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INGRID PROJECT: HIGH-CAPACITY HYDROGEN-BASED GREEN-ENERGY STORAGE SOLUTIONS FOR GRID BALANCING

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Abstract. *INGRID introduces and demonstrates the usage of safe, high-density solid-state hydrogen storage as an effective energy vector to provide services to electricity systems operators for grid balancing purposes.*
To reach its ambitions objective, a new hydrogen storage system based on magnesium hydride is proposed. This technology provides significant advantages such as constant pressure operation and high energy storage density.
A second key issue is the design and development of advanced smart grid tools (Simulation tools, Energy Management System, ICT platform) able to simulate, manage, monitor and dispatch energy according to the power needs of the grid, allowing thus a suitable balance between variable energy supply and demand. The hybrid nature of the facility (electricity, gas) poses a challenge for the overall optimization.
The ultimate objective is to perform a demonstrative scaled-down test where the hydrogen solid-state storage technology is integrated:

1. *In an open loop, coupled with water electrolysers (1.152 kW), where hydrogen (300 kg) can be sold and transported for external use.*
2. *In a closed loop (25 kg) coupled with water electrolysers (1.152 kW) and fuel cell systems (120 kW) to complete a regenerative loop to electricity in order to be dispensed to off the grid utilities as an urban mobility systems. An Electric Vehicle Recharge Station (EVRS) is also included in the system.*

Conventional energy storage systems are entirely controllable by the DSO, whereas the INGRID system is intended to collaborate with the DSO according to different strategies such as income maximization, emissions minimization, compliance with DSO profile or a combination of them.

(1) INTRODUCTION

The FP7 European co-funded INGRID project tries to contribute to the solution of the instability and non-controllability in the grid by the massive introduction of energy produced by Renewable Energy Sources (RES), proposing a close cooperation with the Distributor System Operator (DSO) towards the balance of the energy demand and supply inside the grid.

In order to demonstrate the INGRID project a demonstrative plant is being building. It will consist of a 39 MWh energy storage facility operating in Puglia region (Troia, Italy). The plant will be connected to a middle voltage feeder of a primary substation (150/20 kV/kV) as a variable load (0-1200 kW) and it will be connected to a low voltage power line as a variable generator (0-120 kW).

The primary substation has been identified among the ones having a high value of power reverse flow due to the effect of the growing distributed generation and the low load day during weekend.

The main project innovation will consist of combining hydrogen solid-storage systems, where solid magnesium absorbs the hydrogen gas, with smart grid cutting-edge ICT-based active network control technologies for balancing highly variable power supply and demand in a scenario of high penetration of renewable energy sources.

In this project, a specific simulation tool has been developed for predicting and describing INGRID system behavior before there is any building on the field. The INGRID simulator is divided in several modules with different shared inputs and outputs that create a whole simulation tool.

(2) METHODOLOGY

The INGRID system collaborates with the Distribution Management System (DMS). That collaboration will allow either to adsorb or to inject active or reactive energy considering both DSO indications and results coming from each subsystem.

When needed, the INGRID system may indirectly adsorb the electricity produced by Renewable Energy Sources (RES) based plant outside INGRID system by means of an electrical connection to the grid.

As depicted in figure 1, the adsorbed electricity is used to supply a water electrolyser to produce hydrogen which may be either stocked in an innovative solid-state storage system by exploiting a patented magnesium hydrides-based technology, or directly injected into existent methane pipeline.

