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Insights for Industry 4.0 Applications into a Hydrogen Advanced Mobility

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Abstract

The present paper aims to investigate the integration of a hydrogen fueling infrastructure and a hydrogen advanced mobility system, such as a fuel cell hybrid tram for a new tramway route. A mathematical model has been formalized and implemented in order to analyze the key elements of such integrated energy system. The model is used to carry out a sensitive analysis to investigate the system response to different passengers numbers and journey speed, monitoring the hydrogen daily consumption, the station energy consumption and the overall system efficiency. Results have been used as a support to provide insights on potential interconnections with Industry 4.0 applications.

Keywords: Industry 4.0; Hydrogen infrastructure; Fuel cell-based vehicle; Data monitoring; Advanced mobility.

1. Introduction

1.1. Context and Background

Energy efficiency related actions are needed to address climate changes issues. Among the several options scientific community is investigating on, hydrogen technologies seem to be suitable to tackle de-carbonization and high efficiency operation [1], above all in railway applications [2].

As an emergent trend [3], Industry 4.0 and digitalization could contribute to deep data analysis and thus cost saving [4]. In this train of thought, data driven technologies are beneficial to support and sustain hydrogen advanced mobility technologies in their deployment, thanks to a more efficient energy analysis.

The research activity presented in this paper aims to give its contribution to the scientific community by presenting a mathematical model and investigations on a hydrogen infrastructure connected to an advanced mobility application such a fuel cell hybrid train operation. A sensitivity analysis will be carried out, in order to investigate the performance of such system. Results will be discussed with the goal to stress out how important could be an interconnection between advanced energy systems and digital solutions to guarantee a sustainable energy transition. Insights will be proposed to enter the advantage of these approaches.

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1.2. Literature Review

Literature offers few examples of integration between sustainable energy and Industry 4.0 [5–7]. Other authors investigated the interaction between logistics and Industry 4.0, identifying the importance of digital technologies as key enablers to provide and share relevant information [8,9].

The previous literature review offers a good glimpse on the great number of opportunities on how sustainable energy concepts can be connected to digitalization and Industry 4.0 applications. The same connection could be applied to new advanced energy systems and the hydrogen economy, to enable more flexibility on the energy management systems, to

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improve the energy saving and to increase the chances of success of such business case.

Several authors focused their research activities on mathematical modeling of advanced hydrogen mobility technologies and infrastructures.

Recent literature on environmental aspects of clean-hydrogen production technologies has been investigated and analyzed in [10]. Concerning a water-electrolysis hydrogen production facility, among the variety of articles the literature offers, the most recent activities are worthy to be mentioned to understand the trend of such topics. For PEM electrolyzer models, the research effort in modeling has increased in recent years. In Ref. [11] a techno-economic modelling and analysis of hydrogen station has been performed, focusing on an optimization of the volume of banks to achieve the most cost-efficient design. In Ref. [12] the authors proposed a zero-dimensional model of a PEM electrolyzer, considering several phenomena involved in its operation and capable to simulate the overall performance of the system. Other authors investigated hydrogen as the potential carrier in the future energy transition, serving also multiple applications in several sectors and playing a key role as energy storage in smoothing the intermittency of renewable sources [13].

Regarding a Fuel Cell-based vehicle model, the research focus is mainly looking at optimization strategy able to improve the hydrogen economy. W. Zhang et. al, in [14], analyzed daily operation strategies of a fuel cell – battery tram; a comparison of hydrogen consumption of three strategies is made. In [15], Q. li et al. implement a regenerative braking energy recovery strategy for fuel cell – supercapacitor rail vehicles; an optimized braking speed curve is obtained and the energy recovered, linked to the hydrogen consumption, is evaluated during a cycle. H. Li et. al, in [16], study an equivalent consumption minimum strategy, built using sequential quadratic programming; this control strategy is compared with two other innovative systems and a hydrogen consumption reduction is achieved.

Mayyas and Mann [17] investigated the current challenges for fuel cells and electrolyzers, considering the high initial cost and the availability of hydrogen infrastructure to support FCEV fleets. They performed a deep analysis and investigation on the manufacturing processes used in the production of such technologies, proposing key cost drivers and reductions.

