T1.3.3 EMS recommendations

July 2023

Document History

Revision	Date	Description	Originated by	Reviewed by	Approved by
	Before 2023	Contribution in methods development and implementation	UNICAEN (M Barakat, H Li, A Alex)		
	01/02/2023	Creation of the draft	UNICAEN (R Petrone, H Obeid, Y Toughzaoui, H Gualous)		
	11/07/2023	Review			EMEC (H Turnbull)

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Executive Summary

This deliverable provides a final report summing-up the principles required for Energy Management System (EMS) improvement and the related recommendations. An overview of the different studies performed during the ITEG project development is given, discussing potential solutions and indicating suggestions for future improvement. Several scenarios are proposed ranging from the simplest tidal-hydrogen configuration to introducing other renewable energy system sources such as a wind turbine plant. Recommendations are given directly at the different steps of the analysed scenarios.

The deliverable is organised as follows; Microgrid and EMS objectives definitions are given first. Subsequently, the proposed EMS structure is discussed, differentiating between centralised and decentralised structures. Possible benefits in decentralised structures are introduced. A multi-agent approach is modelled to prove the decentralised structure effectiveness. The importance of system modelling is then underlined. The different units (modules) composing the EMS are presented, focusing on forecasting activities and decision-making processes. Day-ahead and real-time predictions approaches are described for forecasting, while rules-based and optimised approaches are considered for decision-making. Finally, new optimised scenarios are proposed.

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1 Introduction

In the current environment, increasing government focus on clean energy production and carbon emissions reduction has been noted, resulting in a constant growth of Renewable Energy Sources (RESs) applications [1-6]. This trend is observed particularly in remote areas, where the creation of self-sufficient micro-grid is advantageous. A microgrid is composed by *"a group of interconnected loads and distributed energy sources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid, and can operate in grid-connected or islanded modes"*, as defined by the U.S. Department of Energy [1]. Storage systems and other energy conversion and storage devices, such as hydrogen technologies are also included. Based on this definition, it is clear that microgrids are the key to integrate RESs into the electricity grid [2].

To efficiently optimise the microgrid management and its exchanges with the electricity grid, a suitable control system is required. This optimisation is mainly focused on solving the challenges related to the intermittent nature of the RESs, guarantying a self-sufficient energy scenario to reduce both the greenhouse emissions and the energy costs. For this purpose, several factors must be considered, such as the microgrid structure, the strategies adopted for optimisation and control, possible variations in load demand, energy availability, costs and constraints. Some of them are internal, depending on the microgrid structure; other are external, mainly depending on energy price, load demand and weather conditions (in particular for RESs). Considering that microgrids are an important part of actual smart grids, the smart grid definition is probably, more representative of the main challenges involving microgrid EMS. In fact, the European Technology Platform [3] defines a smart grid as *"an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies".* The EMS is a process of control for all the energy system components in the microgrid. It aims to address several challenges in microgrid, such as ensuring reliable production of electrical energy while respecting the limits of the generators and of the energy storage systems by reducing the power losses. Based on these complementary descriptions, it is now evident that EMS optimisation is a complex multi-objective problem involving several aspects, such as energy generation, system operations and control strategies, market laws, service providers and customers' demands.

The ITEG project[1] aims to combine new floating tidal turbines with hydrogen production systems. The all-in-one solution is demonstrated at the European Marine Energy Centre (EMEC) Fall of Warness (FoW) site, situated off the island of Eday in the Orkney Islands, Scotland. The project focuses on clean energy production and carbon emission reduction in North-West Europe. Particularly, the system aims to overcome local grid limitations in remote areas such as island communities. For these reasons, the tidal turbines provide power to the grid, boosting the local energy availability (self-supporting). Once grid capacity limitation is reached, the hydrogen electrolyser comes online to store energy via hydrogen. In this configuration, curtailment of the tidal turbines is avoided and the excess energy produced is converted to hydrogen, as an energy vector. An EMS supervises the hydrogen production by routing / switching the energy generated by the tidal turbines for powering the grid and /or the electrolysers' unit. This final report proposes the main principles required for an optimal EMS. The different strategies analysed during the ITEG project development are then presented for recommendations in future improvement and extensions of new scenarios.

[1] ITEG - Integrating Tidal energy into the European Grid: https://www.nweurope.eu/projects/project-search/iteg-integrating-tidal-energy-into-the-european-grid/

2 EMS structure & purposes in microgrid supervision

In order to present the different purposes of the EMS and the expected outputs, it is useful to clarify the different aspects of the microgrid control. Hierarchical control architectures are commonly used to face challenges on microgrid supervisory controllers, as underlined by authors in [2,8]. This solution allows the simplification of complex multi-objective control systems by organizing the different control strategies and operation requirements into several levels. Each level is then represented by different time scales and it is in charge of specific actions, which are usually depending on how the controller is closed to the system to manage or to the external agents of the microgrid.

According with [2,8], the following classification is given going from the individual components (or sub-systems) to be controlled, to the external agents, such as load and market actors' demands. The lowest level is the primary control level (PCL), that is responsible for supervising/control the local power sharing. Local power, voltage and current values are usually monitored for this purpose. The PCL is aimed to guarantee the correct operation of the sub-system, following the setting points indicated by the upper levels; the recommended/used timeframe is usually given in milliseconds. The secondary control level (SCL) is located on the top of the PCL and mainly controls power quality and exchanges with the main grid. All the questions related to the voltage and frequency balances, the harmonic compensation and the charge synchronisation are treated at this level. The time scale for control/regulation can change from milliseconds to seconds. The SCL follows the long-term scheduling indicated by the upper level to supervise the power quality by setting the operating point of the PCL. Consequently, the tertiary control level (TCL) is in charge of executing the long-term control. Timeframe of the TCL can vary from several minutes to hours, depending on the purposes. The TCL is aimed to supervise the global micro-grid by optimising the energy dispatching. At this level, efficiency, costs and carbon emission reductions are the main selected criteria for the optimisation. The EMS is located and operate at this level. Its primary target is to monitor and manage the energy flows among the different microgrid connected devices by scheduling the commitment for power dispatching based on merits of interest [2,8]. Overall, the EMS represents the microgrid intelligence level [8].