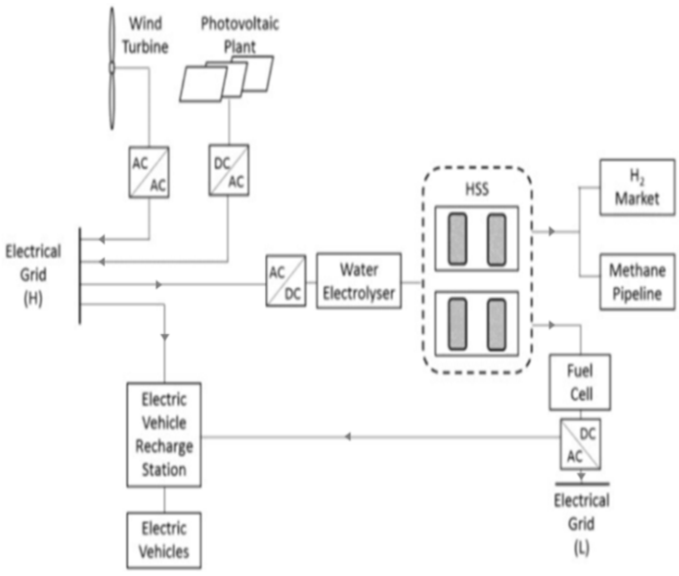

Fig. 1 Ingrid Concept

Two operation modes are considered. The closed loop refers to the scenario when the hydrogen storage system is connected to a fuel cell to generate electricity. In the case of the open loop, the hydrogen is stored in order to sell it in a container to external customers.

The INGRID system requires an EMS in order to provide control data for the real plant and make it work and adapt its outputs to the electricity market. The EMS considers a series of estimated parameters as power production, hydrogen market demand and local load power demand. In the demonstrator, the local load power demand will be the aggregated power demand of electric vehicles considering several recharging points connected to a low voltage power line.

The EMS will receive information from external sources as the DSO and from the INGRID system. In order to these requirements, a specific simulation tool has been developed for predicting and describing INGRID system behavior before there is any building on the field. The idea is that the real EMS can be alternatively connected either to the simulator or to the real devices, being the simulator an adequate tool to fine tune the EMS and analyze its behavior under different operative scenarios.

Regarding the INGRID communication architecture, a client/server topology is implemented so that the EMS can access and control all the operating parameters. All the devices use the same communication channel, the servers listen and the clients send information when the channel is free.

The EMS sends set points through OLE for Process Control (OPC) over TCP/IP considering the state of the INGRID system and the grid requirements of electrical power. The INGRID simulation tool is going to be integrated with the real EMS, considering the same communication protocol.

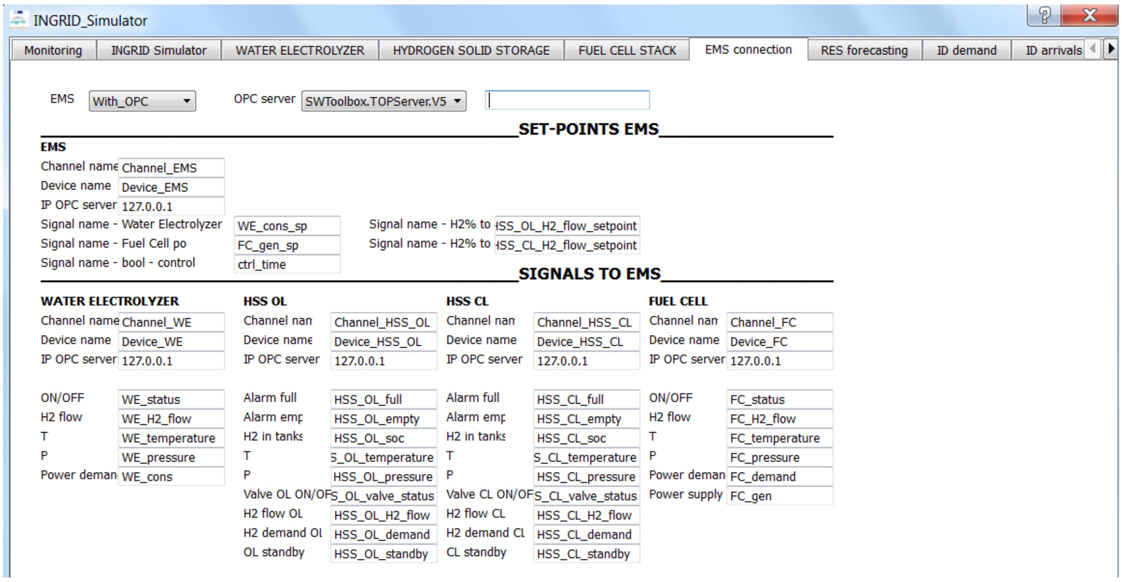

Fig. 2 Connection panel between the INGRID simulation tool and the EMS

The EMS should be successively interfaced to the simulated plant for evaluating the accuracy of the energy balancing processes.