Literature review related to recent years has highlighted how separated aspects related to hydrogen infrastructure and advanced mobility have previously been analyzed, but there are still few energy overall investigations on the integration of the two systems.

This paper aims to analyze the key elements of such integrated energy system (hydrogen refueling station with advanced hydrogen train), identifying the potential of unexploited data to provide insights for making complex decisions or controlling the process. The paper describes from an energy point of view the system operation by means of mathematical models, investigating the hydrogen production phase and a fuel cell hybrid train operation.

A sensitive analysis will be carried out in order to study the powertrain output, such as hydrogen consumption and efficiency, according to vehicle mass and speed variations. The model results will be used as a support to provide insights on a potential application of Industry 4.0 in this advanced field.

2. Numerical Modeling

A numerical model is implemented in order to analyze the hybrid vehicle response to different drive cycles, according to vehicle mass, journey speed and track morphology. Peaks and quick variations, typical of railway applications, characterize the investigated track morphology. Since a total Fuel Cell (FC) vehicle cannot guarantee the required performance in drive cycles with sudden power variations, a hybrid powertrain has been considered for the simulation. Under this consideration, the adopted powertrain is composed of a combination of fuel cell and energy storage technologies [18]. Indeed, the power required by the vehicle to perform its journey is provided by the several energy sources by means of an energy management system, ad hoc implemented [19].

The powertrain components are load-connected through DC/DC converters. Moreover, a regenerative braking strategy is considered to recover the energy in deceleration phases.

The vehicle model is implemented in Matlab Simulink environmental. It has morphology and speed journey as input and vehicle performance as output. It consists of different parts: the power demand calculation (PDC) block, the energy management system (EMS) and the powertrain components. The three subsystems work in series in each moment of time. In detail, the PDC block analyses the track altitude and the journey speed and obtains the total power demand as output. The EMS, by means of a control strategy, elaborates the PDC output and imposes the power demand on each energy source, according to the powertrain block output of the previous moment of time. The powertrain block simulates the vehicle component behavior as fuel cell system, battery pack, DC/DC converters, auxiliary service and regenerative brake strategy.

Concerning the hydrogen infrastructure, the model is focused on a zero-dimensional electrolysis production via PEM (Polymer Membrane Electrolyzer), following a multi-physics and dynamic approach. The mathematical description is based on physical correlations (fluid-dynamic, thermodynamic, electrochemical and thermal laws) and on analytical correlations: part of the main parameters have been extrapolated with regression technique from existing polarization curve and company datasheet [20].

A control protocol has been implemented to monitor pressure and temperature values, as well as switching procedure and operational procedures among the components.

A hydrogen station layout normally includes the presence of the first stage of compression, storage, second stage of compression, cooling systems and dispenser [21]. Since the goal of the present block is to manage the energy demand of the hydrogen infrastructure, the energy demand rates of these components have been extrapolated from the scientific international literature

Based on 2018 specific energy demand for compression of 1.6 kWh/kg for the low pressure compressor (up to 350 bar) [22,23]. The compression (up to 700 bar) and dispenser rate can be included in one value, 2.25 kWh/kg [24]. The cooling block adds a system load of 1.40 kWh/kg [25].

The infrastructure model is connected to the advanced hydrogen train numerical model. The latter works as the block graph shown in Fig. 1 and it is implemented in order to analyze the hybrid vehicle response to different drive cycles, depending on vehicle mass and drive cycle time variations. Starting with these input parameters, the model sets its goal to calculate the power needed to perform the vehicle task [26]. After a time initialization and discretization, the power demand block calculates the traction force needed to execute the track of the journey. The power required is split among the powertrain energy sources, fuel cell system and battery pack, by means of an energy management system. In the end, the powertrain performance are updated and the cycle restarts if the journey endpoint is not reached, otherwise it ends.