To provide more efficient management, the EMS is exchanging information continuously with the different units and actors of the microgrid. Particularly, the EMS makes the link between the system monitoring of the microgrid devices and the external agents. EMS operations can be organised in two main configurations. The centralized structure is the simplest one. All the information is centralized and all the tasks, such as forecasting, optimisation for decision-making, monitoring and control processes are performed on site. The main advantage is the real-time observability and decision making on the entire micro-grid, providing strong supervision. Moreover, the central unit will also guarantee a higher security level for data protection. On the other hand, a large bandwidth for communication is required because of the large amount of data to manage in real-time which will introduce higher computational burden. Reliability is a limiting factor of this design because a single failure on the process can force a whole system breakdown. Finally, this structure is less flexible and it is not recommended for expandible sites and/or scaling-up strategies [2,8]. Considering scaling-up strategies and future extensions, the decentralized structure is more appropriate, having high flexibility and increased reliability. Particularly, it offers the possibility to have fast reconfigurations, local maintenance and local optimisation criteria, which is beneficial when several actors are connected to the grid. In this case the computational burden is reduced, because tasks are separated and directly executed locally. However, information sharing (coordination/synchronisation and protection) becomes crucial [8]. In this context, the use of multi-agent approaches is an interesting solution. Considering a well-defined environment (i.e., our micro-grid) this technique depends on the interaction of several intelligent agents [8,9]. Agents are interconnected for exchanges and coordination, but at the same time are able to optimise their local criteria, by offering more flexibility and reactivity [10]. In hierarchical-decentralized approaches, one agent can be defined as coordinator/controller, while the other agents will perform both the supervision and the optimization of each physical unit, providing feedback to the high-level one. On the other hand, in totally decentralized management systems, many agents will perform the full optimization and supervision of its physical unit, by communicating to each other in peer to peer [9].

Once the different structures and configurations are defined, the main purposes of the EMS are discussed. The EMS is mainly in charge of monitoring, forecasting and decision-making tasks. System monitoring is mainly accounting for the different variables status supervision in real-time. Measurements and recovery actions (if required) are directly performed at the PCL. Subsequently, the information is sent to the upper levels for decision-making purposes. Generally speaking, this task mainly refers to the PCL and to the communication unit, while the EMS only treats the information for decision-making. For this reason, measurements are just seen as input variables in this deliverable, and the monitoring unit will be not further explored. If system monitoring is referring to internal variables and constraints, external factors, such as changes in load demand, weather conditions for RES generation, energy price and policies are representing the external variables. The prediction of which is the main objective of the forecasting unit. Usually, energy price and policies are defined/locked through contracts between the different grid suppliers and customers, while trends in energy generation and load demand are modelled. For this purpose, prediction models are developed, commonly based on artificial intelligence and machine learning techniques. Forecasting is mandatory for decision-making activities, such as scheduling and process optimisation. It is possible to differentiate two time-scales for forecasting: the 24h forecasting, that is responsible for day-ahead scheduling, and the short-term forecasting, which is mainly involved in real-time dispatching. The 24h forecasting mainly utilises historical data analysis based on energy price, generation and load variations; the common timestep used in prediction models is hours. The short-term forecasting is mainly based on the analysis of the monitored data trends. Depending on the sampling frequency, the timescale can vary from a few milliseconds to a few minutes, depending on whether the forecasting is referring to real-time or short-term applications. Some examples of forecasting activities for ITEG project EMS improvement are proposed in the next section. Finally, the decision-making unit is responsible for effective scheduling of power dispatch and energy balance. For this purpose, the main inputs are characterised from both monitoring and forecasting outputs, grid and system constraints and optimisation criteria. Summing-up, the decision-making process can involve both rules-based approaches and optimisation problems, depending on physical unit complexity (constraints) and management-imposed objectives. The problem solution will give the operational scheduling and the input for short-term dispatch. The first one, also named Unit Commitment is referred to as the day-ahead scheduler [2,8] and it is consequently based on the energy generation / consumption 24h forecasting. The objective of the unit commitment is to properly coordinate the different devices to supply the load at the minimum cost. While the second one, named Economic Dispatch is mainly aimed to meet the instantaneous demand, by considering unit commitment and real-time grid and connected devices operations and constraints [2,8]. The implementation of which is usually applied by lower-level controllers. The SCL will consider the aspects related to power, voltage and frequency balance, while the PCL will be in charge of local supervision and regulation. The economic dispatch focuses on improving the grid connected devices' utilization by enhancing the microgrid performance at the least-cost. ITEG contributions to rules-based and optimised approaches are proposed in the next section.

3 ITEG Project microgrid configuration

The integrated solution combines Orbital's next generation 2 MW floating tidal energy converter (TEC), with the EMEC's 670 kW electrolyser and the energy management system at EMEC's onshore hydrogen production site on the Orkney Island of Eday, as shown in Figure 1.

