

Article

Study of Different Scenarios for Wind Farm–Electrolyzer–Fuel Cell Integration into Smart Grid Using Energetic Macroscopic Representation-Based Modeling

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Abstract

A smart grid is an advanced electricity network that uses digital technology to manage the electrical energy in real time to improve global efficiency and to facilitate the integration of renewable energy sources into it. Therefore, energy management is a real challenge in smart grids with distributed generation units, as they have an intermittent production nature, which affects the stability of the grid and economic benefits for investors. In this paper, this challenge is analyzed for the integration of a wind farm, an electrolyzer, and a fuel cell into an electrical network. Some scenarios are studied based on electrical energy availability and/or economic assumptions in the smart grid. For this purpose, the macroscopic energy representation (EMR) formalism tool is used for modeling the elements of the studied system. EMR is useful for simplifying complex multi-domain systems, helping with design control strategies and providing a clear physical interpretation of system behavior. The different scenarios were evaluated and implemented in the MATLAB-Simulink environment, and the simulation results are presented. Finally, a conclusion is developed based on the different aims and obtained results.

Keywords: smart grid; wind farm; electrolyzer; fuel cell; EMR; energy management

1. Introduction

A smart grid is an advanced electricity network that uses digital technology to monitor, control, and optimize the production, distribution, and consumption of electricity in real time. Unlike traditional power grids, which mostly deliver electricity one way from power plants to consumers, a smart grid allows for two-way communication between utilities and users [1–3]. Also, smart grids enable bidirectional energy and information flow, real-time operation, distributed generation integration, and intelligent energy management. These features make smart grids highly suitable for integrating renewable energy resources. Indeed, smart grids have emerged as an advanced solution for integrating renewable energy sources, distributed generation units, and intelligent control strategies into modern power systems [2,4]. This responds to the rapid increase in the global energy demand and the transition toward sustainable energy systems while considering the environmental concerns and the depletion of fossil fuel resources [1]. In a smart grid, the electricity systems are more reliable because of fewer and shorter outages; more cost-effi-

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cient because of optimized energy use and pricing; and more sustainable because of better use of renewable energy [5–7].

Among renewable energy sources, wind energy has experienced substantial growth because of its clean, abundant, and economically attractive characteristics [8]. However, the intermittent and stochastic nature of wind speed introduces several operational challenges, including voltage instability, frequency deviations, power fluctuations, and energy imbalance within electrical grids [4,9]. To address these challenges, hydrogen energy technologies may be considered promising long-term energy storage solutions in smart grids [2,10]. Electrolyzers and fuel cells enable the conversion of surplus electrical energy into hydrogen and the reconversion of hydrogen into electricity when required [11,12]. During periods of high wind power generation and low electricity demand, excess electrical energy can be used by electrolyzers to produce hydrogen through water electrolysis [13]. The generated hydrogen can then be stored and later utilized by fuel cells to generate electricity during low wind generation or peak demand periods or be sold and used in other applications [14–20]. Therefore, integration of wind farms, electrolyzers, hydrogen storage systems, and fuel cells within smart grids has become an important research area in recent years [4,7]. Hybrid wind–hydrogen systems offer several advantages, including enhanced renewable energy penetration, reduction in greenhouse gas emissions, increased energy security, and improved grid stability [16–22]. Electrolyzers can operate as flexible, controllable loads capable of absorbing surplus renewable energy and providing ancillary services such as frequency regulation and demand response [13,23]. Meanwhile, fuel cells can act as distributed generation units that support voltage regulation and backup power supply during energy shortages [24]. Furthermore, hydrogen storage systems provide long-duration energy storage capabilities that are difficult to achieve using conventional battery technologies [10,25].

Despite these advantages, the coordinated operation of wind turbines, electrolyzers, fuel cells, hydrogen storage units, converters, and electrical loads creates significant challenges for energy management systems (EMSs) because of the nonlinear dynamics of electrochemical devices, renewable generation uncertainty, variable load demand, and grid operational constraints [20,26]. Therefore, efficient EMS strategies are required to optimize power flow, maximize renewable energy utilization, minimize operational costs, and ensure stable system performance [21,27]. Several advanced control approaches have been proposed in the literature, including rule-based control, fuzzy logic, dynamic programming, artificial intelligence, optimization algorithms, and model predictive control (MPC) [28,29]. In particular, MPC-based approaches have demonstrated high effectiveness for managing hybrid renewable-hydrogen systems because of their predictive capability and ability to handle multiple constraints simultaneously [9,15]. Chen et al. proposed an AI-aided MPC strategy for a grid-connected wind–hydrogen–fuel cell system in [29], demonstrating improved energy efficiency and enhanced operational stability. Similarly, Guilbert and Vitale developed an improved hydrogen production-based power management strategy for a wind turbine system coupled with PEM electrolyzers in [13]. Their results showed that advanced energy management techniques can significantly improve hydrogen production efficiency and overall system reliability. In parallel with control and optimization developments, accurate modeling methodologies are essential for analyzing and controlling hybrid renewable-energy systems [20]. Among the available modeling tools, Energetic Macroscopic Representation (EMR) has emerged as a powerful graphical methodology for describing complex multiphysics energy systems based on action–reaction principles and energy exchange between system components [23,30]. Although this methodology can become complex for large systems, emphasizes structure and energy relationships rather than detailed equations, and is not optimal for every problem, it provides a systematic and hierarchical representation of energy conversion systems by facilitating

inversion-based control design. EMR has been successfully applied to electrical machines, hybrid electric vehicles, renewable-energy systems, and fuel cell-based applications because of its ability to represent complex interactions between subsystems in a structured and intuitive manner [5,31].

In this paper, a permanent magnet synchronous machine-based wind farm–electrolyzer–fuel cell integrated into a smart grid is studied, as shown in Figure 1, by using EMR tools. Although EMR has been applied to some electrical systems, it is applied for the first time to such a system with complex interactions between subsystems in a structured and intuitive manner, leading to the simple modeling of a complex system that allows for studying different scenarios in a smart grid. Application of EMR to this system offers several more advantages. First, EMR enables the clear visualization of energy exchanges between wind turbines, electrolyzers, fuel cells, storage systems, converters, and electrical loads. Second, it allows for the modular modeling of multi-domain systems involving electrical, mechanical, electrochemical, and thermal phenomena. Third, EMR facilitates the derivation of maximum control structures (MCSs), which simplify controller design and energy management implementation. Recent research has increasingly focused on hydrogen-integrated smart grids and advanced control architectures and applications for renewable-hydrogen systems [2,10,18,19]. Several studies have also investigated optimization and scheduling strategies for hydrogen-based energy systems [17,21,27]. Therefore, the development of an EMR-based energy management framework for smart grids integrating wind farms, electrolyzers, hydrogen storage systems, and fuel cells represents a highly promising research direction. Such a framework can provide a systematic representation of energy exchanges, which may enable the efficient control and optimization of the power flow between renewable generation, hydrogen production and storage, and electrical loads. The proposed approach can improve renewable energy utilization, enhance grid stability, support the development of sustainable and resilient smart grid infrastructures, and especially reduce operational costs. That is why in this paper, an EMR modeling tool is developed for different elements of the smart grid by considering several energy management scenarios. The results of this study will allow for establishing models for a techno-economic evaluation of the energy in a renewable-source-based smart grid according to usage cycles and systems analysis. It should be mentioned that a techno-economic study is not the aim of this paper and that this will be analyzed in detail in another one. Techno-economic analysis is complementary to this study and has been interesting for researchers, companies, grid managers, and investigators, as presented in [27,32,33].

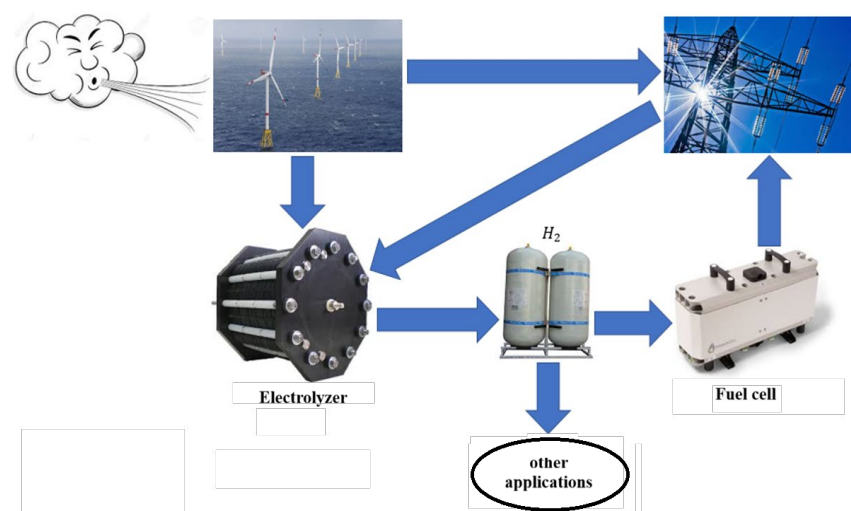


Figure 1. General scheme of studied renewable-source-based smart grid.

The second section of this paper describes the principals of system modeling by using EMR. Then, the model of the different elements of the studied system is presented in the third section, followed by an explanation of the control strategy for different scenarios in the smart grid as well as simulation results. Finally, the conclusion of the paper is presented in the last section.

2. Principles of Modeling of Systems Using EMR

Use of EMR allows one to have a synthetic representation and to deduce the control of systems to perform a systemic study [20]. EMR uses four main elements representing different phenomena, which are based on the following principles for studying any energy system: action and reaction and integral causality [31].

2.1. The Principle of Action and Reaction

Any action of one subsystem on another one imposes a reaction. In this way, the reaction is proportional to the action but not necessarily equal. Also, the product of the action and reaction is always equivalent to an instantaneous power. Figure 2 shows an example of this principle, where the power transferred from subsystem A to subsystem B leads to an action from A to B and a reaction from B to A. The force exerted by A on B is not necessarily equal to the force exerted by B on A in reaction but is simply proportional.

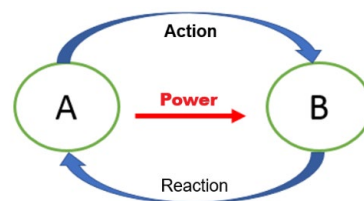


Figure 2. Energy transfer between two elements.

2.2. The Principle of Integral Causality

This principle relies on the relationship between a phenomenon (the cause) that gives rise to another phenomenon (the effect). By its own nature, this relationship can only be unidirectional from the cause to the effect in time, which is the concept of an integral. Figure 3 provides an example to illustrate this principle. Let F be a force applied to the mass m , moving at the velocity V . In this case, the force is the cause of the velocity. Therefore, the velocity cannot appear before the force.

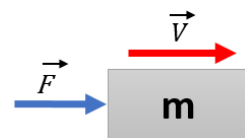


Figure 3. Force applied to a mass.