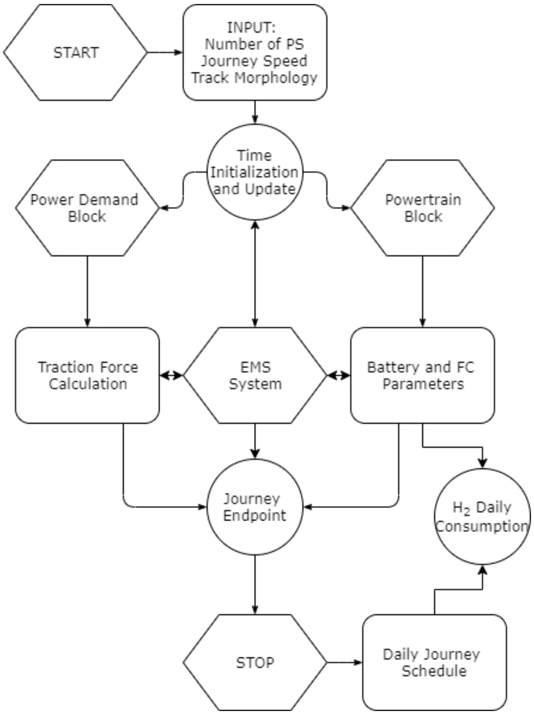

Fig. 1. Advanced hybrid tram flow chart

Simulation stops when the journey has been completed within the range of time bonded to the journey speed. Indeed, the model calculates the hydrogen needed by the tram fuel cell system. Finally, considering a daily schedule of 12 trips, the model extrapolates the hydrogen daily consumption, that will be the input of the hydrogen infrastructure model, as shown in the flowchart of Fig. 2.

Simulating a dynamic operation of the hydrogen infrastructure, the model takes into account the station energy consumption and the overall system efficiency since they are the main parameters that can affect the advanced hydrogen mobility system.

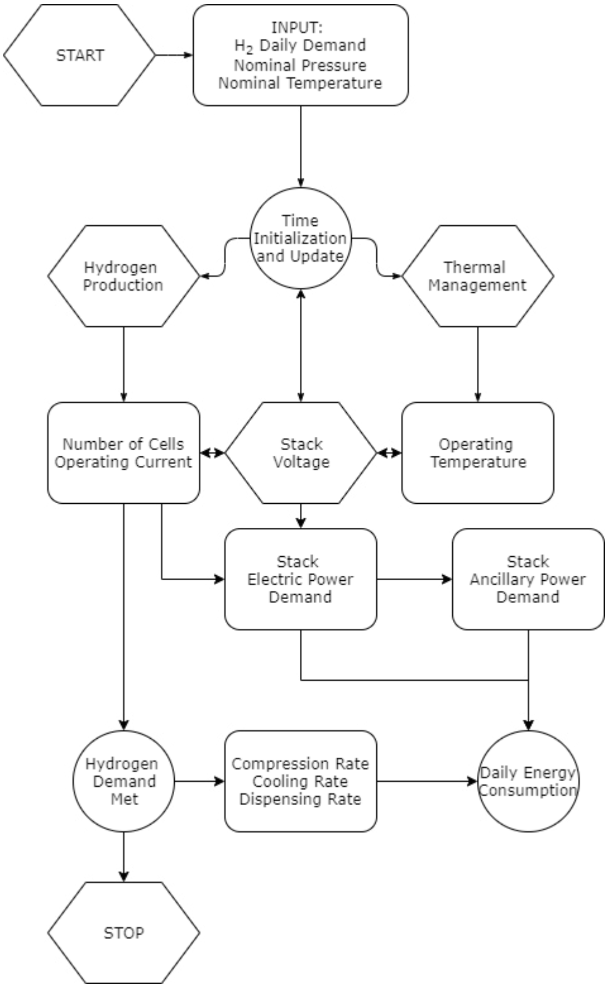

Fig. 2. Hydrogen Infrastructure flow chart

Other important inputs are the nominal pressure and the nominal temperature: they become the pressure targets to be met in order to start the production. After a transient period of time when the operating temperature reaches the nominal value, the hydrogen production starts. As already mentioned above, the value of the number of cells and the current are chosen to allow the system to operate with high efficiency. They main outputs of the model are the power demand rated for each components. Simulation stops when the production achieves the requested value and the hydrogen demand target is met.