The INGRID simulation tool has got different modules as:

- The power production estimation module includes both renewable energy sources (modeled according to weather conditions, solar panels and wind turbine characteristics) and other sources (modeled as a scheduled power profile).
- The estimation of green hydrogen market includes constant and discontinuous demands.
- The estimation of electric vehicles power demand was evaluated according to a model based on statistical arrival curves, estimations for the required energy according to the battery model and the recharging power.
- The green energy storage system. The main components of this module are a water electrolyser, a hydrogen solid-storage system and a fuel cell stack.

The power production estimation module

The estimation of the total electricity supply includes power supplies from RES and non-RES (modelled as a scheduled power profile).

In case of the RES, the power production is from wind and photovoltaics generators. Weather data are required for the estimation of electricity supply, including clouds, temperature, wind speed and others. Weather data are collecting from numerical weather prediction web service [1], where the RES localization is defined by a site and a country.

In the case of the wind power model, was used several wind turbine power curves, where input is a known wind speed and output is the generated power of the wind turbine. When the wind speed exceeds the cut-out speed, the wind power supply immediately drops to zero.

The wind speeds can vary significantly over short time periods, and the impact of this variation needed to be assessed in greater detail. The wind speed was simulated by a random number based on a Weibull distribution rather than an actual wind speed distribution, as is commonly done [2].

In the case of the wind photovoltaics model, the photovoltaics power strongly depends on the time of day and weather conditions [4] & [5].

The power supply from photovoltaics is given by normalized operation curve for the period of time between sun rise and sun set, similar to the figure 3, based on maximum photovoltaics power, weather factor, temperature, time and an empirical normalized operation curve panels.

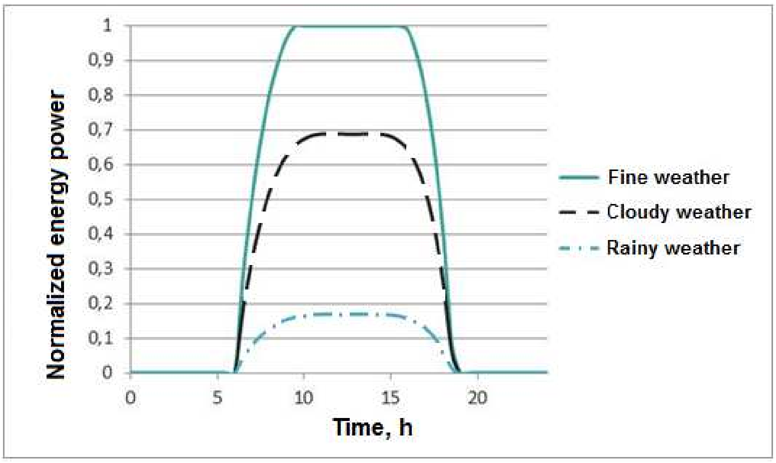

Fig. 3 Relative photovoltaics power vs hours according to weather conditions

Finally, the power production estimation module generates an energy cost profile that depends on the agreement of user with electricity retailer. In the INGRID simulation tool is possible to introduce the profile of the electricity price (€/MWh) by hour or the on-line connection with an electricity price portal in Spain [7].

The green hydrogen market estimation module

In order to establish the algorithms for hydrogen production and distribution system, it will be necessary to consider the green hydrogen market.

The hydrogen demand may be forecasted by means of historical data and a relational model according to machine-learning algorithms. The hydrogen requests is emulated with the hydrogen and electricity market tag from the INGRID simulator that provides the amount of the hydrogen volume to produce within a fixed time interval.

The hydrogen demand and the hydrogen price profiles are generated with the INGRID simulator through a text file. These profiles may be provided through a web service, as future steps.

The electric vehicles power demand estimation module

The power demand prevision considers different scheduling strategies for full electric vehicle recharging according to several vehicle arrival and departure models.