2.3. Elements of the EMR

To represent mathematical equations corresponding to the physical phenomena of a system, the EMR uses four symbols or elements: source, accumulation, conversion, and coupling elements. Each of these elements is interconnected according to the principle of action and reaction and respects the principle of causality that is explained below.

2.3.1. Source Element

Generators and receivers of energy are the source elements in EMR modelization. They have a single input and a single output, which can be scalar or vector. A source

element is influenced by the reaction of the system to which it is connected. For example, in Figure 4, when the source acts on element X via the action vector, element X reacts via the reaction vector. This latter vector influences the source element. The product of the action and the reaction is always equal to a power.

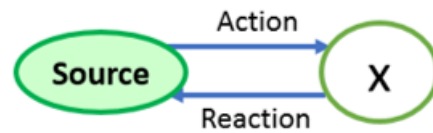


Figure 4. Source element.

2.3.2. Conversion Element

By definition, the equations that govern the conversion element are timeless, and so there is no energy accumulation. The energy is converted either in the same form, which is called monophysics conversion (Figure 5a), or in a different form, which is called multiphysics conversion (Figure 5b).

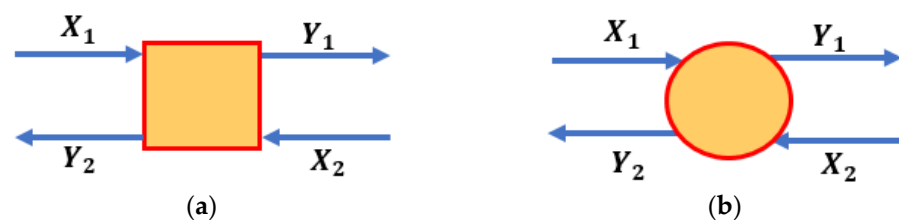


Figure 5. Different forms of conversion element: (a) monophysics. (b) multiphysics.

2.3.3. Storage Element

A storage element naturally has the intrinsic of causality. Therefore, the elements interconnected to it can only follow the imposed causal orientation. A storage element internally stores energy, and so its outputs are integral functions of its inputs to respect integral causality. These inputs and outputs can be scalar or vector. Capacitors, inductors, mechanical inertia, etc., are some examples of storage elements. A storage element is symbolized in Figure 6 by the variables X_1 and X_2 as inputs and the vectors Y_1 and Y_2 as outputs, the latter representing a state quantity of the system.

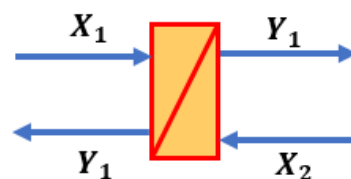


Figure 6. Accumulation element symbol.

2.3.4. Coupling Element

The coupling element is a conversion element that connects several energy conversion chains. Depending on the direction of energy transfer, it can distribute, concentrate, or reorganize the energy. Like the conversion element, it distributes energy without accumulation. Therefore, its inputs and outputs cannot be defined before it is connected to the other elements of the system. This element has several upstream inputs and outputs, as well as several downstream inputs and outputs. When the shape of the energy entering the coupling point differs from that of the outgoing energy, it is called multiphysics coupling (Figure 7a); otherwise, it is called monophysics coupling (Figure 7b).

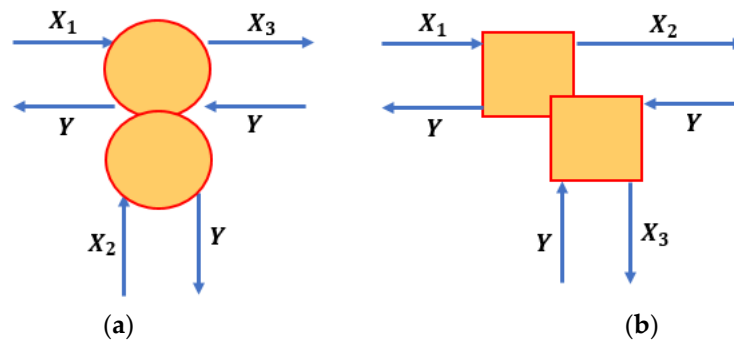


Figure 7. Coupling element: (a) multiphysics; (b) monophysics.

2.4. Principles of Element Association

The fundamental objective is to study a system by taking into account the interactions between its constituent subsystems. Consider a system, S , composed of two subsystems, S_1 and S_2 , schematically represented in Figure 8. With EMR, the connection between S_1 and S_2 is possible if and only if the output of S_1 is equal to the input of S_2 and the input of S_1 is equal to the output of S_2 , that is, $X_1 = X_2$ and $Y_1 = Y_2$. Otherwise, two solutions are used: the permutation of non-causal elements and the merging of accumulation elements [34]. When all the elements of the chain are correctly associated and the representation is correctly performed, the order of the chain is deduced by inverting the latter, as described in the following section.

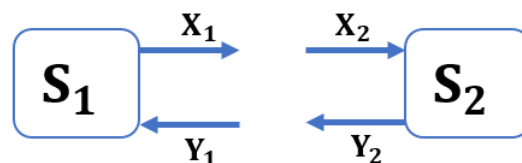


Figure 8. Combination of elements.

2.5. System Inversion Control

The control chain in EMR is constructed by inverting the conversion chain. Thus, the control structure of a system aims to determine the input that should be applied to obtain a desired output; it is therefore considered an inversion of the physical operation of the studied system. Figure 9 shows the principle of the system inversion control where the desired value of the system output ($I(t)$) is applied to the input of the control block, called the setpoint ($I_{ref}(t)$). The resulting output ($V_{ref}(t)$) of the control block then aims to regulate the system input ($V(t)$).

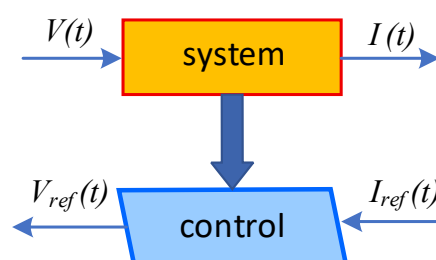


Figure 9. Principle of inversion control.

To invert the conversion system and obtain the control chain, four important steps are required:

- Determination of the adjustment chains;
- Determination of the control chains;
- Determination of the maximum control structure (MCS);
- Deduction of the practical control structure (PCS) [31].

In the following section, the EMR tool is employed for modeling the studied system, and all the steps are explained.

3. Modeling of Elements of Studied System Using EMR

The studied system is composed of the various elements shown in Figure 10, which are modeled in this section using the principal of the EMR tool explained in the last section.

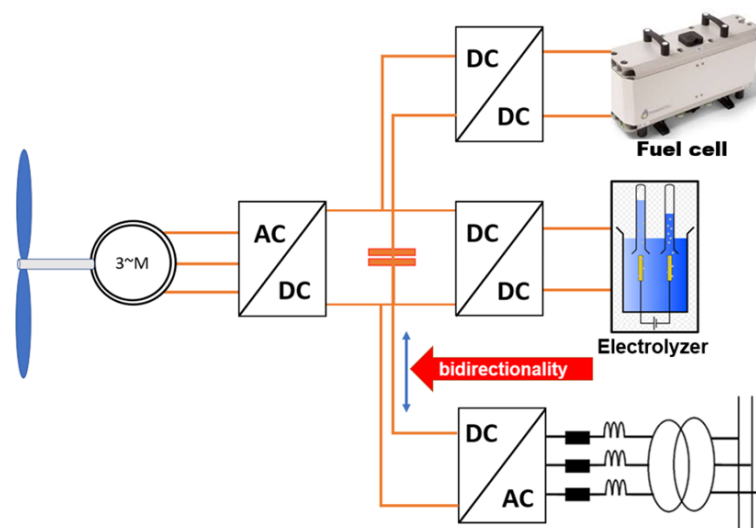


Figure 10. Different elements of studied system to be modeled using EMR.

3.1. Model of Wind Energy Connected to Grid

Figure 11 shows an overview of the wind energy conversion system connected to the grid. In order to deduce the EMR scheme of this conversion chain, it is necessary to understand the physical operation of each subsystem and to name the physical phenomena that describe them. The first rule to follow is that the product of the input and output of each block must be equivalent to an output power, as indicated in the description of each block below.

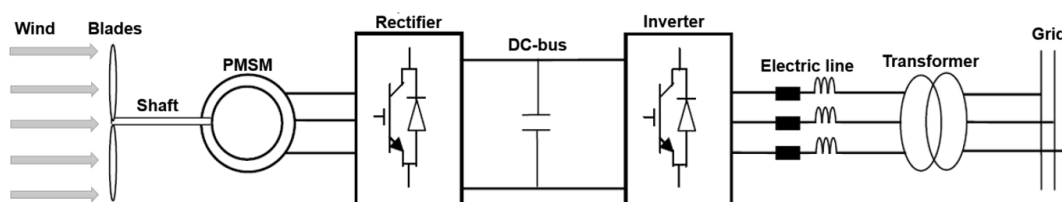


Figure 11. Overview of wind energy conversion system.

3.1.1. Wind

Wind is the source of mechanical energy that acts on the turbine blades to set them in motion. This action on the blades causes them to rotate, generating a force that drives the rotation of the generator's rotor. It is therefore a source of mechanical energy.

3.1.2. Turbine

The turbine ensures transformation of wind speed (mechanical energy) into force (mechanical energy); it is therefore a purely mechanical (monophysical) conversion. This element takes the wind speed as input and reacts with a force that is proportional to the torque developed, as described in Equation (1):

$$\begin{cases} F_{tur} = \frac{1}{2} \rho_{air} \cdot \pi \cdot R_{tur}^2 \cdot V_w^3 \\ T_{tur} = \frac{2 \cdot C_p \cdot F_{tur}}{R_{tur} \cdot \Omega_{tur}} \end{cases} \quad (1)$$

The ratio between the turbine speed and the wind speed (λ) is expressed by Equation (2):

$$\lambda = \frac{\Omega_{tur} \cdot R_{tur}}{V_w} \quad (2)$$

3.1.3. Shaft

The shaft is the connection between the turbine and the generator. Since there is no reduction gear between the two parts, the rotational speed of the generator rotor will be the same as that of the turbine, excluding friction. As this shaft connects two moving masses, it is a storage element. It takes as input the difference in torques developed by the two parts to produce a speed, as described by Equation (3):

$$J_{tur} \frac{d\Omega_{tur}}{dt} + f_v \cdot \Omega_{tur} = T_g - T_{tur} \quad (3)$$

3.1.4. Permanent Magnet Synchronous Machine (PMSM)

It is assumed that the PMSM is used without a speed multiplier, and so the turbine's shaft is directly connected to the generator rotor. This allows the generator to directly convert the mechanical energy supplied by the turbine into electrical energy. It is mentioned that the electrical model of the PMSG is usually presented in the d - q Park model given in Equation (4) [35]:

$$\begin{cases} L_d \frac{di_{sd}}{dt} + R_s \cdot i_{sd} = v_{sd} + e_{gq} \\ L_q \frac{di_{sq}}{dt} + R_s \cdot i_{sq} = v_{sq} - e_{gd} \end{cases} \quad (4)$$

Therefore, the operation of the PMSM is characterized by two physical phenomena: energy conversion and energy accumulation. Both elements convert electrical energy into electrical energy. Thus, they are both represented by monophysical conversion elements, as shown in Figure 12.