3. Results

A new tramway route is analyzed. The line links the Cosenza Train Station to Rende Train Station. It is around 9 km length with 20 stops for each way. The morphology is illustrated in Fig. 3. The altitude is in a wide range, around 80 m, considering the rail purpose (tramway) and the track length; consequently, the altitude slope assumes high values, between -30 ‰ and 30 ‰. Regarding the vehicle track, a basic cycle is imposed for each drive time between two stops, composed of acceleration, constant speed and deceleration phases, according to the travel time imposed.

The vehicle chosen for the simulation is a low-floor multiple-unit tram, with two articulate section, with 50 ton unladen weight.

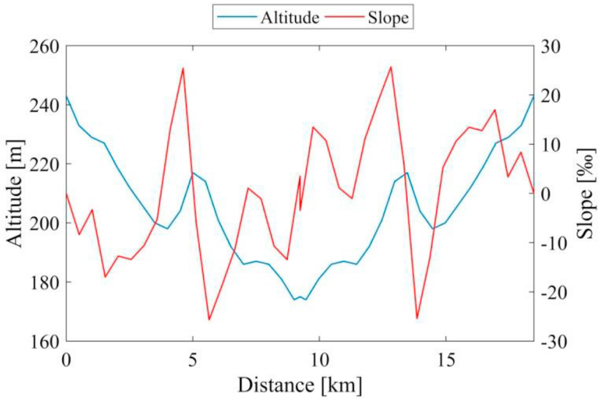

Fig. 3. Vehicle track

The performance achieved are discussed and processed in order to carry out a sensitive analysis. The trend of hydrogen consumption and system efficiency have been evaluated for different initial conditions. The passenger number and journey time, and consequently the vehicle mass and drive speed trend, are varied and imposed as input parameters with the aim of studying the system response, in terms of performance. Tables 1 and 2 summarize the parameters used as inputs for the model.

Table 1. Infrastructure Simulation Parameters

Parameter	PEM-E	
Membrane Cross Section Area	100.00	[cm^2]
Nominal Temperature	353	[K]
Anode Nominal Pressure	2.00	[bar]
Cathode Nominal Pressure	13.44	[bar]
Anode Volume	0.001	[m^3]
Cathode Volume	0.001	[m^3]
Simulation Time	24	[h]
Operating Current	135	[A]
Initial Temperature	293	[K]

Table 2. Vehicle Simulation Parameters

Parameter	PEM-FC	
Gross power	180	[kW]
Weight	654	[kg]
Fuel (Hydrogen)	>99.98%	[%]
Maximum current	500 A_{DC}	[A_{DC}]
Maximum voltage	720 V_{DC}	[V_{DC}]
Peak efficiency	55	[%]

A sensitive analysis is carried out in order to study the powertrain output, such as hydrogen consumption and efficiency, according to vehicle mass and speed variations.

Fig. 4 shows the partial results of the sensitive analysis. The powertrain is tested for five load levels, varying the number of passengers, from 0 to 120 passengers, and for five drive cycle times, from 70 min to 90 min. Therefore 25 different scenarios are achieved and the hydrogen consumption of each case is plotted in Fig. 4. The H_2 consumption is in a wide range, between roughly 6.5 kg/cycle, for unladen weight and 90 min track, and 9.8 kg/cycle for max load and 70 min track. As expected, the achieved trends are strictly increasing functions, namely the H_2 consumption increases for increasing passenger number and/or decreasing time track. In addition, the time track reduction affects mainly compared to the load variation; in fact, the H_2 consumption variation due to a weight increasing is less compared to the one achieved for a time track reduction.

