydrogen Gas Meter device placed at each home entrance.

In Fig. 21 it is shown the general design for the Hydrogen-Hythane-Methane Residential Distribution Network.

According to Table 5, some 173 kg H_2/day will be available for hydrogen residential uses, plus 2500 Nm^3CH_4/day of methane and some more 225 kg H_2/day for hythane generation.

Also, some 375 kW h_e of renewable hydrogen electricity and about 980 kW h_t as CoGen hot water will be available for domestic like uses.

Hydrogen Touristic Facilities

In Fig. 22 it is shown the general design for the hot water production and delivery from hydrogen Power Station Co-Generation system.

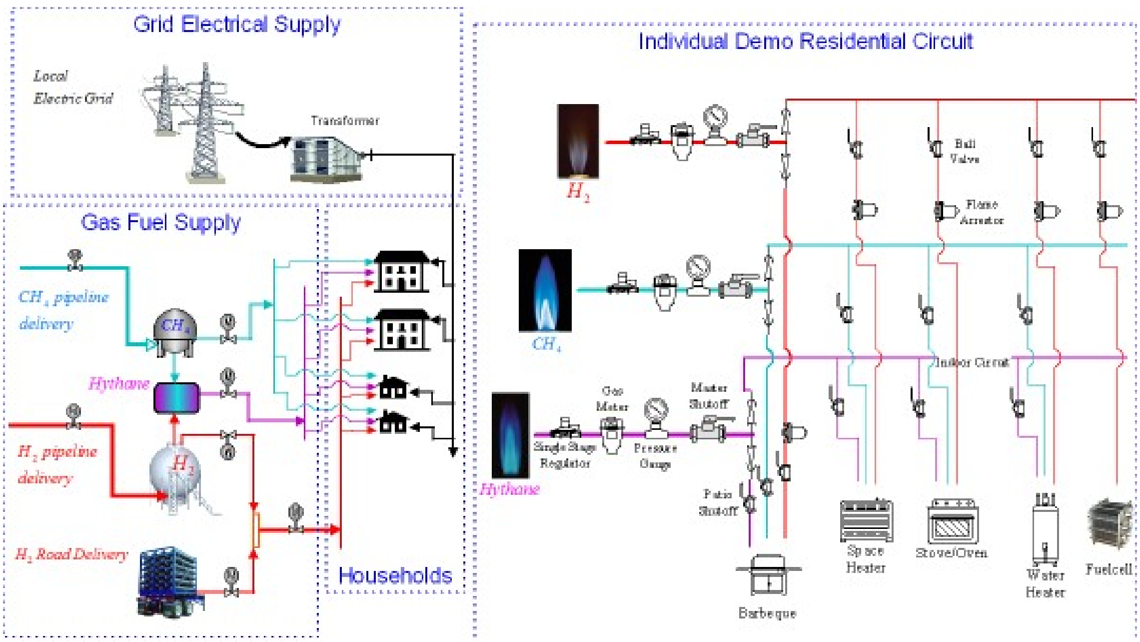

Fig. 21. Hydrogen-Hythane-Methane Residential Distribution Network design for experimentation and demonstration.

These facilities will be mainly composed of public swimming pools using sea water heated by CoGen at the Hydrogenopolis Power Station.

According to Table 5, these Touristic Facilities will consume about 875 kW h_e as renewable hydrogen electricity and 16700 kW h_t as CoGen hot water.

A first crude calculation can be made using a salt water specific heat value of C_p(35USP, 0 °C, 1 bar) = 3987 J/(kg K). In this case, we note that with 1 kW h_t it is possible to heat up, for example, 10 °C a mass of 90.3 kg of sea water, from 0 to 10 °C. With the daily access to 16700 kW h_t it is possible to heat up a volume of 1500 m^3 of sea water some 10 °C above the local sea surface temperature with no significant thermal loses. Assuming a daily 20 % heat loss to the atmosphere, a 100 m×50 m×2 m = 10000 m^3 equivalent swimming pool will take 10000/(1500×0.8) = = 8.3 days to heat up its full volume and will require a daily thermal energy input of some 16700×0.2 = = 3340 kW h_t to keep its heat content constant for a full recycling water batch. However, if a cascade of swimming pools is used to cool the warm water down to the surrounding sea temperature, then the full thermal energy available may be used. Assuming that 1500 m^3 of heated sea water is entering 24h/day into the swimming pools, whose mean level is 4 m higher than the mean sea level, a total elevation pump power (with 70 % electrical to mechanical efficiency) of 1500000 kg×9.8 m s^{-2}×4 m/(86400 s×0.7) = = 0.972 kW_e will be required (with a water flow of 17.4 kg/s). If the thermal energy is only available 12 h/day, than a pump of about 2 kW_e is needed (water flow of 34.8 kg/s). Still some 850 kW_e will remain free for other tourist uses and sea water desalination.

The research facilities will operate using the renewable electricity and CoGen Hot Water delivered by the Praia da Vitoria Hydrogenopolis Power Station, while the hydrogen, oxygen and methane gases will be delivered by the Hydrogenopolis, Angra do Heroismo Industrial park and "Serra do Cume" generation units.