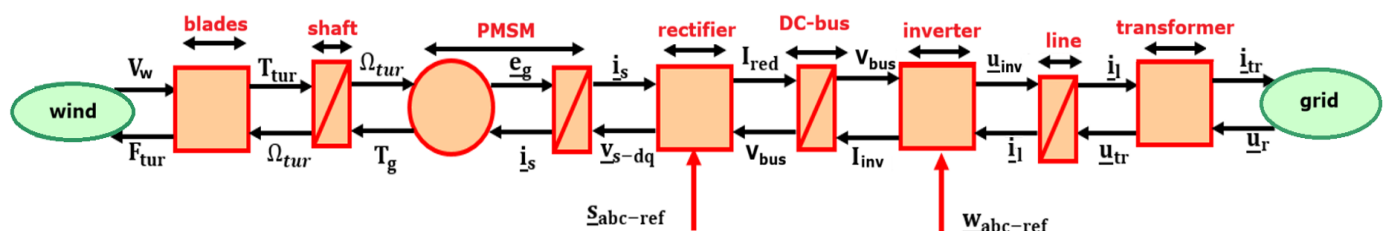


Figure 12. EMR scheme of wind energy conversion chain.

3.1.5. Static Converters

The wind energy conversion system consists of two static converters: a rectifier on the electric machine side and an inverter on the grid side, separated by a DC bus, as shown in Figure 11. The DC bus voltage is calculated based on the difference between the rectified

current and the inverter input current, according to Equation (5). Since the output is the integral of the inputs, the DC bus must be modeled by a storage element:

$$V_{bus} = \frac{1}{C_{bus}} \int (I_{red} - I_{inv}) dt \quad (5)$$

3.1.6. Electric Line

The line connecting the wind energy conversion system to the electrical grid is characterized by an impedance, or more precisely, by its resistance and impedance. Therefore, it acts as a storage element, taking a voltage difference as its input to provide a current at its output.

3.1.7. Transformer

The connection between the wind energy conversion chain and the electrical grid is made via a step-up transformer, which can be modeled by its transformation ratio. So, this transformer acts as a converter.

3.1.8. Electric Grid

The electric grid is considered a bidirectional source where the current can flow in both directions depending on whether the network supplies or absorbs the electric current.

The principal of modeling different elements by EMR allows one to deduce the overall scheme, as illustrated in Figure 12.

$\underline{s}_{abc}$ and $\underline{w}_{ond}$ are PWM control signals which are yields from the control strategy. The control chain principal is explained in Section 4.

3.2. Model of Electrolyzer Connected to DC Bus

As can be seen in Figure 10, the electrolyzer is fed by the DC bus through a DC-DC buck converter. In this study, to simplify the structure, the electrolyzer is presented as the multiphysics conversion element and the storage tanks as the source element receiving the hydrogen. Figure 13a,b show the functional diagram and the EMR model, respectively, between the DC bus and the electrolyzer. The equations describing these diagrams are given in Equation (6):

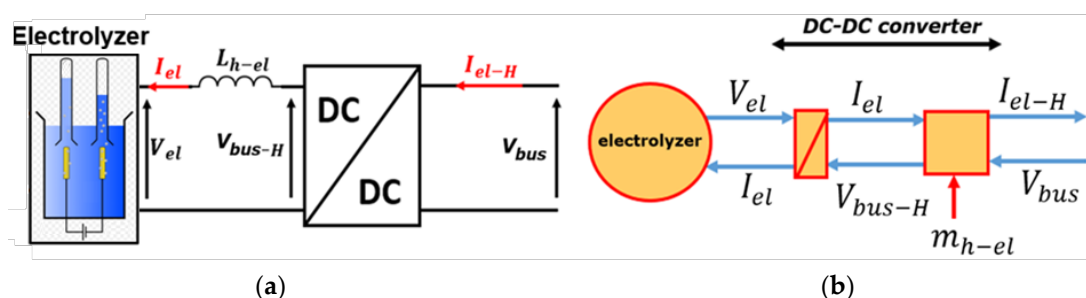


Figure 13. EMR representation of converter–electrolyzer coupling. (a) Synoptic diagram. (b) EMR.

$$\begin{cases} V_{bus-H} = m_{h-el} \cdot V_{bus} \\ L_{h-el} \frac{dI_{el}}{dt} = V_{bus-H} - V_{el} \\ I_{el-H} = m_{h-el} \cdot I_{el} \end{cases} \quad (6)$$

The mathematical model used to describe the dynamic behavior of the electrolyzer is based on physical laws and empirical equations and involves parameters with physical significance. The equations which are used in this model are designed to describe every

parameter of the circuit, including the reversible potential (V_{rev}), as well as the overvoltage resulting from the activation overvoltage (η_{act}) in the anode ($\eta_{act,a}$) and cathode ($\eta_{act,c}$), the ohmic overvoltage (η_{ohm}) and the diffusion overvoltage (η_{diff}) [36–39].

$$\left\{ \begin{array}{l} V_{cell} = V_{rev} + \eta_{act} + \eta_{ohm} + \eta_{diff} \\ V_{rev} = 1.229 - 0.9 \times 10^{-3} \times (T_{cell} - T_0) + \frac{RT_{cell}}{nF} \times \ln \left(\frac{P_{H_2}(P_{O_2})^{0.5}}{P_{H_2O}} \right) \\ \eta_{act} = \eta_{act,a} + \eta_{act,c} \\ \eta_{ohm} = \eta_{ohm,mem} + \eta_{ohm,ele} \\ \eta_{diff} = -\frac{RT}{nF\alpha_a} \ln \left(1 - \frac{j_{cell}}{j_{lim}} \right) \end{array} \right. \quad (7)$$

3.3. Model of Fuel Cell Connected to DC Bus

According to the control strategy, the fuel cell may inject electric power into the DC bus through a DC-DC boost converter. Figure 14a,b show the functional diagram and EMR-based model of the chain between the DC bus and the fuel cell, respectively. The equations describing these diagrams are given in (8):

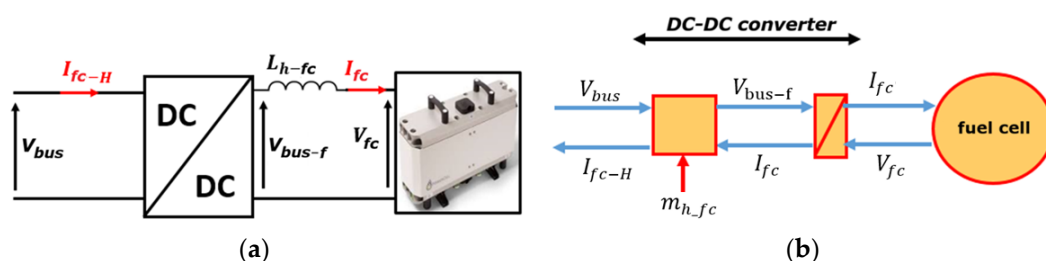


Figure 14. EMR representation of converter–fuel cell coupling. (a) Synoptic diagram. (b) EMR.

$$\left\{ \begin{array}{l} V_{bus-f} = (1 - m_{h-fc}) \cdot V_{bus} \\ L_{h-fc} \frac{dI_{fc}}{dt} = V_{bus-f} - V_{fc} \\ I_{fc-H} = (1 - m_{h-fc}) \cdot I_{fc} \end{array} \right. \quad (8)$$

In this equation,

$$V_{fc} = N_{cell} \cdot V_{cell}, V_{cell} = E_{rev} - \frac{RT}{2F\alpha_{an}} \ln \left(\frac{i}{i_{0,an}} \right) - R_{ion} \cdot i - E \cdot \exp(C \cdot i) \quad (9)$$

E and C are parametric coefficients [40,41,42].

4. Control Strategy and Simulation Results

In the last section, the model of the different parts of the studied system is presented. The macroscopic model based on the EMR tool is useful for developing various strategies and for studying the economical energy management in the smart grid, integrating the renewable energy sources and storage devices. In this manner, some control strategies are explained here, and the control signals of the power converters are generated for each strategy; then, the simulation results are presented.

It should be mentioned that an economic study is not the subject of this paper; however, the results may be used for this purpose. The studied scenarios are based on the production and injection of electrical energy into the grid and/or the production of hydrogen for reconversion to electrical energy or storage. For each scenario, the system is presented and simulated in the Matlab-Simulink environment using the models developed in the previous section. It should be noted that the overall energy conversion chain is composed of a wind energy conversion system, an electrolyzer, hydrogen and oxygen storage tanks, a fuel cell, and the electrical grid, as shown in Figure 1. The studied scenarios are as follows:

1. Production of 100% electricity: it is produced by the wind farm and is injected into the grid.
2. Production of 100% hydrogen by the PEM electrolyzer, which is fed by the wind farm and the electric grid, with a condition on the electricity purchase cost.
3. Hydrogen production and then electricity injection into the grid using a wind farm and fuel cells.
4. Hydrogen production and then electricity injection into the grid using a wind farm, a fuel cell, and the EPEX SPOT network, with a condition on the electricity price.

4.1. 100% Electricity Production by Wind Farm and Injection into Grid

As presented in Figure 15, in this scenario, the electric grid can absorb all of the wind farm's electrical energy production. Therefore, the fuel cell and the electrolyzer are not used, and the wind turbine is controlled with an MPPT strategy [35].

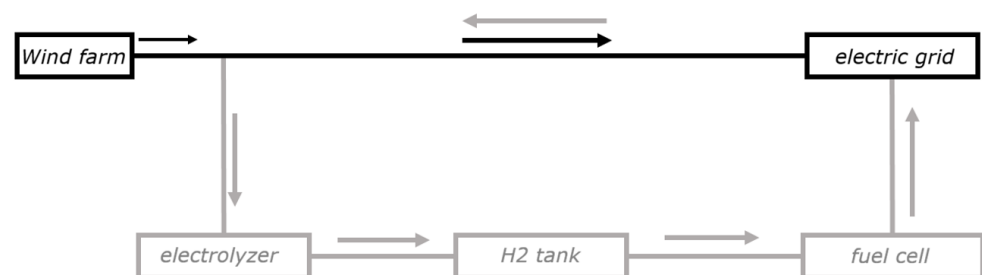


Figure 15. First scenario: 100% electricity production by wind farm.

To evaluate the technical performance of this scenario, the model was implemented in the MATLAB Simulink environment. For all cases, the wind speed profile shown in Figure 16 was used, where the wind turbine develops a maximum power of 5 MW for a wind speed of 11.55 m/s.