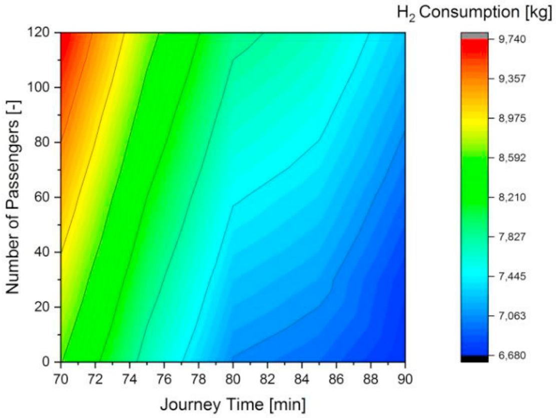

Fig. 4. Vehicle H2 consumption

The hydrogen station has been sized according to the highest demand: considering a daily schedule of 12 trips, the highest rate the tram required to achieve its target is 117 kg/day. It results in an electrolyzer electric size of 275 kW_{DC}, working with an energy efficiency of 57% and a Faraday efficiency of 94%. The number of cells composing the stack resulted to be 1022. The required cooling energy is about 1.62 MWh/day, in order to ensure a constant operating temperature (353 K).

Considering the tram hydrogen consumption according to the 25 different scenarios, the daily hydrogen demand resulted to be in the range of 80-117 kg per day. With the goal to create an energy consumption map for the hydrogen station daily operation, simulations have been run using the 25 different load scenarios (from 80 kg to 117 kg per day). As shown in Fig. 5, the energy consumption of the station increases when more hydrogen is required. It is relevant to notice how the process is energy-intense: the whole systems requires 5097 kWh when the tram operates with no passengers with a single cycle time of 90 minutes. As soon as the number of passengers increases to 120 and the tram is trying to perform the drive cycle more efficiently in terms of cycle time (70 minutes instead of 90 minutes), the energy demand is 7420 kWh (whose 91.73% is required by the electrolysis process, 2.52 % by the low pressure compressor, 3.55 % by the dispensing process and 2.2% from the cooling block). Despite the high value, the overall efficiency of the station presents a very good performance of 52%, index of the great potential of such technology.

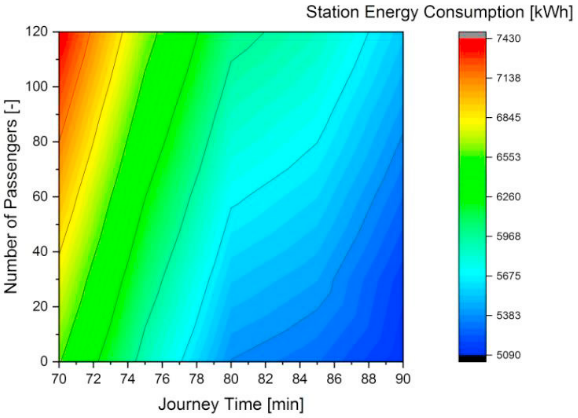

Fig. 5. Station energy consumption.

4. Insights

As already discussed in the previous section, a numerical model has been implemented in order to analyze from an energy point of view the integration between a hydrogen infrastructure connected to an advanced mobility application such a fuel cell hybrid train operation. The sensitive analysis has the aim to provide, by way of example, a glimpse on the importance of the choice on the operational parameters and on monitoring in a real-time the performance of the advanced mobility system. The results of such energy system highlight the importance of the sensitivity analysis, emphasizing the role of the energy efficiency of the two systems and the parameters they are affected by, such as the number of trips, vehicle mass (thus number of passengers), journey speed and track morphology.

Monitoring these parameters could lead to important benefits: gaining percentage points in energy efficiency and working with high performance are index of a great level of flexibility, low H_2 consumption and cost-effective operation.

The control system implemented in the hybrid tram model is associated with an equivalent consumption minimization strategy. In this way, the EMS calculates the fuel cell power demand, minimizing the hydrogen consumption, according to vehicle mass and demanded speed. As a matter of fact, built-in sensors are needed to manage and to control the tram power train efficiency by implementing the minimization strategy. Considering the difficulties already described in the introduction in the rolling up and spreading out of the hydrogen refueling stations, reduction in the hydrogen consumption is a key enabler for hydrogen mobility technologies. An Internet of Things (IoT) application in this field could allow to sense and remotely control the main parameters of the system, minimizing the needed resources.