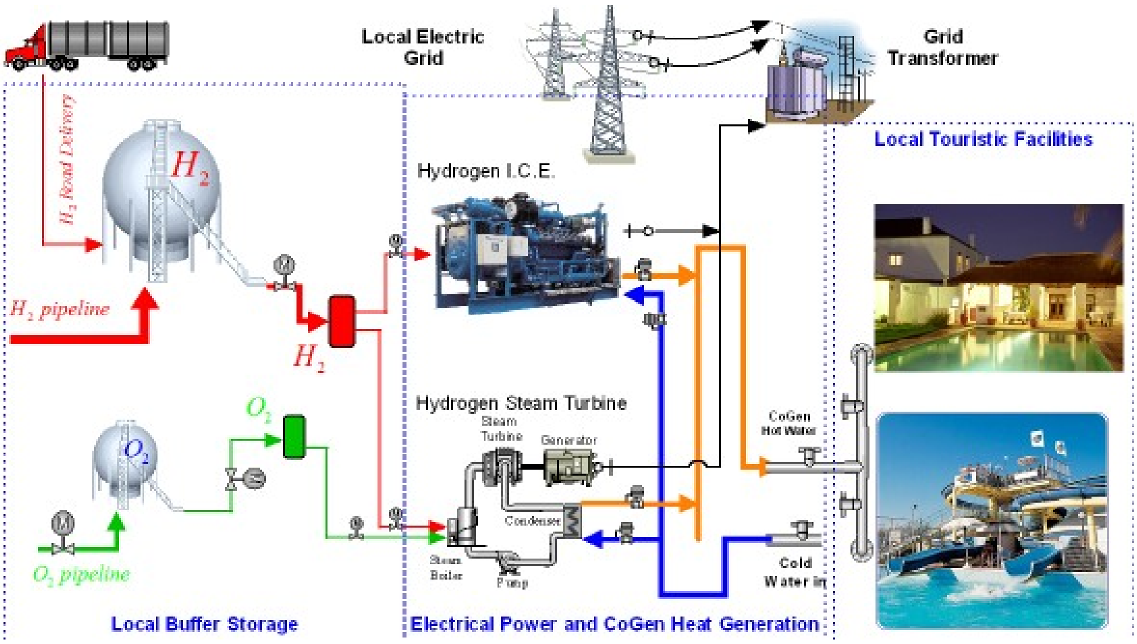

Fig. 22. Hydrogen heated swimming pools and tourist facilities. Oceanic swimming pools will be directly heated using CoGen hot water from the Praia da Vitoria Hydrogenopolis Power Station.

Hydrogen Research Centre

The Hydrogen Research Centre will be mainly an applied research centre devoted both to the development of new solutions and concepts and to the technical support of all campus installed units.

The general research target will be the implementation of safe and reliable solutions for the whole hydrogen economy line.

Hydrogen Information and Technological Park Centre - PTEC

Another important unit of the Praia da Vitoria Hydrogenopolis will be the Hydrogen Information and Technological Park Centre - PTEC.

This unit will coordinate the interface between the several hydrogen demonstrators installed at the Hydrogenopolis and the public awareness and demonstration. Any public visit to any of these demo units will be organised by PTEC. This unit will also promote an intensive marketing of the whole hydrogen universe of solutions in order to attract an increasing number of potential future users.

The safety aspects will be a constant concern. Hydrogen as any other fuel must be handled adequately in order to avoid any accident. This is true all the time and for all units, no matter if there is or not public access to it. However, one must be aware that any accident at this early stage of hydrogen introduction can affect negatively the public perception for its consumption and, thus, have a negative impact on its marketing. Now, as in the future, a strict obligation to respect rules and norms must be a mater of permanent concern.

General implementation time schedule

Some of the above mentioned facilities are already under construction. This is the case of the hydrogen production unit at "Serra do Cume" campus, of the Methane & Hythane generation unit and of the R&D and PTEC units (Table 6). Each consumption unit will be installed during the last implementation phase, after hydrogen availability from the production units. R&D and PTEC activities will also support local University of Azores graduation and post-graduation activities.

With an interest rate of 8 % and a breakeven period of 10 years a production cost of 1.00 €/kg H_2 can be achieved. Present costs will be compared with those considered by Padró C.E.G. and Putsche V. (1999) and J. Beurskens and P. H. Jensen (2001) reports, in order to benchmark the selected solutions.

The whole project implementation will be supported by SGC Energia SA company.

Table 6. Global time schedule for the implementation of the Renewable Energy/Hydrogen units at Terceira Island

Subject	2008				2009				2010			
Engineering project and licenses	■	■	■	■	■	■	■	■				
“Serra do Cume” H_2 production unit			■	■	■	■	■	■				
H_2 power station at I.Z. of Angra Heroismo							■	■	■	■	■	■
Hydrogenopolis H_2 production unit					■	■	■	■				
Hydrogenopolis H_2 power station					■	■	■	■	■	■		
Methane + hythane generation unit		■	■	■	■	■	■					
H_2 filling station + H_2 vehicles							■	■	■	■	■	■
H_2 residential unit					■	■	■	■	■	■	■	
Touristic facilities									■	■	■	■
Energy grid for local harbour industry									■	■	■	■
R&D	■	■	■	■	■	■	■	■	■	■	■	■
PTEC	■	■	■	■	■	■	■	■	■	■	■	■

Acknowledgements

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