The vehicle arrival time refers to time when the electric vehicle arrives at the recharging point and the vehicle departure time refers to time when the electric vehicle departures from the recharging point. The rate parameter can usually be determinated from historical data or estimated from real time traffic data.

The aggregated power demand is the number of vehicles being charged at a particular time multiplied by the recharging mode. The power demand by an electric vehicle depends of the state of charge of its battery. The electricity price profiles for the recharging of electric vehicles are generated with the INGRID simulator.

The green energy storage system module

A water electrolyser, a hydrogen solid-storage system and a fuel cell stack are the main components of the green energy storage system.

Modeling of water electrolysis for hydrogen production

In the INGRID simulation tool the electrode kinetics of an electrolyser cell can be mathematically modeled using empirical current-voltage relationships. The current –voltage relationship (the polarization curve) can be represented as a sum of linear, logarithmic and exponential functions.

The balance of energy applied to the system is as follows:

$$V = E_0 + r \cdot I + s \cdot \ln(I) + m \cdot \exp(n \cdot I), \tag{1}$$

$$r = r_a + r_b \cdot T, \tag{2}$$

$$s = s_a + s_b \cdot T, \tag{3}$$

$$m = m_a \cdot \exp(m_b \cdot T), \tag{4}$$

where “E_0“ is the theoretical potential , “I” is the current, “T” is the operational temperature, “r_a”, ”r_b”, ”s_a”, “s_b”, “m_a”, “m_b“ and “n“ are empirical coefficients that can be numerically calculated using non-linear regression techniques.

The temperature of the electrolyte, which affects the polarization curve and the Faraday efficiency, can be estimated using simple or more complex thermal models. The overall thermal energy balance on the electrolyser could be expressed by the linear, first order, non-homogeneous differential equation.

Modeling of hydrogen solid-storage systems

The hydrogen solid-storage systems developed for the INGRID project are based on metal hydride. The magnesium hydride (MgH_2) was chosen for mass storage because it offers a totally reversible storage. The hydrogen can be absorbed and stored at typical electrolyser outlet pressure and later hydrogen can be reversibly desorbed at pressure typically adopted into fuel cells and H_2 gas turbines with no intermediate compression stage. Using different temperatures and low pressures, hydrogen is either absorbed or desorbed by the metal.

The tank is connected via a valve to the constant pressure water electrolyser output. Once the valve is opened, the hydrogen enters the tank and flows through the porous metallic medium. The exothermic absorption process starts and the heat is removed by a cooling fluid in order to get a constant temperature.

The filling kinetics depends on equilibrium relationships between the equilibrium pressure, the ratio of hydrogen to magnesium mass and the temperature.

The equilibrium relationship is similar to the Langmuir-Freundlich isotherm,

$$x = \frac{b_c \cdot P_{eq}^{\frac{1}{c}}}{1 + b_c \cdot P_{eq}^{\frac{1}{c}}}, \tag{5}$$

$$x = \frac{q}{q_m}, \quad (6)$$

where "P_{eq}" is the equilibrium pressure for a temperature, "q" is the fraction mass and "q_m" is the equilibrium fraction mass of hydrogen in magnesium.

The kinetics of absorption depends on the absorption coefficient, the balance mass and the movement of the fluid, given by Darcy law.

In isotherm conditions an approximation to evaluate the kinetics of absorption is given by the next equation,

$$\frac{dx}{dt} = \frac{3 \cdot k}{2} \cdot \frac{(1-x)^{\frac{2}{3}}}{1-(1-x)^{\frac{1}{3}}} \Rightarrow x = 1 - \left(1 - \sqrt{k \cdot t}\right)^3, \quad (7)$$

$$k = k_0 \cdot \left(\frac{P - P_{eq}}{P_{eq}} \right) \cdot \exp\left(\frac{-E_a}{R \cdot T} \right), \quad (8)$$

where k_0 is a specific constant for the absorbent solid, $8 \cdot 10^{-6}$ and T, 613 K.