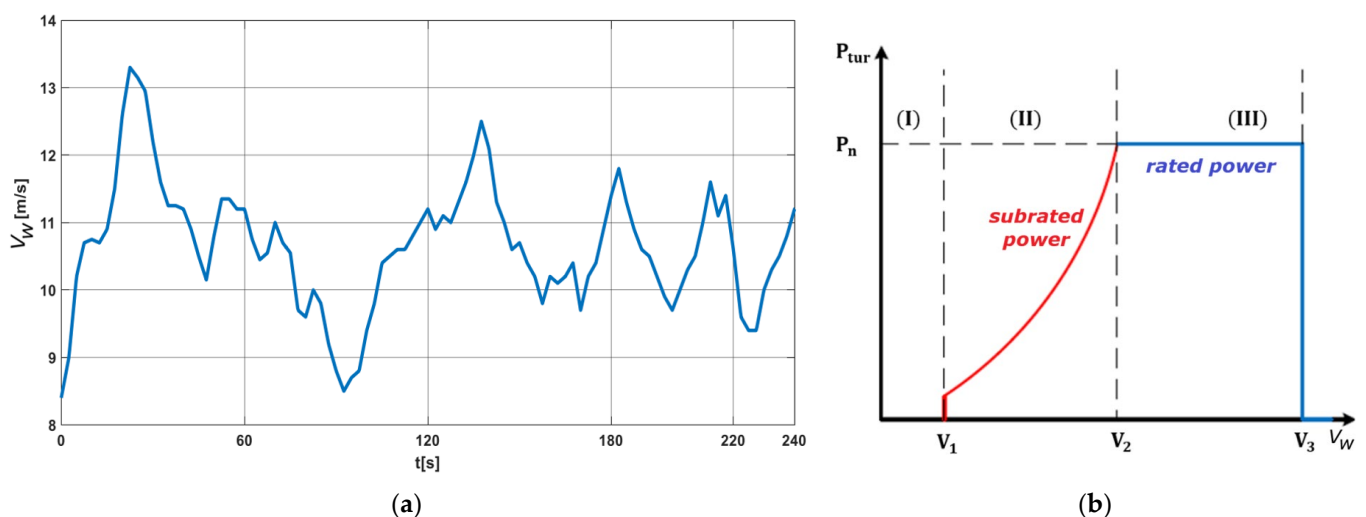


Figure 16. (a) Wind speed. (b) Operating limits of variable-speed wind turbine.

4.1.1. Control of Wind Energy Conversion System

After developing the EMR diagram of the overall system, the EMR model should be reversed to obtain a practical control chain. The objective of the control of the wind energy conversion system is the extraction of the maximum power from the wind and the injection of the demanded reactive energy into the grid. Therefore, two specific constraints must be taken into account: controlling the speed of the PMSM and controlling the DC

bus voltage. To achieve these objectives, two degrees of freedom at the static converters (rectifier and inverter) are relied on. This yields $\underline{s}_{abc}$ and $\underline{w}_{abc}$ switching signals for the converters. The system can thus be divided into two parts, as shown in Figure 17. Subsequently, the four steps leading to the practical control structure are applied to each part, as described below.

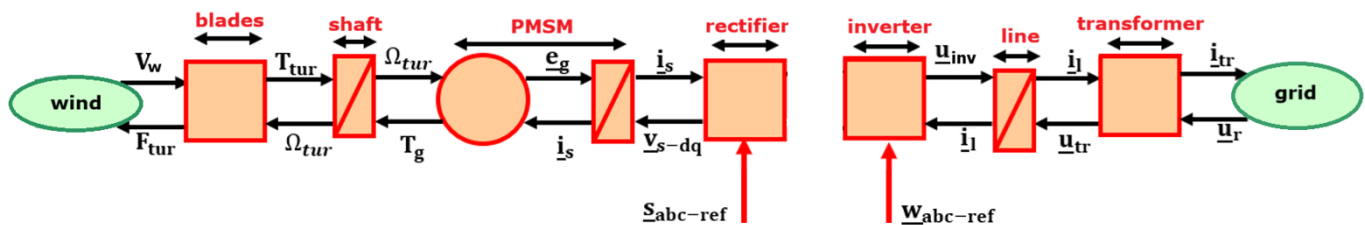


Figure 17. Division of the EMR diagram of the wind energy conversion chain.

4.1.1.1. Determination of the Adjustment Chains

Determination of the control chain depends on the system and is done through cause and effect. In this case, the control chains are constructed by the paths that run from the control vectors to the sources; that is, from $\underline{s}_{abc}$ and $\underline{w}_{abc}$ to F_{tur} and i_{tr} , respectively, which gives the control chains shown in Figure 18.

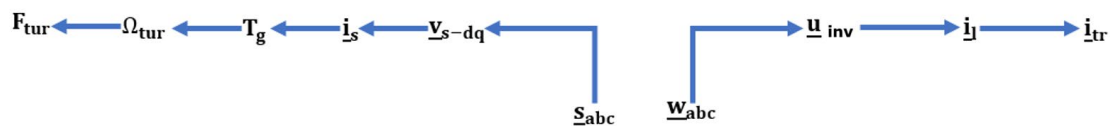


Figure 18. Determination of the control chain.

4.1.1.2. Determination of the Control Chain

The control chains are obtained by inverting the control chains, and the quantities become reference quantities, as shown in Figure 19.

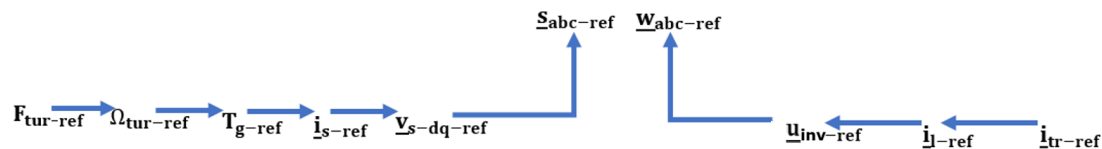


Figure 19. Control chain of wind energy conversion system.

4.1.1.3. Determining the Maximum Control Structure (MCS)

This is the chain obtained by inverting all the elements of the conversion chain one by one. No simplification is made at this stage, as shown in Figure 20.

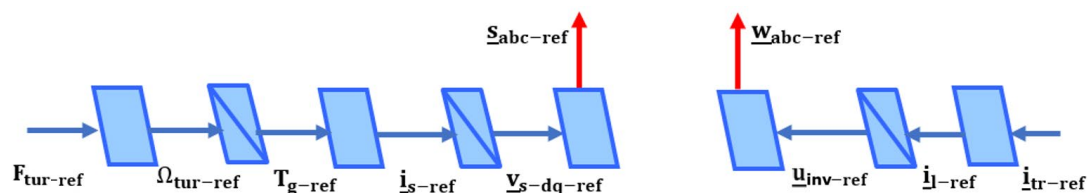


Figure 20. Maximum control structure of wind energy conversion system.

The reference vectors are derived from the conversion chain data, except for the two input vectors on the left and right, which come from the global strategy given in the specifications. These strategies are written in the blocks shown in Figure 21. The vectors that

do not appear in the control chain are considered disturbances that have no significant effect. The parameters used by these strategy blocks are calculated in the following section.

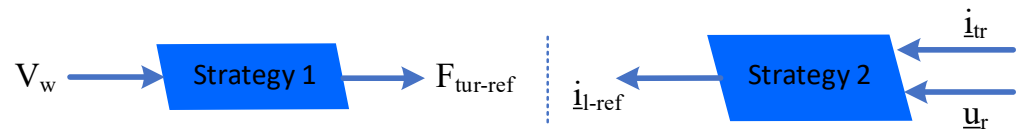


Figure 21. Strategies of global control.

The overall wind energy conversion scheme with the maximum control structure is presented in Figure 21. As described in the following section, a final step is used to simplify the structure.

4.1.1.4. Deducing the Practical Control Structure

This final step consists of the objective simplification of the SMC. This is done based on strategic and technological choices, which degrade the control system but also facilitate its implementation. For example, the transformer and blade conversion blocks are merely multiplication factors. Their inversions are also numerical factors. Therefore, their presence has no particular significance in the control structure. Their numerical values are then integrated into other blocks. The simplified diagram is presented in Figure 22. In the following section, the equations governing these controls are deduced.

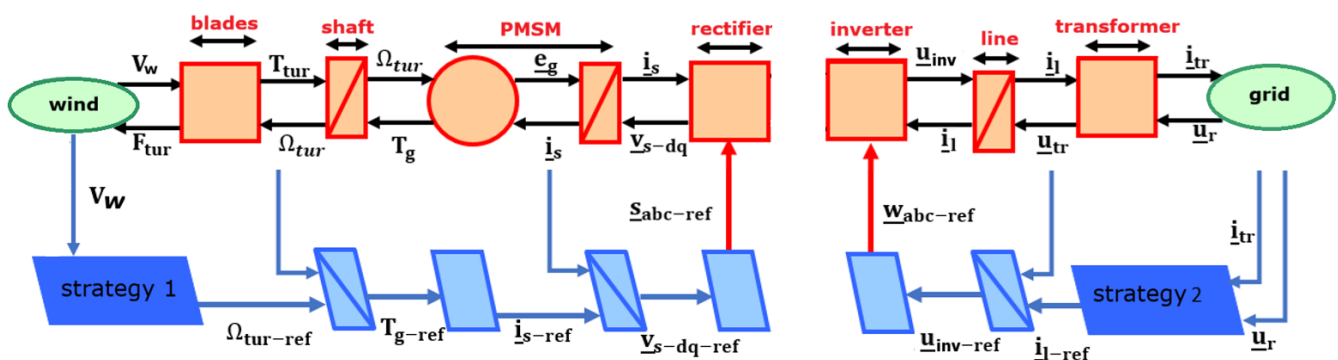


Figure 22. Conversion chain with practical control structure.

4.1.1.5. Control Strategy

The overall control, also called the control strategy, is developed based on the control requirements and is tailored to the available degrees of freedom. In our case, the aim is to control the speed of the PMSM in order to extract maximum power from the wind, on the one hand, and to control the reactive power injected into the electrical grid, on the other.

The initial demand consists of extracting maximum power from the wind with the turbine. This leads to optimal use of the turbine. Therefore, the first strategy is used to obtain the reference rotation speed, which yields Equation (10):

$$\Omega_{tur_ref} = \frac{\lambda_{opt} \cdot V_w}{R_{tur}} \quad (10)$$

λ_{opt} is deduced from the characteristic curve of the power coefficient as a function of the specific speed for different values of the pitch angle (β).

In the control chain, T_{g-ref} and $\underline{v}_{s-dq-ref}$ are calculated from the speed and current controllers, respectively. Also, the reference current ($\underline{i}_{s-ref}$) is calculated by:

$$i_{s-q-ref} = \frac{2}{3P\phi_f T_{g-ref}} \quad (11)$$

In order to avoid demagnetization of the permanent magnets due to the armature reaction along the d-axis and to reduce joule losses in the machine, the current component along the d-axis is minimized ($i_{s-d-ref} = 0$). Finally, the rectifier is controlled by inverting the rectifier conversion block. This is a direct inversion; therefore, a monophysical conversion element, as shown in Figure 23, is used. $\underline{s}_{abc-ref}$ is the vector of control signals performed just after the inversion.