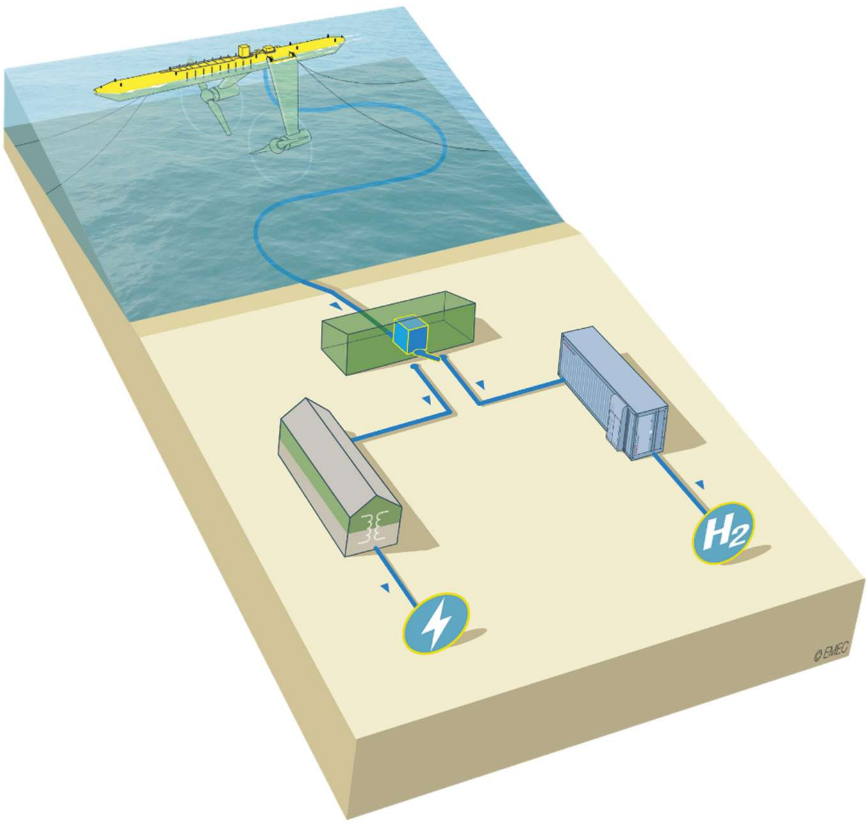

Figure 1: ITEG all-in-one solution at the EMEC's onshore hydrogen production site on the Orkney Island of Eday (ITEG project website[2]).

During the different configurations' studies the possibility to integrate a second electrolyser of about 500 KW nominal power to the hydrogen production unit is considered for microgrid expansion. Unfortunately, due to global supply chain issues, the second electrolyser initially scoped could not be delivered within the timeframe of the project[2]. Consequently, the updated solution combining tidal power and hydrogen is physically demonstrated based on the Orbital O2 TEC, and on the EMEC's 670kW electrolyser with a smart onshore energy management system. The EMS system enables EMEC to supervise the tidal power generated routing to the national grid, or directly into the hydrogen electrolyser as appropriate. The EMS optimisation studies proposed

[2] Note that the project objectives were modified to reflect the supply challenges suffered by Elogen (the second electrolyser customer). https://www.nweurope.eu/projects/project-search/iteg-integrating-tidal-energy-into-the-european-grid/

in case of two electrolysers' units are considered in this deliverable for recommendation in future system expansion. The possibility to integrate other RES, such as the existing wind plant is also considered.

Figure 2 proposes an overview of the Tidal-Grid-Hydrogen energy system basic configuration [11]. The ITEG micro-grid basic structure consists of a floating TEC connected to the constrained local grid, and a PEM electrolyser group for onsite hydrogen production. A subsea transmission line is used to connect the offshore TEC to the onshore hydrogen production plant. An export power limit of 4MW and an import power limit of 500 kW are considered for exchanges with the local electrical grid.

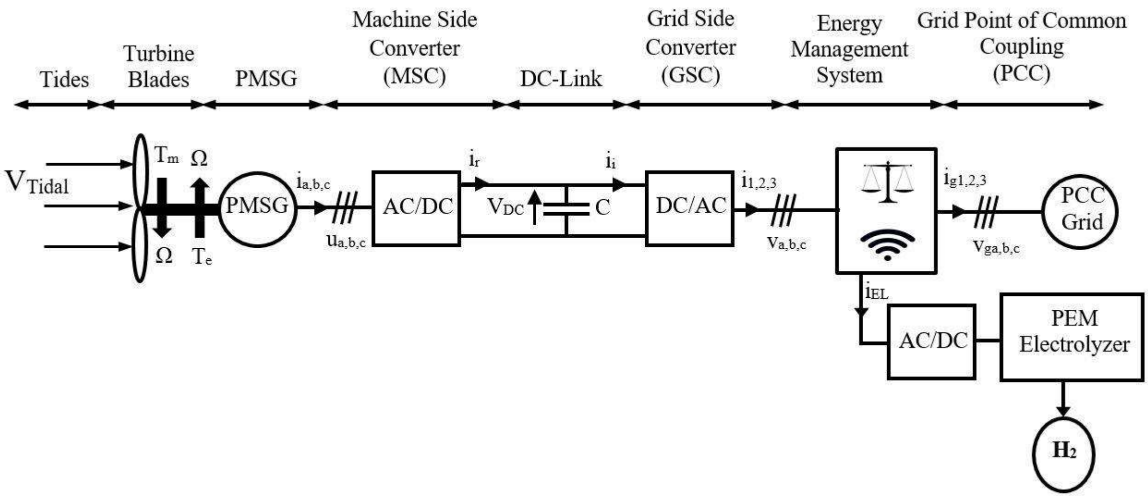

Figure 2: ITEG micro-grid structure (ITEG deliverable T1.3.1)

The complexity in EMS study increases as the number of the microgrid elements and constraints increases. Consequently, several approaches are analysed in the next section by considering both constraints and microgrid configuration variations. In the first considered scenario, the major EMS purpose is to avoid the tidal curtailment in case of grid demand reduction by giving priority (maximising) hydrogen production. Subsequently, new scenarios are introduced to study the microgrid capabilities and flexibilities. If energy exchanges with the grid are considered in all the studied scenarios, new options and constraints are introduced in energy balance optimisation criteria. Initially, efforts are dedicated in energy production forecasting activities, grid demand and energy costs analysis for stand-alone configuration. Subsequently, an onshore wind-grid connected energy system managed from external operators is finally added to the configuration of Figure 2 to evaluate different possibilities in microgrid expansion.

4 ITEG EMS study & recommendations

The evolution of the microgrid configuration of Figure 2 during the ITEG project EMS study is reported in this section focusing on both results' analysis and recommendations. For better understanding, the relevant EMS topics are grouped and analysed in the following sub-paragraphs.

4.1 Microgrid structure analysis & recommendation

The first step in EMS study and development is commonly the microgrid structure analysis. For this purpose, the global configuration is considered by evaluating the different connected devices functionalities, needs and constraints. Energy sources and generators, loads and storage elements are defined at first. Subsequently, the different connections on the voltage buses and related converters are considered. The configuration proposed in Figure 2 is a typical example of a first microgrid schematisation. It is possible to distinguish the part related to the tidal turbine generator, the electrolyser, the grid and the different converters. At this level, it is evidence that the presented microgrid can have both AC and DC components, the characteristics of which will be introduced in the following steps. Once the different parts are well defined, it is possible to distinguish between what will be managed locally and remotely by defining a suitable structure for system supervision and management.