The variation of the energy in the different steps is evaluated by means of energy balances, where the cooling fluid removes the heat of the exothermic reaction of hydrogen absorption by magnesium. When hydrogen is absorbed and reacts with magnesium to form MgH_2, this heat can be stored, evacuated to be used elsewhere or lost. On the opposite, the reaction of hydrogen desorption by magnesium is an endothermic heat consuming process.

This energy can be provided by the heat stored during the absorption reaction or by external components such as electrical heating. In the case of the closed loop the heat is stored as latent heat by means of a cooling fluid (phase change material cooling). This way it is possible to heat the MgH_2 for desorption process when the fuel cell needs hydrogen. The mathematical model is identical in the case of desorption, considering other equilibrium conditions (11 bar and 340ºC for absorption and 2 bar and 310ºC for desorption).

Modeling of hydrogen fuel cell

The fuel cell is modeled as a generic Polymer Electrolyte Membrane fuel cell (PEM), since that's the technology to be used in the INGRID system.

Depending on the current drawn, the fuel cell converts hydrogen and thereby generates voltage as a function of current. The equations used depend on the empirical form of the fuel cell model.

The considered model is similar to the electrolyser model where the balance of energy applied to the system is as follows,

$$V = E_0 + rfc \cdot I + sfc \cdot \ln(I) + mfc \cdot \exp(nfc \cdot I), \quad (9)$$

$$E_0 = 1.299 - 8.5 \cdot 10^{-4} \cdot (T - 25) + 4.3085 \cdot 10^{-5} \cdot (T + 273.15) \cdot (\ln(P_{H2}) + 0.5 \cdot \ln(P_{O2})) \quad (10)$$

$$rfc = rfc_a + rfc_b \cdot T, \quad (11)$$

$$sfc = sfc_a + sfc_b \cdot T, \quad (12)$$

$$mfc = mfc_a \cdot \exp(mfc_b \cdot T), \quad (13)$$

where "E_0" is the theoretical potential , "I" is the current, "T" is the operational temperature, "P_{H2}", "P_{O2}" are the effective partial pressure for hydrogen and oxygen, "rfc_a", "rfc_b", "sfc_a", "sfc_b", "mfc_a", "mfc_b" and "nfc" are empirical coefficients that can be numerically calculated using non-linear regression techniques.

The overall thermal energy balance on the fuel cell could be expressed by a linear, first order, non-homogeneous differential equation.

(3) RESULTS

The INGRID simulation tool was connected with the EMS through OPC over TCP/IP. The variables of the components are monitoring and sending to the EMS. On the other hand, the EMS provides control set-points (the water electrolyser power, the fuel cell power and the quantity of hydrogen that stores in open loop and closed loop).