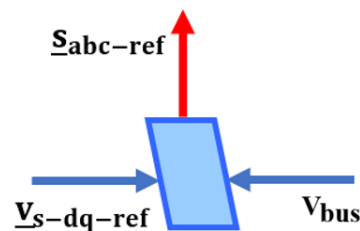


Figure 23. Rectifier block inversion.

The second control strategy should include generation of the reactive power and DC bus voltage references. This allows us to obtain the two components of the vector $\underline{i}_i-ref$, namely, $i_{i-1-ref}$ and $i_{i-2-ref}$, which are calculated from the DC bus and reactive power regulators, respectively. Finally, inverter control is achieved by inverting the inverter's conversion block. This is a direct inversion and, thus, a monophysical conversion element, as shown in Figure 24. $\underline{w}_{abc-ref}$ is the vector of control signals immediately after inversion. It is composed of three reference signals for PWM, as shown in Equation (12):

$$\underline{w}_{abc-ref} = [w_{a-ref}, w_{b-ref}, w_{c-ref}]^T \quad (12)$$

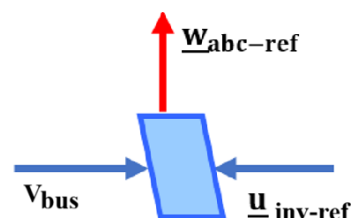


Figure 24. Inversion of the inverter block.

4.1.2. Simulation Results

After presenting the method for deducing the control structure using EMR, the system with the developed control chain is simulated in the MATLAB-Simulink environment. Figure 25 shows the simulation results of the wind energy conversion system.

Figure 25a shows the power produced by the wind turbine. Figure 25b shows the rotation speed. Figure 25c,d show the reactive power generated and the DC bus voltage, respectively. It can be seen that the measured variables follow the references well. It can also be seen that the shaft speed and active power vary with the wind speed. Despite the variation in wind speed, the DC bus voltage remains constant, and the power is controlled according to the setpoint.

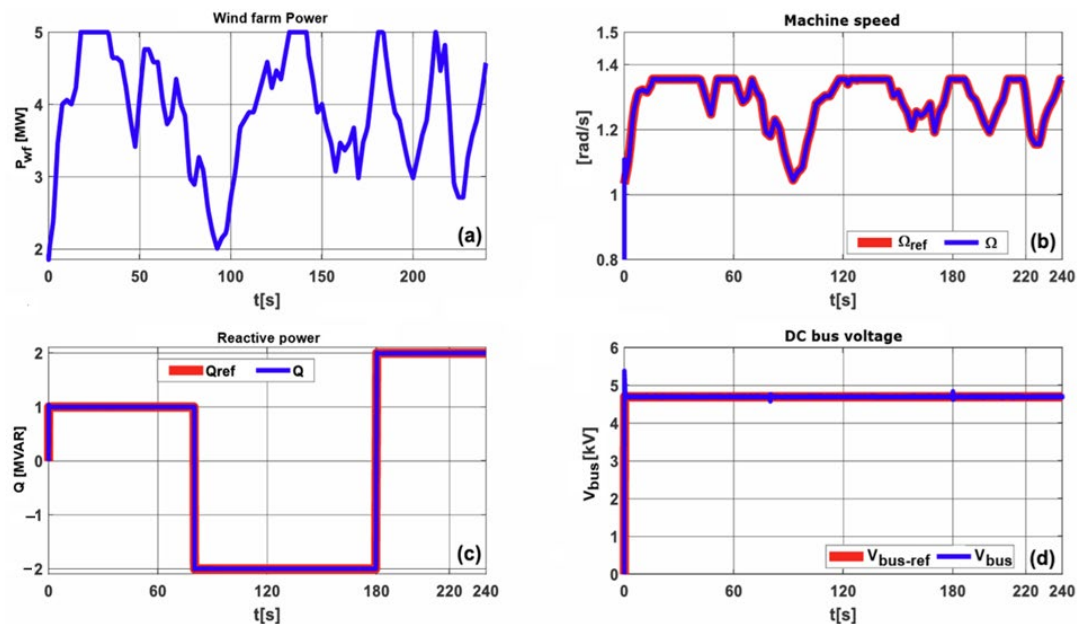


Figure 25. PMSM speed and wind turbine power.

4.2. Production of 100% Hydrogen by the PEM Electrolyzer Which Is Fed by the Wind Farm and the Electric Grid, with a Condition on the Electricity Purchase Cost

In the green city with a smart grid, production of green hydrogen may be one of the objectives of the grid manager [39,40,42]. In this case, a scenario based on hydrogen production through an electrolyzer, which is fed not only by the wind farm but also by the electric grid when the price of the electricity is too low, is studied. Indeed, the electrolyzer is fed by the grid when the economic benefits are considerable. For this purpose, a condition based on the price of electricity on the market is considered for participation in the grid (EPX SPOT) to feed the electrolyzer. To carry out the simulation, the electricity price is extracted over one day with a sampling period of 15 min from EPX SPOT. Since the purpose of this part is management of the system's energy for the different scenarios, the time interval of the price table is compacted to the same interval of the wind profile, namely, 240 s. In this scenario and as presented in the flowchart of Figure 26, it is assumed that the electrolyzer is fed solely by the wind farm as long as the electricity purchase price is higher than €40/MWh. Otherwise, electricity is purchased from the grid to complete the wind farm power for feeding the electrolyzer with its rated power. This scenario allows us to calculate the purchased electrical energy and the quantity of hydrogen produced, which we need to conduct an economic analysis of the scenarios. In the studied system, twelve 420 kW electrolyzers with the configuration in Figure 27 are considered. Parameters of the 420 kW electrolyzers are presented in Table 1. The voltage and current at the operating point (420 kW) are around 620 V and 675 A, respectively. Therefore, the nominal supply voltage and current of the electrolyzer pack will be around 1.9 kV and 2.7 kA, respectively.

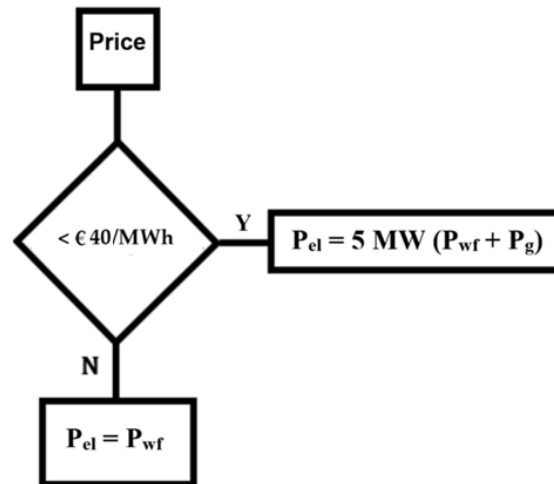


Figure 26. Flowchart of energy management strategy for second scenario.

Table 1. Parameters of the 400 kW electrolyzer.

Parameter	Value
Power [kW]	420
Current [A]	675
Voltage [V]	620
Current Density [A/cm ²]	1
Production [m ³ /h]	93

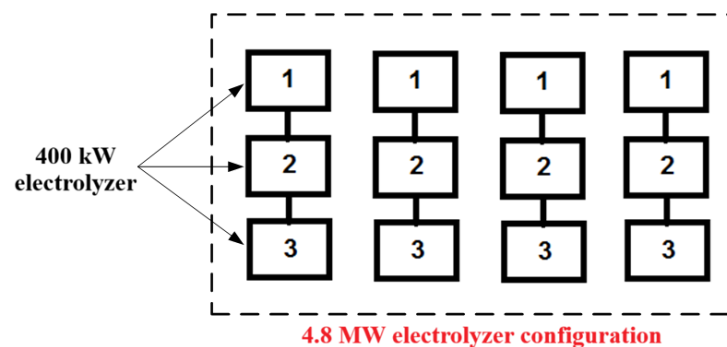


Figure 27. Electrolyzer scaling configuration.

As can be seen in Figure 10, the electrolyzer is connected to the DC bus, whose voltage is set to 4.7 kV, by a DC/DC converter. To generate the control signal for this converter, the system inversion principle with the EMR is used.

4.2.1. Control of the Hydrogen Production Chain

To develop the control of this system, the same principle as the wind control chain is followed, where the EMR diagram is inverted to construct the control chain, and so the different stages are not explained again here. To simplify the structure, the electrolyzer is presented as the multiphysics conversion element and the storage tanks as the source element that receives hydrogen. The storage system is connected to the conversion chain at the DC bus, which allows direct use of the DC power. However, the DC/DC converter is used to adapt the DC bus voltage level to the electrolyzer supplying the voltage level (Figure 13). Figure 28 shows the control strategy developed for the electrolyzer. The upper figure shows the EMR layout, and the lower one shows a block diagram of the electrolyzer control strategy. It is clear that the electrolyzer will not permanently operate at its nominal power due to the variable and intermittent nature of the wind and price of the electricity.

This allows us to verify the PEM electrolyzer's ability to respond when it is powered by a variable energy source.

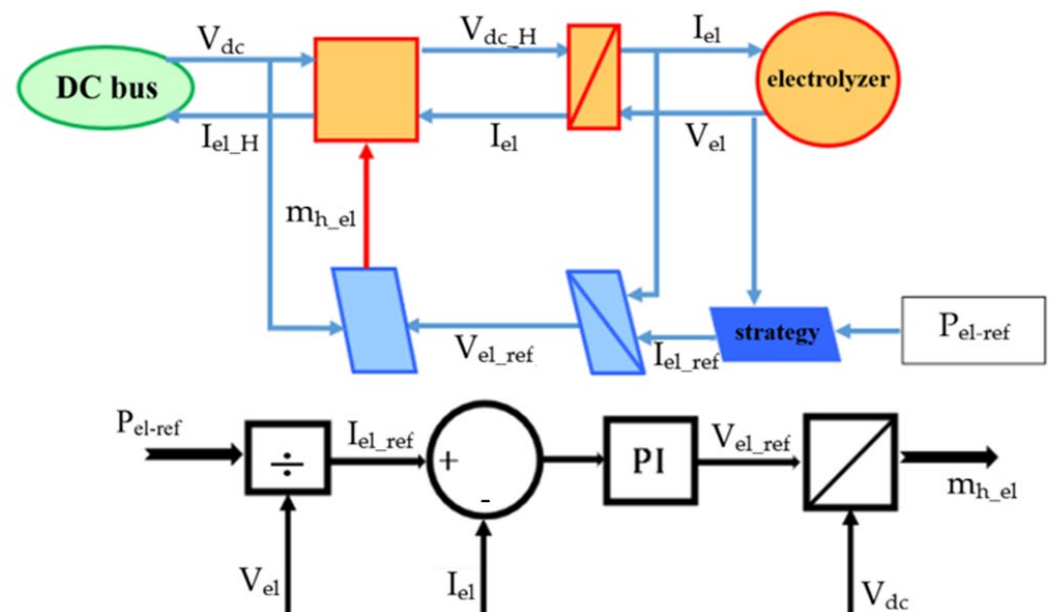


Figure 28. Electrolyzer control strategy.