Based on ITEG specifications, the EMS is located at the EMEC's onshore hydrogen production site on the Orkney Island of Eday. The controller has a bidirectional link with the EMEC SCADA system for monitoring and control purposes. It is configured to communicate with the different system devices via Ethernet and hardwired links, and it can be operated in manual and automatic modes, with direct local and external/remote control. The controller is able to supervise the entire system and manage the energy flows between the TEC, the electrolyser and the grid. As the main switchgear, it can be considered as an electrical node where all the microgrid devices are connected. In case of microgrid expansion with other RES plants, their connections will be also considered at this point. Concerning recommendations in microgrid structure, a centralized architecture appears as the simplest and most economically viable choice. All the information is centralized and control processes involving monitoring, forecasting and optimisation for decision-making activities are performed on site for the entire microgrid, providing a high level of supervision. However, this configuration is normally used for small EMS architectures as it is less flexible and it is not recommended for expandible sites. Considering the possibility of the plant scaling-up and/or future extensions, the decentralized structure could be a more appropriate choice. In fact, this configuration enhances the EMS flexibility, reliability and reactivity allowing fast reconfigurations. On the contrary, the implementation of the decentralised structures is more complex. In order to match the microgrid simplicity criteria, with possible expansion requirements, the use of multi-agent approaches is an interesting solution. In this case a hierarchical-decentralized structure can be created by defining a master agent (the controller) and a series of agents for the supervision of each physical units (i.e. one for TEC, one for the hydrogen production unit and one for the grid). The level of decentralization is then defined depending on how the physical units are operating under slave mode conditions or as local supervisors, providing feedback to the master agent and exchanging in peer-to-peer. Based on the original centralised structure, a multi-agent approach is discussed in section 4.3.

Once the first recommendations in microgrid architecture are given, the main controller modules (or units) are discussed. The first unit is the system monitoring aimed to collect information from the TEC, the electrolyser, and the grid status. While the information exchanges are managed via the communication unit. Although both the monitoring and the communication units are not analysed in this deliverable, it is recommended to verify the different aspects related to the storage memory capacity, the available bandwidth for communication, and protocols for information sharing (coordination, synchronisation and protection/security protocols). Concerning the input variables for system control, a forecasting (or predictive) module is defined. It is recommended in this case to involve not only the prediction of the RES energy production, but also the load demand and the economic aspects. For these purposes, the forecasting unit will consider the day-ahead information on both tidal behaviour and energy price variations. The outputs of both monitoring and forecasting units are used to meet the results of the prediction with the instantaneous load demand by maximising the hydrogen production at the minimum cost. This task is operated by the decision-making unit, that is responsible for system set-points. At first instance a rule-based approach is tested to validate the EMS structure. Subsequently, an optimized approach is proposed for microgrid performance enhancement by integrating new scenarios. System modelling activities are then required. All these topics are discussed in the next sub-paragraphs.

4.2 Importance of system modelling

System modelling is a powerful tool for EMS development and usage. It is possible to model the different system components of the microgrid and coupling them with respect to the real/physical connections and constraints. Model-based approaches can be used for system design validation, forecasting activities and optimisation purposes. The model complexity and the time frame of the simulation will depend on the model aims in EMS. Models can be based on physical equations, empirical data or mixed. Mathematical, statistical and machine learning techniques are commonly employed. Mixed physical-empirical models are usually suited to characterise the system components, while machine learning techniques are more applicable in forecasting and optimisation problems, depending on the available data-set.

In ITEG project two different approaches are tested. The Energetic Macroscopic Representation (EMR) formalism [9], that is a graphical representation of the system based on the action-reaction principle, is introduced to study the instantaneous power dispatching. While simplistic physical-empirical models are coupled to artificial intelligence and machine learning techniques to meet both forecasting and optimisation purposes. Consequently, the first approach refers to the Economic Dispatch and it is mainly aimed to meet the instantaneous demand, by considering unit commitment and real-time grid and connected devices operations and constraints. While the second one, is referred to the Unit Commitment for day-ahead control scheduling and it is consequently based on the energy generation / consumption 24h forecasting. The objective of the unit commitment is to properly coordinate the different devices to supply the load at the minimum cost. Two different EMR models have been developed: one from the GREAH laboratory of the University of Le Havre Normandy and one from the LUSAC laboratory of the Université de Caen Normandie. Models are used for hydrogen production prediction and energy management to support the optimal microgrid design and the EMS structure development. The GREAH EMR model, proposed in ITEG project deliverable T1.3.4 (Power variation report between the electrolyser and tidal turbine) is aimed to support the control strategy development for tidal to grid connection and tidal to electrolyser connection, as shown in Figure 3. Two control strategies are proposed. The first one concerned the rotor side control to maximize the output power, while the second one mainly focused on the grid side control to manage the required injected reactive power. The model was tested with the 10 years tidal current data-set provided by EMEC to predict the daily and annual energy and hydrogen production. Results suggest to supervise the following control parameters: the speed of the permanent magnet synchronous generator, the DC bus voltage and the injected reactive power.

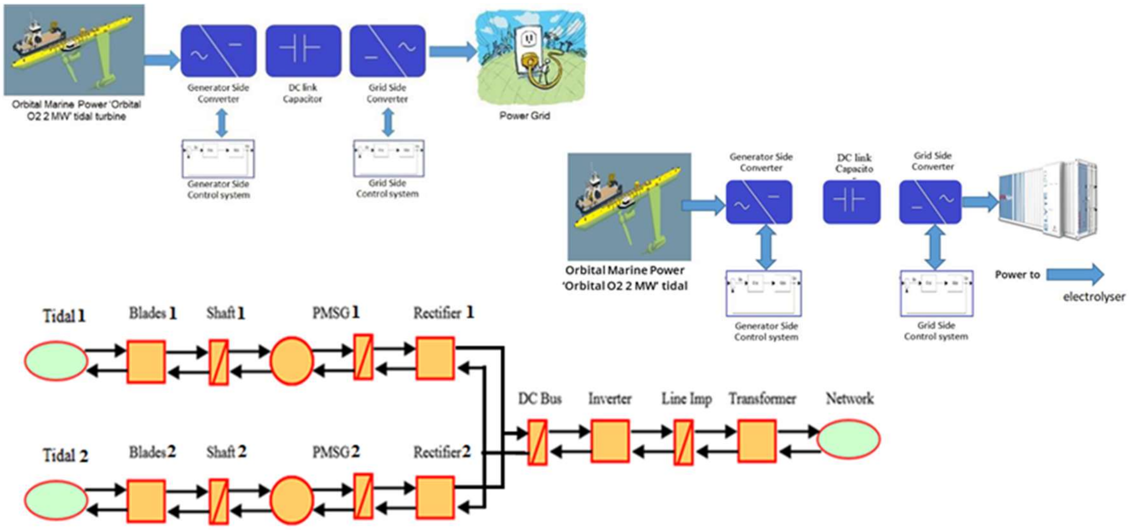

Figure 3: GREAH EMR model and control strategies (adapted from T1.3.4 ITEG deliverable).