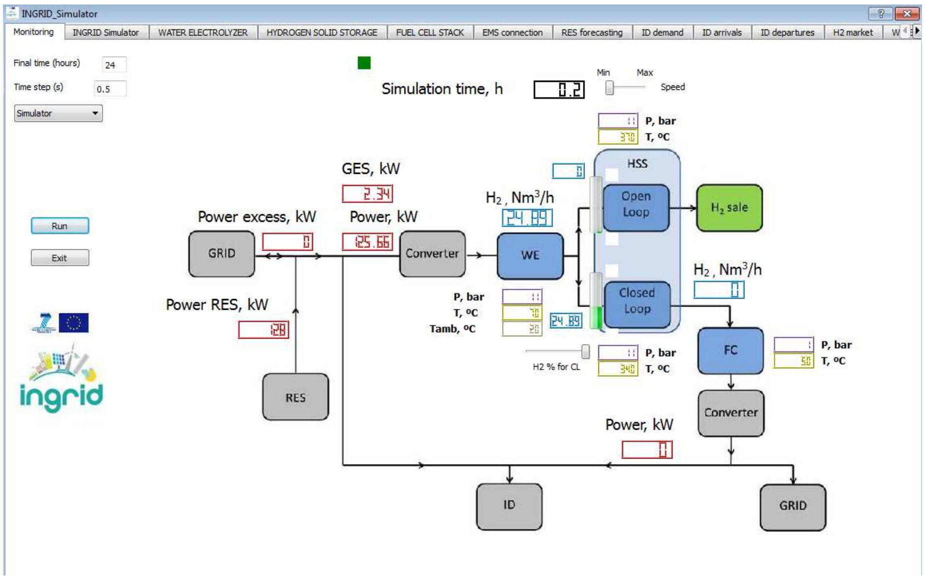

Fig. 4 The INGRID simulation tool configuration

Next figure shows the estimation of surplus power production and the storage of energy when the INGRID system is operating during 24 hours. The simulator receives set points from the EMS indicating the required surplus power production to be stored. According to the hydrogen demand and electric vehicle demand curves, the EMS operates the water electrolizer and the fuel cell in order to fulfil the corresponding requirements.

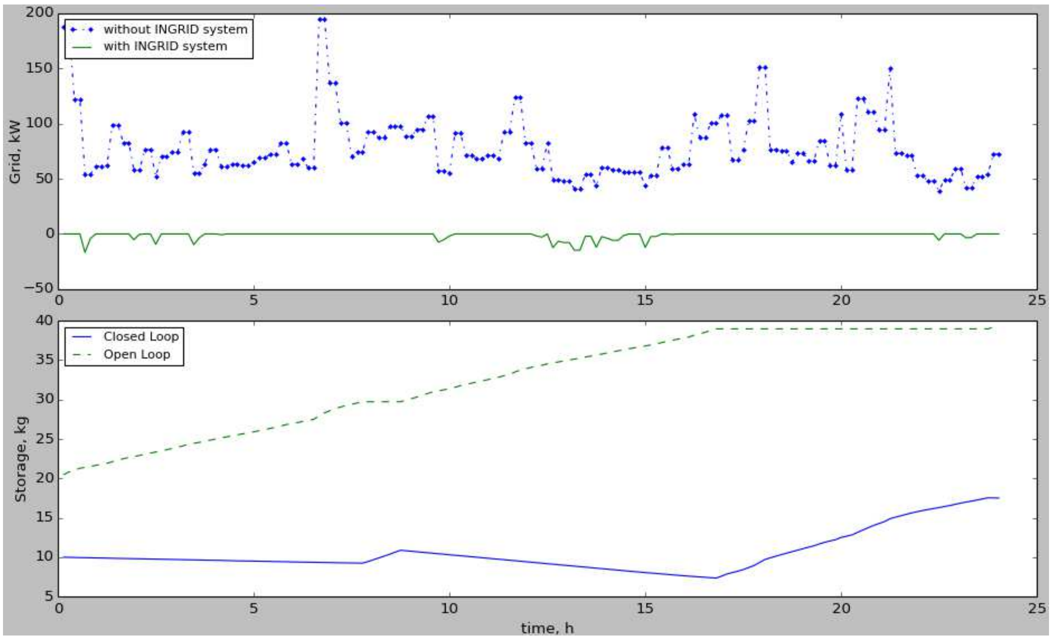

Fig. 5 Surplus power production with and without INGRID system and hydrogen storage in closed and open loop.

The behavior of the water electrolyser is given by its mathematical model and the power set-point provided by the EMS. Next figure shows the time evolution of the water electrolyser.