The hydrogen infrastructure performance has also a strong dependence on the operating temperature and nominal pressure at the cathode and anode side. These parameters affect the stack life and the system efficiency. It could be truly important to have the possibility to monitor them with a real-time active data acquisition system capable of collecting and processing data, in order to maximize the energy output of the station, operating with reliability and providing smart service. Besides, even if hydrogen has a great potential as an energy vector, it has to be carefully handled [27]. As well as the model monitors the pressure level and the temperature trend, a comprehensive use of interconnected sensors could monitor the production process and the station operation with a higher level of safety. Indeed, it could enable real-time checks and inspections, as well as it could allow preventive maintenance actions. As final result, savings on extraordinary maintenance costs are expected, guaranteeing a better match with the related safety standards [28,29].

Installation of active sensors and generation of a database of the hydrogen station has other potentialities. The model provides for the energy consumption of the whole hydrogen infrastructure. Such approach, if adopted in real applications, could strongly promote demand response with renewable energies: since water electrolysis is an energy intense process, but also flexible in time (hydrogen can be produced, stored, and then used), it is convenient to start and schedule the production according to the availability and the surplus of renewable energy. Monitoring and managing the hydrogen generation could represent a powerful action to decarbonize the grid, reduce the peak loads and exploit in a smart and efficient way renewable sources. For these applications, Internet of Energy (IoE) technologies could help to control the actual demand, and to introduce energy savings.

A smart interaction between the hydrogen tram and the hydrogen infrastructure has a great potential. Considering the emergent trend of the Smart City, where transportation is gaining more and more the connotation of service, a digital communication between hydrogen production and hydrogen load could be a dynamic enabler to address the common static asset of the hydrogen infrastructures. In this train of thought, a hydrogen fueling station acquires a digital role of partner rather than a simple provider, ensuring accessibility for the entire value chain. In the same time, this approach enables a better logistic management of the tram journey, with service delivered at the scheduled time to target destinations.

As last opportunity, a gigantic amount of data could surely aim and promote new business models (Big Data applications).

5. Conclusions

In this paper, an integrated view of the concept of Industry 4.0 and the advanced hydrogen mobility has been presented. In order to support the provided insights, a mathematical model has been developed, and a sensitivity analysis has been carried out. The sensitive analysis highlighted the importance of monitoring the energy efficiency of such system.

Considering a 25 different scenarios, the tram H_2 consumption is in a wide range, between roughly 6.5 kg/cycle, for unladen weight and 90 min track, and 9.8 kg/cycle for max load and 70 min track. The corresponding hydrogen station size resulted to be 117 kg/day, with an electrolyzer electric size of 275 kW_{DC}, operating with an energy efficiency of 57% and a Faraday efficiency of 94%. With 120 passengers and a cycle time of 70 minutes, the station energy demand is 7420 kWh, with an overall efficiency of the station presents of 52%, index of the great potential of such technology.

Actually, interconnected sensors could create several opportunities with economic potential. The present paper tried to provide a contribution for this context, presenting a series of considerations and insights. As summarized guidelines, some future benefits could be derived:

- Pressure, temperature and energy level monitoring could prevent safety issues improving the safety standard;
- Data monitoring and big data analysis could lead to learn and implement a new system flexibility, where the infrastructure and the train could improve their interconnection and thus the customer satisfaction and system performance;
- A minimizing control strategy has been proposed and it could improve the hydrogen consumption during the tram journey;
- A control system capable to capture the most important energy parameters could easily help to trace the system operation and it could help operators to analyze and schedule maintenance in a predictive way.

Sensors and actuators installation is strongly advised in order to monitor, control and manage in a real time the system operation. As insight and potential application, through a well-designed control system, the advanced hydrogen train control could communicate with the hydrogen infrastructure monitoring system, improving the energy performance of the mobility. Furthermore, Industry 4.0 applications could enable new opportunities for hydrogen economy, supporting also the deployment of renewable energies and energy efficiency-related actions.

Being both cutting-edge solutions, Industry 4.0 and advanced hydrogen mobility are influenced by technological fostering and improvements. It is reasonable to envisage a future when advanced sustainable technologies and innovative digital solutions will create mutual advantage with synergy towards unexploited applications and results.

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