The LUSAC UNICAEN EMR model, results of which are proposed in ITEG project deliverables T1.2.2 (Energy generation forecast) and T1.3.1 (Maximizing energy production) is aimed to support the EMS structure design and control by modelling all the microgrid components and connections (tidal turbine, inverters, converters AC/DC, switches, electrolyser, and grid). An example of tidal turbine EMR modelling is given in Figure 4, while Figure 5 shows the global microgrid structure model.

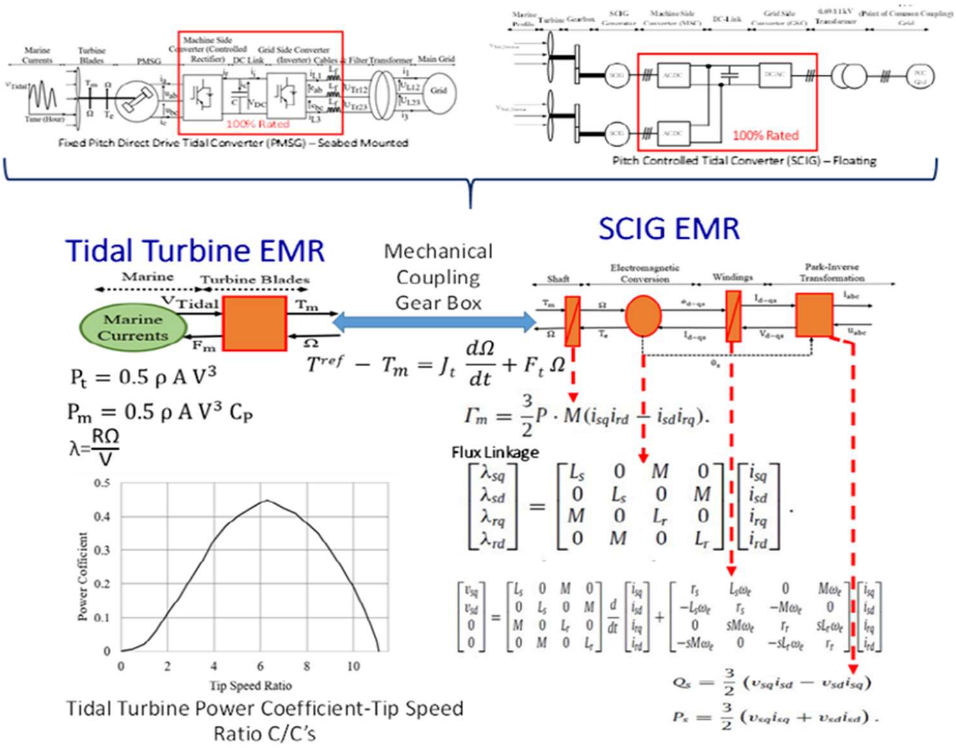

Figure 4: LUSAC UNICAEN EMR Tidal energy converter modelling (ITEG deliverable T1.2.2).

At first instance the LUSAC UNICAEN EMR model was used for daily and annual energy and hydrogen production prediction. Predictions were based on the 10 years tidal current profiles' data-set provided by EMEC. In this case, results of prediction that will be commented in sub-paragraph 4.4, are used for microgrid structure case study and future scenarios development. Subsequently, the entire microgrid is considered to model the all-in-one solution energy management and control strategies. At this level, all the physical connections are considered (involving all inverters, converters AC/DC and switches) to test several EMS strategies for power balance and dispatching; this part will be discussed in the next subparagraph. Figure 5 proposes the complete microgrid model, each block of which is representing a single component model. It is possible to distinguish the TEC unit, the hydrogen production unit (both electrolysers and storage system), the grid and the different converters and inverters. The PI controllers, responsible for the low-levels control (PCL and SCL), are piloted via the multi-agent approach. Results confirmed the EMR modelling approach as a suitable method for EMS development and low-levels control verification to meet both accuracy and speed requirements.

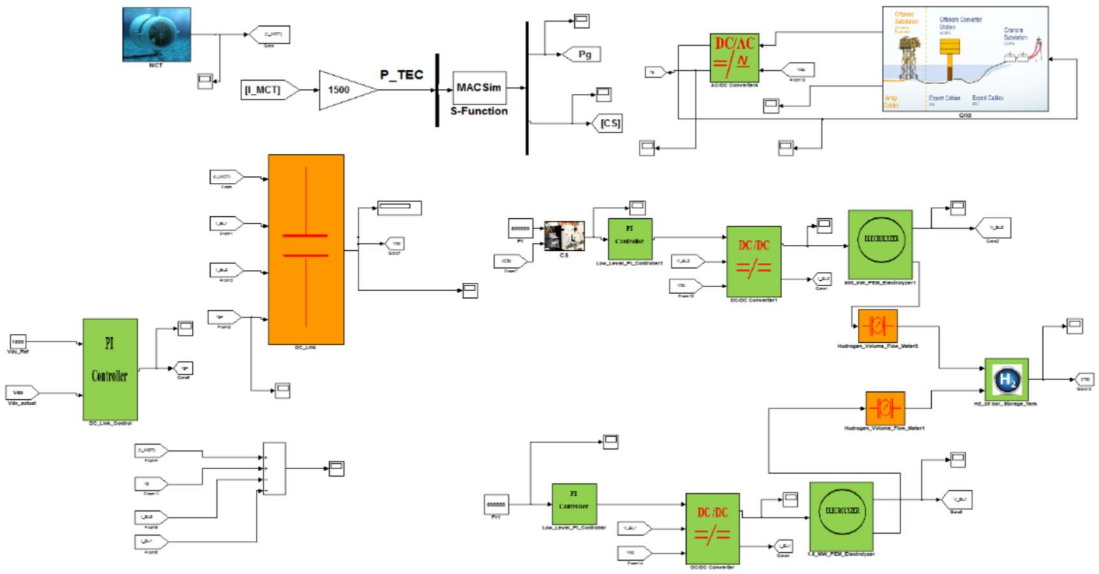

Figure 5: LUSAC UNICAEN global microgrid model interface for multi-agent approach (ITEG deliverable T1.3.1).