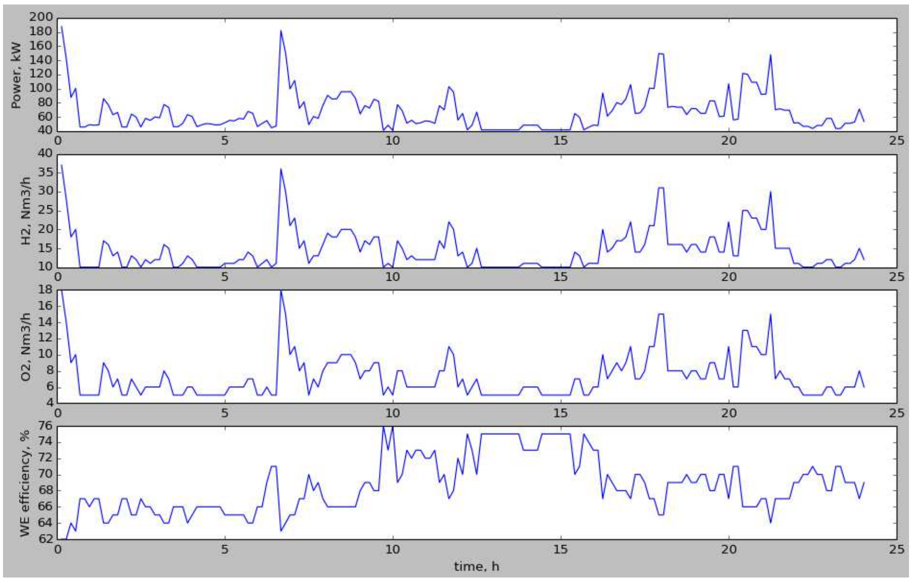

Fig. 6 The water electrolyser behavior according to the EMS logic.

In this example, the electric vehicle demand is given by an electric vehicle that needs to recharge its battery.

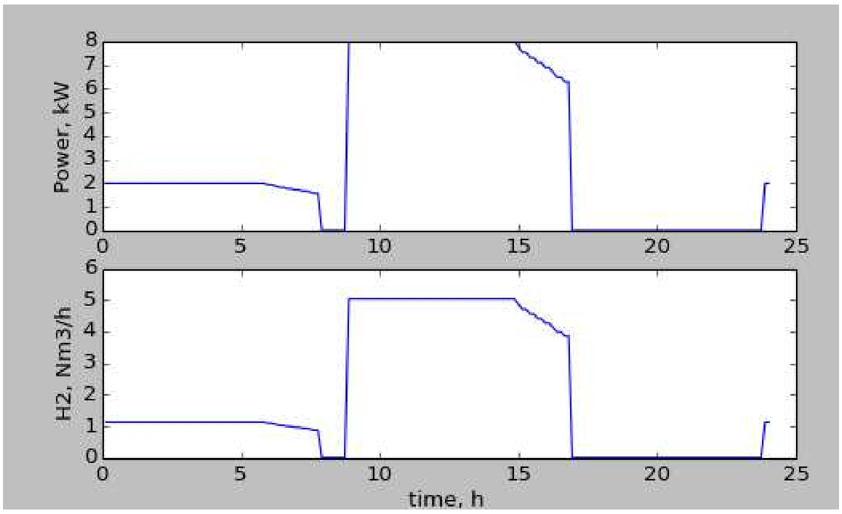

Fig. 8 Fuel cell dynamics for the required electric vehicle power demand.

DISCUSSION

The final efficiency of the INGRID system will depend on a lot of parameters as temperature, pressure, control system, energy quality of the electric energy, connection grid…The main product of the INGRID system will be the hydrogen because of the electricity to electricity efficiency loop (closed loop), is low considering other alternatives.

The hydrogen potential market analysis, starting from survey on different industrial applications, mobility or power to gas where the resulting hydrogen is injected into the natural gas grid (directly, 5%) or combining the hydrogen with carbon dioxide in order to convert to methane using a methanation reaction.

CONCLUSIONS

This work describes the INGRID system through the INGRID simulation tool in cooperation with an EMS. The EMS establishes the power set-points for the water electrolyzer and the fuel cell based on the surplus power production, the estimation of hydrogen demand and the power demand of electric vehicles. The simulator is thus a key tool to fine tune the EMS and anticipate the INGRID plant behavior under different conditions. According to data provided by several partners of INGRID project, physical plant elements have been modeled. Simulation results have been checked against data obtained by vendors. Anyway, the behavior and performance of INGRID plant components working jointly may differ from those indicated by individual tests. Since there is no data related to the whole plant behavior, further developing time will be essential for data acquisition and simulator tuning.

The INGRID system stores electricity as hydrogen. In order to generate 5.2 KWh is necessary about 19 kWh of electricity consumption, so that the exploitation of this alternative system to store electricity will depend on the external hydrogen market. The scenario concerning the hydrogen as fuel, as hydro-methane (a mixture with natural gas and hydrogen) may represent a strategic and profitable asset for the Puglia economy in the future.

ACKNOWLEDGEMENTS

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