4.2.2. Simulation Results

For this part of this study, the electricity price curve taken from the European EPEX SPOT electricity market is represented in Figure 29a, where the fixed threshold condition is shown with the red line. Figure 29c shows the power provided by the wind farm to supply the electrolyzer. It is seen that this power profile is variable and cannot power the electrolyzer at its nominal power during the process. Thus, grid production is used, but only when its cost is less than €0.04. Otherwise, the electrolyzer is fed only by the wind power. This difference is indeed observed in the current absorbed by the electrolyzer, as shown in Figure 29b,d, which presents the hydrogen production volume.

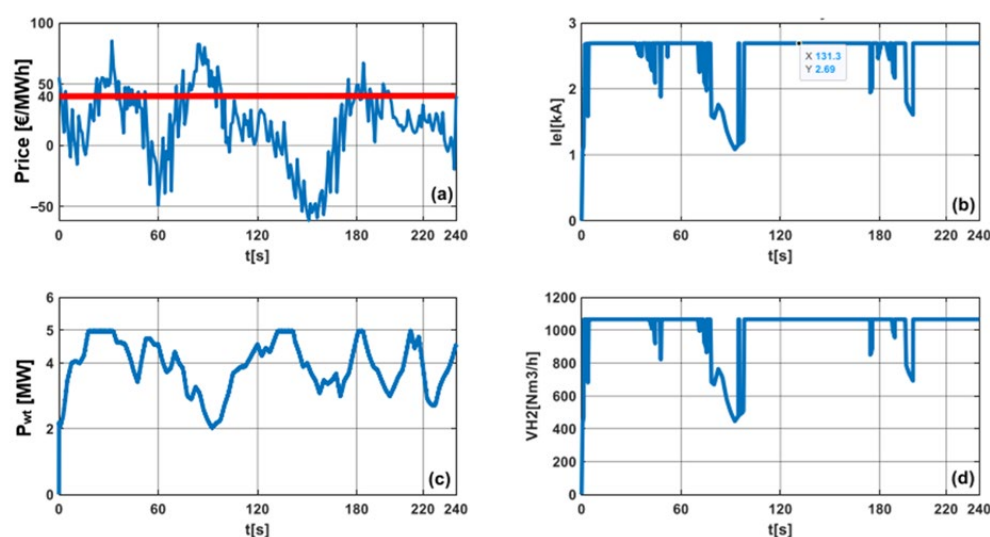


Figure 29. Wind speed and electricity purchase price. (a) Electricity price. (b) Current of electrolyzer. (c) Power of wind farm. (d) Hydrogen production volume.

Figure 30 presents the different power outputs. The blue curve represents the wind farm's contribution, the red curve shows the contribution of the electricity grid (EPEX

SPOT), and the yellow curve represents the power absorbed by the electrolyzer. It can be seen that the electrolyzer is not always supplied at its nominal power. This is due to the fact that the price condition is not always met. These figures demonstrate the success of the control technique implemented for this scenario.

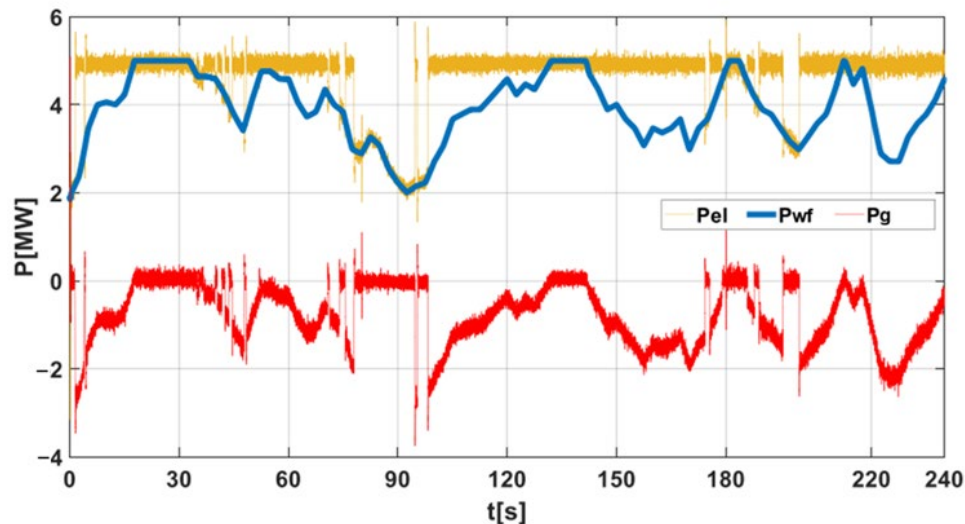


Figure 30. Power distribution for hydrogen production.

4.3. Hydrogen Production and Electricity Injection into the Grid Using a Wind Farm and Fuel Cells

For this scenario, shown schematically in Figure 31, it is assumed that a constant power of 3.5 MW should be injected into the grid with the assistance of the fuel cell. Therefore, the excess production of 3.5 MW from the wind farm is used to produce hydrogen.

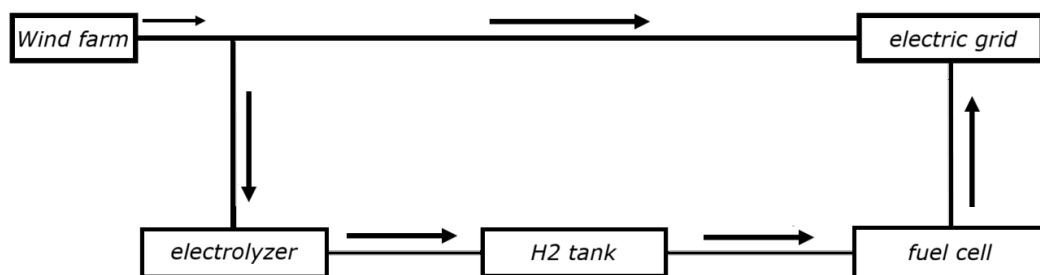


Figure 31. Mixed production of electricity and hydrogen with the participation of a fuel cell.

To supply 3.5 MW of power to the grid, the production of the wind farm is used at first. When it cannot produce enough energy, it is then supported by the fuel cell, which supplies the lack of energy by converting the hydrogen produced by the electrolyzer into electricity. Note that any surplus production from the wind farm will be used to produce hydrogen, and in this scenario, no electricity is purchased from the grid. This scenario is shown schematically in the flowchart in Figure 32. In this figure:

1. When the wind farm's production equals the grid's demand, 3.5 MW, the electrolyzer and the fuel cell do not operate. All of this production is injected into the grid.
2. If the wind farm's production exceeds the grid's demand, the excess electrical energy is used to produce hydrogen via the electrolyzer and store it.
3. When the wind farm's production is lower than the grid's demand, the fuel cell transforms the hydrogen stock into electricity to supplement the wind farm's production and meet the grid's demand.

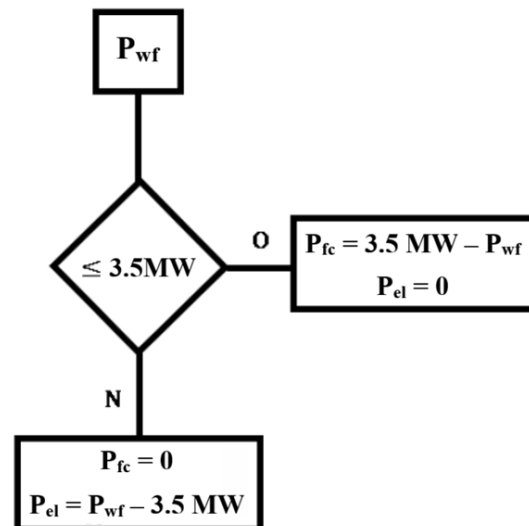


Figure 32. Energy management flowchart for scenario 3.

It is assumed that the rated power of the fuel cell pack and electrolyzer pack is equal to 1.5 MW, and that the fuel cell pack and electrolyzer pack are composed of four 400 kW units, according to the configuration of Figure 33. The voltage and current of the fuel cell at the operating point (400 kW) are 1.33 kV and 300 A, respectively.

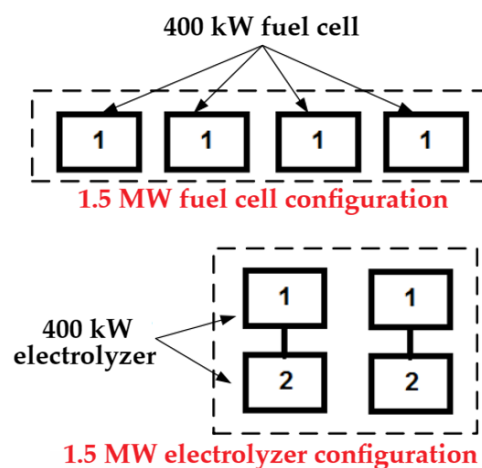


Figure 33. Fuel cell and electrolyzer scaling configuration.

As can be seen in Figure 13, the fuel cell is also connected to the same DC bus as the electrolyzer, whose voltage is set to 4.7 kV. To generate the control signal of the converter connected to the fuel cell, the system's inversion principle is used for the fuel cell, like the electrolyzer, and so only the control of this converter is explained as follows.

4.3.1. Control of the Fuel Cell Chain

Figure 14 shows the scheme and the EMR of the coupling between the DC bus and the fuel cell, respectively. A DC/DC boost converter is used to connect the fuel cell to the DC bus, and an inductor is added between the converter and the fuel cell to smooth the current produced by the latter. Figure 34 shows the control strategy for generating m_{h_fc} .