Once the low-levels control conditions (mainly concerned by sub-systems power balance and dispatching) are verified, strategies for tertiary-level units are analysed. For this purpose, simplest model, based on empirical approaches are adopted for energy balance to reduce the computational burden. The main objectives being the unit commitment, hourly based approaches are developed for day-ahead / 24h forecasting and microgrid optimisation. Figure 6 proposes the generic structure of the LUSAC UNICAEN model developed for the EMS optimisation. The model is a flexible tool for validating rules-based and optimised approaches. It can be used for tidal-grid-electrolyser configuration studies and for analysing future scenarios and support scaling-up activities by adding new RES sub-systems. Input data, such as tidal current and wind velocity profiles are directly provided by the forecasting models. Concerning forecasting activities, several approaches can be used, anyway a constant enhancement in using machine learning techniques and artificial intelligence approaches is stated. The method proposed by the LUSAC laboratory is the Long Short-Term Memory (LSTM). As a variant of the recurrent neural network (RNN), LSTM overcomes the shortcoming of RNN, long training time, and vanishing/exploding gradients. LSTM presented a strong ability in the time series data and has been widely used in various tasks such as battery remaining useful lifetime estimation and wind speed prediction. LSTM results and recommendation are given in sub-paragraph 4.4.

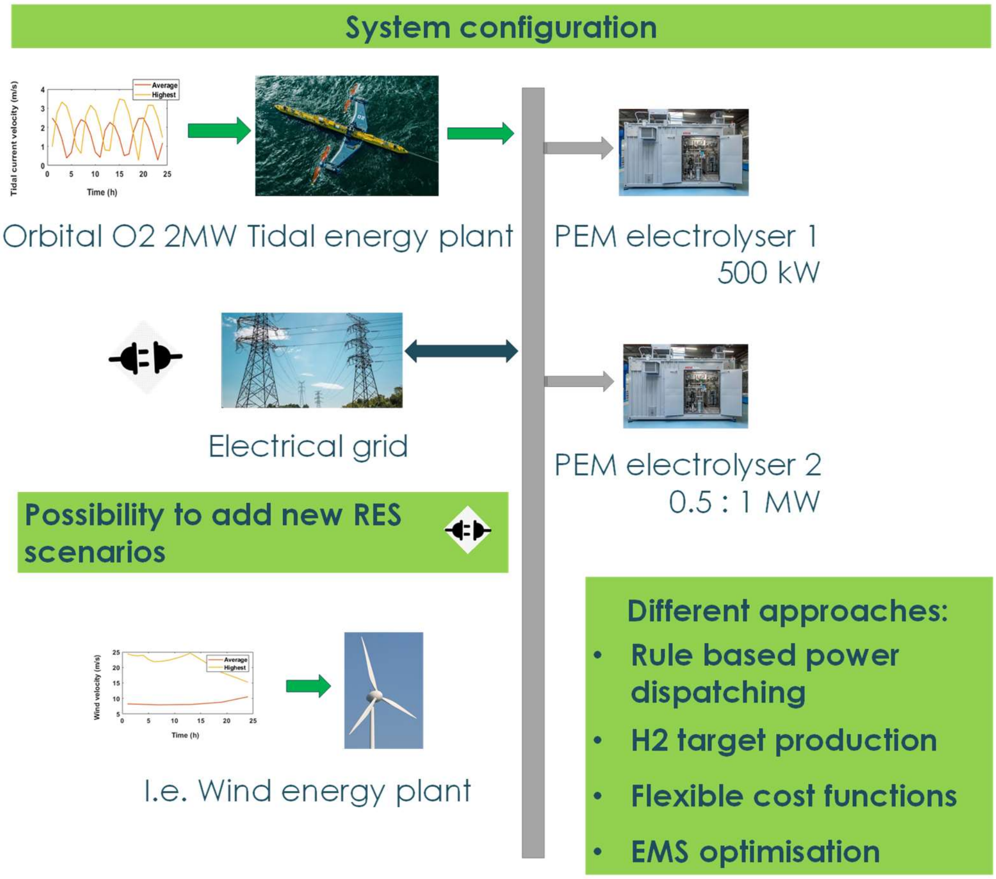

Figure 6: LUSAC UNICAEN model generic structure for EMS optimisation [12].

4.3 Recommendation to move from centralised to decentralised structures: the multi-agent system

As discussed in sub-paragraph 4.1, compared to centralised controllers the decentralised EMS structures offer more flexible solutions, and are better suited when new microgrid expansion are scheduled. In this domain a recommended technique [2,8,9] is the multi-agent system (MAS). In ITEG project, the LUSAC UNICAEN EMR model is coupled to a decentralized JADE based multi-agent platform to simulate and validate the effectiveness of the proposed EMS strategies. The proposed MAS consists of two main agents that provide the low-level control system of the EMR model by selecting the reference values to be tracked and a coordinator-agent (master unit). The reference values are referred to the power exchanged with the grid (imported/exported) to be followed by the GSC (Grid Side Converter), and/or by the electrolyser CS (Control Signal). In the considered scenario, the 1MW hydrogen production unit consists of two 500 kW PEM electrolysers: the first is permanently connected and the second is controlled in On/Off configuration by the CS signal due to the operating conditions.

The coordinator agent is mainly used to supervise the low-levels control agents exchanges. The different systems management is obtained by evaluating in continuous the power difference between the TEC generation and the hydrogen unit consumption. This task is executed by the the MACSimJX Agent Environment (AE). The Grid Agent is responsible for the energy management and the power exchanges with main grid. Firstly, it communicates with the MACSimJX Agent Environment (AE) based on the updated values of the power difference. It continuously estimates the amount of the power (Pg) required from the grid (imported/exported). Consequently, the grid agent feeds the Pg value back to the AE that feeds it to the EMR model as the GSC control system updated reference value. In parallel, the Electrolyser Agent is responsible for the energy management of the hydrogen production unit. Firstly, it communicates with the AE based on the updated values of the power difference (power surplus) and continuously estimates the electrolyser operating point (1 MW or 500 kW) before converting it into a binary 0-1 signal for the CS. The 0 value of CS represents the operating point of 500 kW while the 1 represents the 1MW. Consequently, the electrolyser agent feeds the CS value back to the AE which feeds it to the EMR model as the electrolyser block control system updated reference value. Thus, it manages the electrolyser-consumed energy, which is related to the amount of the produced hydrogen. The communication between the different agents is represented in Figure 7. The proposed decentralized JADE based multi-agent EMS is tested firstly under daily and weekly tidal speed profiles. Results of the simulations for a daily profile are given in Figure 8. Results are obtained simulating the MAS operation with a rules-based decision-making approach.

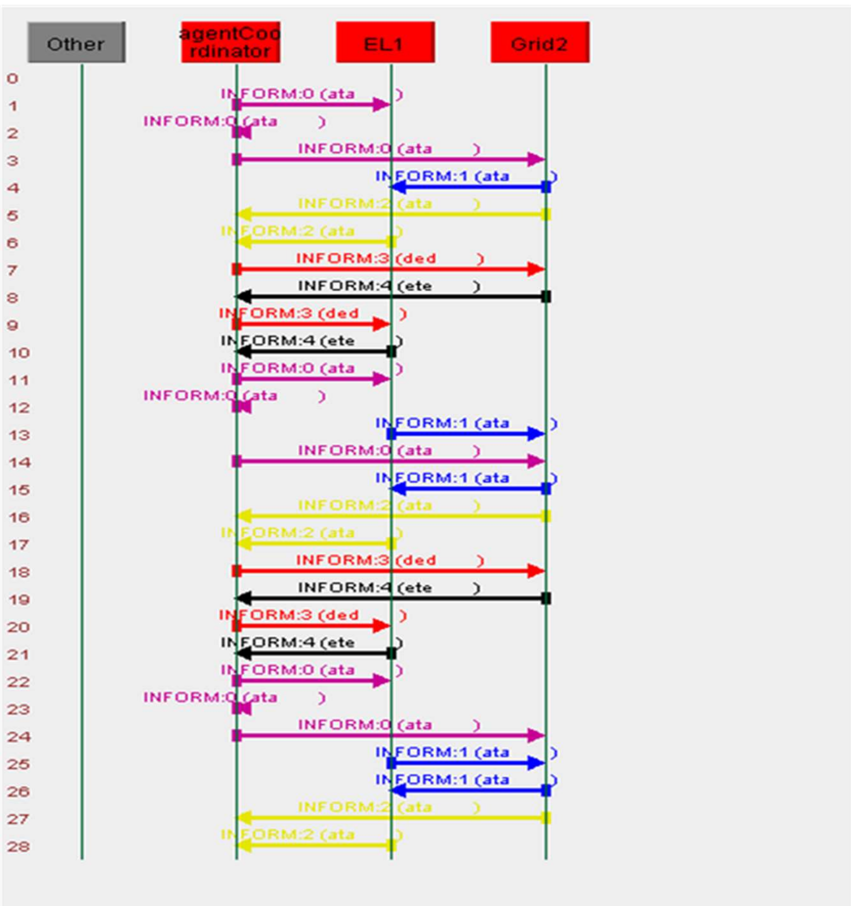

Figure 7: LUSAC UNICAEN Multi-Agent System communication.

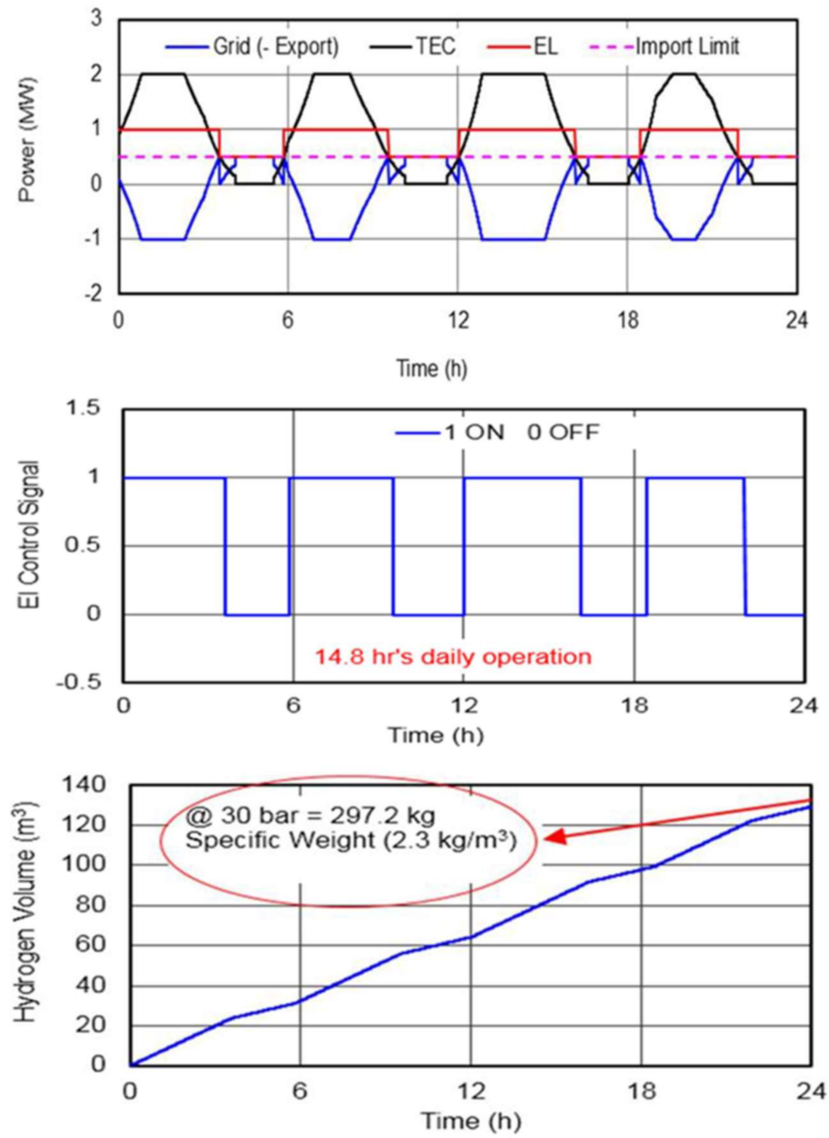

Figure 8: Multi-Agent Rule-Based EMS results (ITEG deliverable T1.3.1).