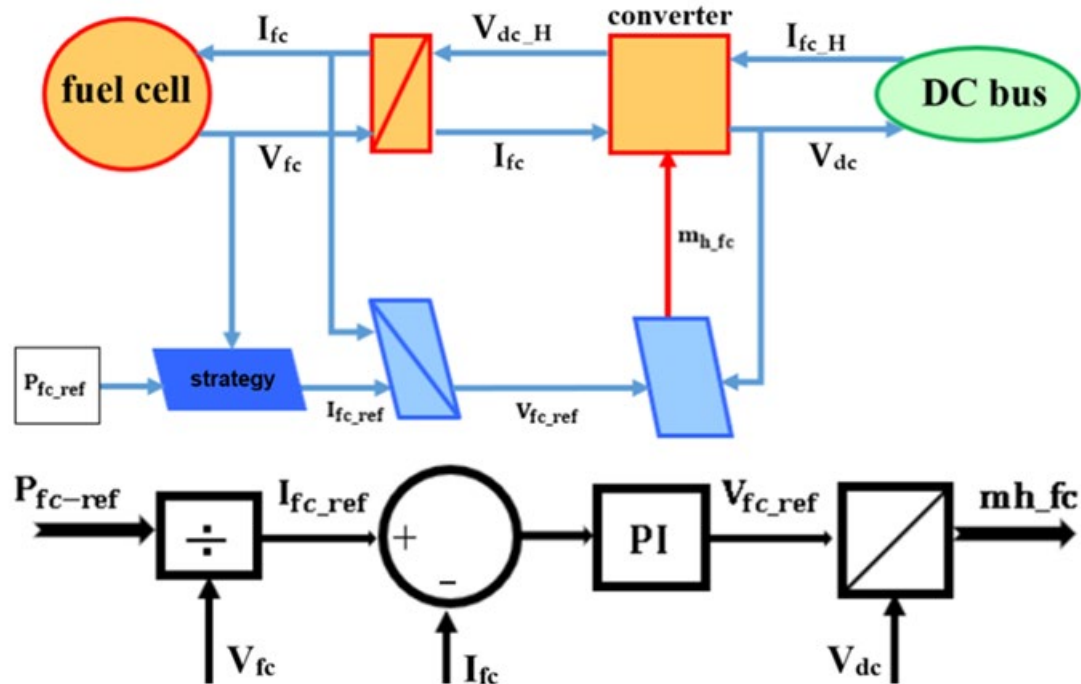


Figure 34. Fuel cell control strategy.

For the fuel cell-side control chain, the parameters are calculated from Equation (13):

$$\begin{cases} I_{fc_ref} = \frac{P_{fc_ref}}{V_{fc}} \\ V_{fc_ref} = CONT_{fc}(I_{fc_ref} - I_{fc}) \\ m_{h_fc} = \frac{V_{fc_ref}}{V_{dc}} \end{cases} \quad (13)$$

P_{fc_ref} is the power requested from the fuel cell calculated from Figure 32. $CONT_{fc}$ is the fuel cell-side PI voltage controller.

4.3.2. Simulation Results

This developed model for the fuel cell was implemented in MATLAB, and the results are presented in Figures 35 and 36. Figure 35 shows the power curves of the units that were used in this scenario. The power applied to the electrolyzer is shown in blue, the power supplied by the wind farm is shown in red, the power supplied by the fuel cell is exposed in green, and the power injected into the grid is shown in purple.

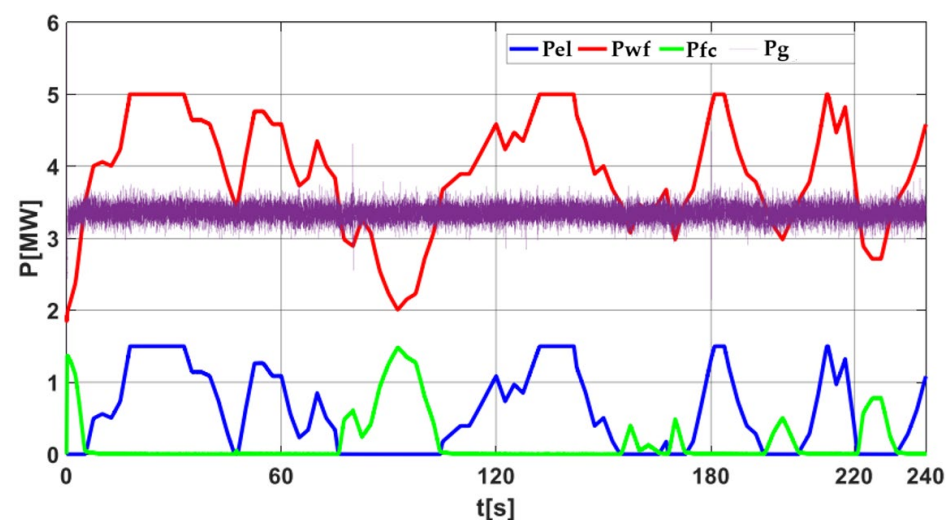
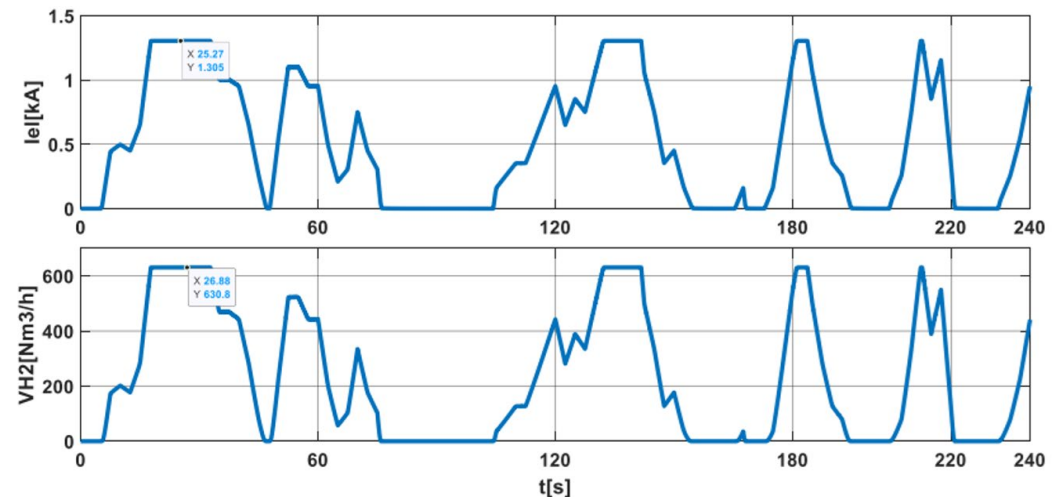


Figure 35. Powers of different units.

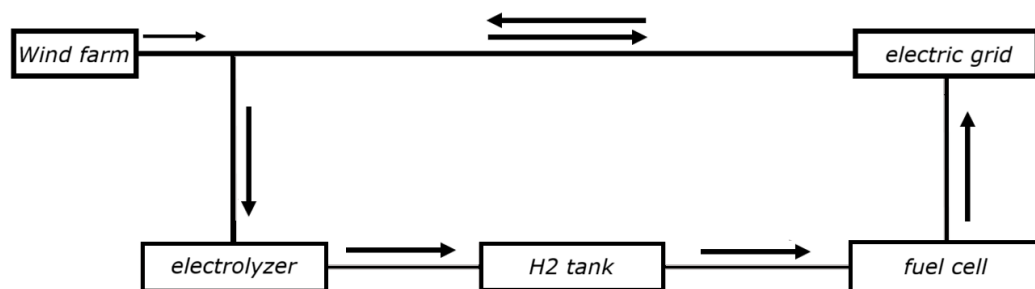
The goal is to meet the grid's permanent demand of around 3.5 MW, where the priority is given to the wind farm. When the grid's input power falls under 3.5 MW, the fuel cell is used to supplement the demand, as seen in Figure 36.

**Figure 36.** Electric current of electrolyzer and hydrogen production volume.

We can clearly observe this complementarity between the power sources to meet the electricity grid's demand. However, we also see that the entire output of the wind farm is used, thereby avoiding wasting the wind farm's output when it exceeds the electrolyzer's demand. The upper part of Figure 36 shows the curve of the electric current absorbed by the electrolyzer during the process. The lower part shows the curve of the hydrogen production volume flow. We can see that the two curves are proportional. This justifies the direct relationship between these two parameters.

4.4. Hydrogen Production and Electricity Supply to the Grid Using Wind Power, Fuel Cells, and the EPEX SPOT Network, Under Electricity Price and Power Conditions

This scenario involves powering an electrolyzer with the optional obligation to supply electricity when the demand is high. The diagrams are shown in Figure 37. Figure 38 presents the operating diagram for this last scenario, for which the primary condition is to purchase electricity on the EPEX SPOT market when the cost per MWh is less than 40€. Also, it is necessary to inject a constant electrical power of 5 MW to the electricity grid when the demand is high, assumed here to be between 180 s and 220 s.

**Figure 37.** Hydrogen production and grid service with fuel cell use, under electricity price and power conditions.

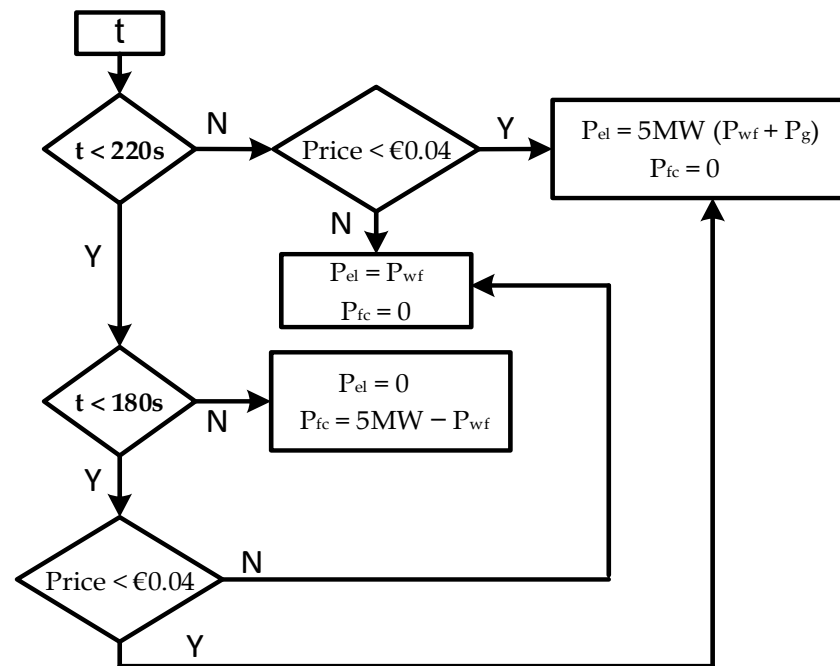


Figure 38. Flowchart of fourth scenario.

The entire scenario is explained as follows. Before 180 s and after 220 s, if the electricity cost is less than 40 €/MWh, it is purchased to supplement the wind farm's production to produce hydrogen. Here, there is no obligation to inject electricity into the grid; therefore, the fuel cell is not commissioned. However, if the electricity cost is greater than 40 €/MWh, it is not purchased, and hydrogen is produced solely by wind power. The fuel cell is still not commissioned. Between 180 s and 220 s, the grid demand is assumed to be substantial (5 MW), so the electrolyzer is not powered, and so the fuel cell supplements the wind power generation.

The curves in Figure 39 show, in the upper and lower sections, the electrical current absorbed by the electrolyzer and the volume flow rate for hydrogen production, respectively. Indeed, we observe perfect consistency between the previous interpretation of the scenario and the hydrogen production curve. Hydrogen is produced throughout the entire process except between 180 and 220 s, which corresponds to the interval of high demand on the grid, where the system is forced to supply 5 MW at full capacity.

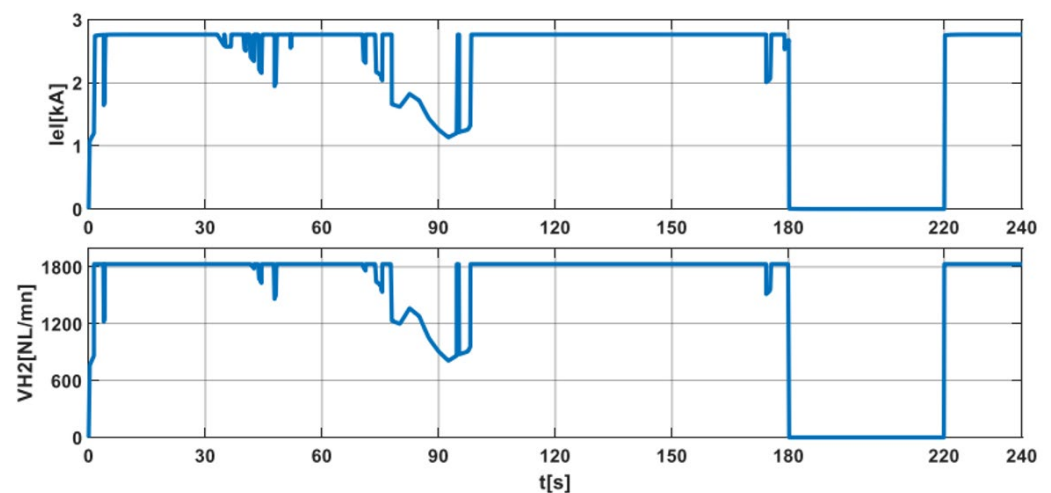


Figure 39. Current of electrolyzer and hydrogen volume.

Figure 40 shows the electricity price and the power inputs involved in this scenario.

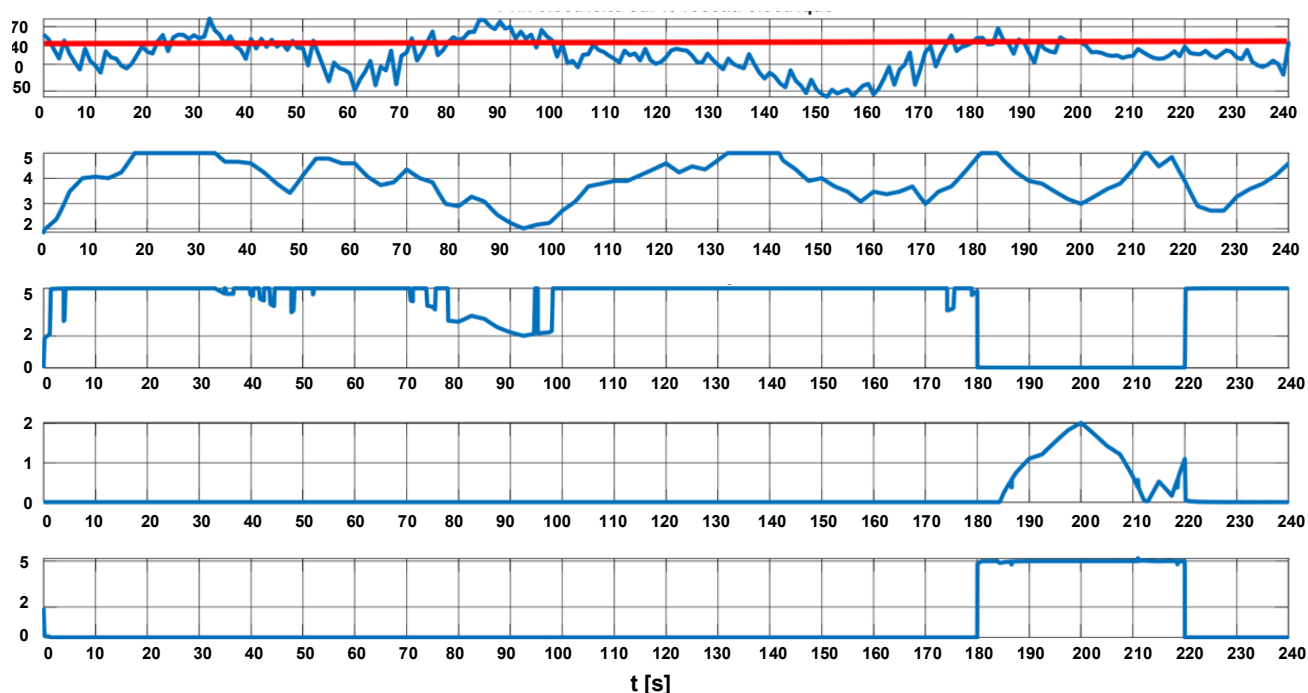


Figure 40. Simulation results for hydrogen production and network service using a fuel cell, depending on electricity tariffs.

Table 2 presents the results of hydrogen production and grid service in this scenario for different intervals. In the interval [4 s–18 s], the wind farm's production is lower than the electrolyzer's rated power, $P_{elz_n} = 5$ MW, and the electricity price on the grid is less than 40 €/MWh. Therefore, purchasing from the electricity grid is preferred over converting the hydrogen stock via the fuel cell. Thus, the electrolyzer is powered at its nominal power using the wind farm's production and electricity purchased from the electricity grid. In the interval [20 s–30 s], the wind farm's production is equal to the electrolyzer's nominal power, and the electricity price on the grid is greater than 40 €/MWh. Therefore, there is no purchase of electricity from the electricity grid and no conversion of the hydrogen stock via the fuel cell either, since the wind farm alone can operate the electrolyzer at its nominal power. In the interval [80 s–90 s], the wind farm's production is lower than the electrolyzer's nominal power, and the electricity price on the grid is higher than 40 €/MWh. It is then powered solely by the wind turbine's production, which is less than 5 MW during this interval. There is also no conversion of the hydrogen stock via the fuel cell because there is no demand from the electricity grid during this interval. Finally, in the interval [180 s–220 s], there is an obligation due to the specifications to supply electricity to the electricity grid during this period. The fuel cell is then used to supplement the missing power from the wind farm's production in order to supply 5 MW to the electricity grid.

Table 2. Results of hydrogen production and grid service with fuel cell use subject to electricity tariffs for different intervals.

t [s]	P_{wf} [MW]	Price [€/MWh]	P_{fc} [MW]	P_g [MW]	P_{elz} [MW]
4–18	$<P_{elz_n}$	<40	0	$P_{elz_n} - P_{wf}$	$P_{wf} + P_{fc}$
20–30	$=P_{elz_n}$	>40	0	0	P_{wf}
80–90	$<P_{elz_n}$	>40	0	0	P_{wf}
180–220	$<P_{elz_n}$	>40	$5 - P_{wf}$	$P_{wf} + P_{fc}$	0

220–230	$<P_{elz_n}$	<40	0	$P_{elz_n} - P_{wf}$	$P_{wf} + P_{fc}$
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The studied scenarios are some examples of different scenarios in smart grids for which energy management is developed. They can be compared according to predefined criteria, such as economic benefits. For this purpose, an economic model must be presented with full details as well as specific conditions and assumptions. For example, the levelized cost of energy (LCOE), which is the most widely used metric in the literature, can be used. This model represents the net present value of the unit cost of energy over the lifetime of a production asset [43]. It takes into account the initial investment cost, annual operating costs and the annual energy production of the system. It is commonly considered an indicator of the average price of electricity that the generating asset must receive in the market to break even throughout its lifespan.

5. Conclusions

This paper studies energy management in a smart grid composed of a wind farm, an electrolyzer, a fuel cell, and an electrical grid. Four scenarios were evaluated based on electricity injection into the grid and/or hydrogen production. To study these scenarios, different elements of the system were modeled by using an energetic microscopic representation (EMR) tool. It was shown that complex multiphysics energy systems can be simply modeled by EMR based on action–reaction principles and energy exchange between system components. Indeed, the difference in the dynamics of various energy sources and storage systems between the subsystems can be taken into account by using an EMR modeling tool. It was proved that energy management can be more easily analyzed by this tool in smart grids. The different scenarios were implemented in the MATLAB-Simulink environment, and the simulation results are presented. The scenarios were based on energy production and/or economic considerations. An advantage of this study is that the energy sources and storage devices can be optimally sized, which prevents oversizing them. Furthermore, smart grids can be improved to maximize the benefits of renewable energy production by studying these scenarios.

To complete this study and to compare the scenarios, an economic analysis, for example, one based on the LCOE (levelized cost of energy), may be carried out. This would allow for the development of an optimal energy management policy, which could significantly reduce operational costs while improving renewable energy utilization and system reliability.

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Abbreviations

The following abbreviations are used in this manuscript:

EMR	Macroscopic Energy Representation
EMSs	Energy Management Systems
MCS	Maximum Control Structure
PCS	Practical Control Structure
PMSM	Permanent Magnet Synchronous Machine
LCOE	Levelized Cost of Energy

Nomenclature

ρ_{air}	Area density equal to 1.22 [kg/m ³];
C_p	Unitless power coefficient equal to 0.593;
R_{tur}	Turbine radius [m];
T_{tur}	Mechanical torque developed by turbine [N.m];
V_w	Wind speed [m/s];
Ω_{tur}	Turbine rotational speed [rad/s];
J_{tur}	Moment of inertia of turbine [kg.m ²];
P_{tur}	Aerodynamic power of turbine;
P	Number of pole pairs of PMSM;
Φ_f	Flux of PMSM's permanent magnets;
f_v	Viscous friction coefficient of generator [W];
T_g	Electromechanical torque of PMSM [N.m];
v_{ds}, v_{qs}	d-q axis voltages of generator;
i_{ds}, i_{qs}	d-q axis currents of generator;
L_d, L_q	d-q axis inductances;
R_s	Stator phase resistance;
e_g	Electromotive force of PMSM;
V_{bus}	DC bus voltage;
C_{bus}	Capacitor of DC bus;
I_{red}	Rectifier current;
I_{inv}	Inverter current;
$\underline{i}_l$	Electric line current;
$\underline{u}_{tr}$	Phase-to-phase transformer voltage;
$\underline{u}_r$	Phase-to-phase grid voltage;
V_{rev}	Reversible potential of electrolyzer;
η_{act}	Activation overvoltage;
$\eta_{act,a}, \eta_{act,c}$	Overvoltage in anode and cathode of electrolyzer;
η_{ohm}	Ohmic overvoltage;
η_{diff}	Diffusion overvoltage;
F	Faraday constant;
R	Gas constant;
T_{cell}	Cell temperature;
P_{O_2}, P_{H_2}	Oxygen and hydrogen pressures;
n	Number of moving electrons in chemical reaction ($n = 2$);
α_a	Charge transfer coefficient;
j_{cell}	Cell's current density;
V_{cell}	Voltage across fuel cell's cell;
E_{rev}	Theoretical voltage of fuel cell;
$i_{0,an}$	Exchange current density;
α_{an}	Charge transfer coefficient at anode of fuel cell;
R_{ion}	Resistance of membrane of fuel cell.

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