A basic MAS simulator including only two low-levels control agents is then developed to show the decentralised approach capabilities. Considering new possible scenarios aimed to integrate other energy production and storage systems to the actual microgrid, a novel MAS structure must be scheduled as proposed in Figure 9. In this case, it is possible to distinguish one agent for the electrolyser (EL), one for the fuel cell (FC), one for the battery (Batt), one for the hydrogen storage unit (H_2 Tank) and one for grid demand side management (DSM). Finally, as complementary information, MAS allows to define different control strategies, such as the economically oriented control strategy and the grid-oriented control strategy. The first one is typically used to minimize the cost of power feeding from the generation units, making the link with typical optimisation problems studied in decision-making processes. While the second one is responsible for the safe and reliable operation of the microgrid, especially under grid reconfiguration and/or transient conditions. For more details on MAS capabilities the reader can refers to the PhD thesis of Mahmoud Barakat [9].

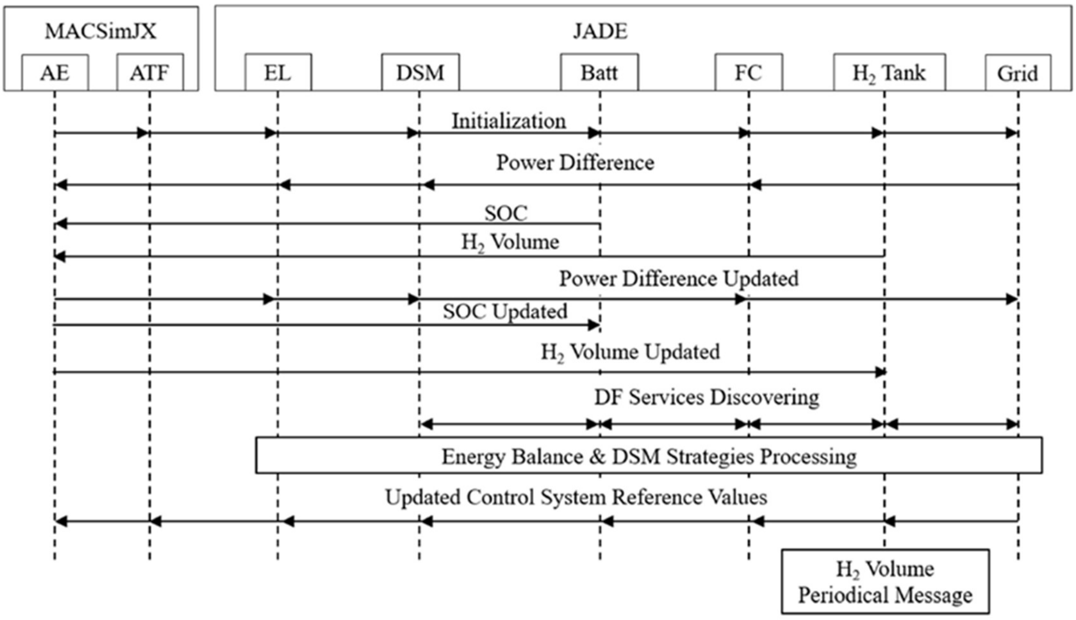

Figure 9: MAS interaction scheme for extended scenario (adopted from [9]).

4.4 Recommendation in forecasting

The EMS forecasting unit is aimed to predict the input variables variation for day-ahead scheduling of energy and hydrogen production. This kind of process is mainly accounting for temporal parameters to predict the energy production of RES. This is a sensible point for microgrid energy management due to the intermittent nature of RES generation. Concerning TEC, highest accuracy in prediction is obtained due to the periodic behavior of tidal. In the following, the prediction strategies suggested in the ITEG project for tidal conditions prediction are reported. If the methodology is proved for the energy production, it is recommended to extend it also to load demand variation and energy price fluctuation for future EMS improvement.

Initially, the tidal current profiles are analysed for off-line energy and hydrogen production prediction. For this purpose, the 10-years data-set of daily (1h occurrence) local tidal current provided by EMEC is used. The LUSAC UNICAEN EMR model of Figure 4, created to study the energy production of the TEC, is fitted and tested on eight test berths situated at the Fall of Warness site near the Island of Eday in Orkney (composing the EMEC data-set). To do that, the input data have been clustered respecting the operating modes of the tidal converter. During the maximum power point tracking (MPPT) mode, the frequency of repetitions has been applied to provide the average energy production. The energetic model results show the potential of the considered eight berths exhibiting the highest and the lowest potential sites. Results, accounting for TEC shut-down, maximum power point tracking (MPPT), power limitation (PL) and shutdown conditions are summed-up in Figure 10. The ITEG TEC location is in berth 5, matching high energy availability (in terms of tidal current potential) and MPPT operations, with lower PL and over-cutting / shut-down conditions. This study also underlined that except for berth 8 (the worst one), all the berths' locations have a production capacity factor included between 40% and 50%, recommending them for future microgrid extension and tidal farm scaling-up solution.

Berth	Number of Hours			
	Shutdown ($v_t < v_{tci}$)	MPPT	PL	Shutdown ($v_{t_{co}} < v_t$)
1	24131 (27.55%)	46315 (52.87%)	17220 (19.66%)	4 (0.005%)
2	25247 (28.82%)	49301 (56.28%)	13122 (14.9%)	0 (0%)
3	21077 (24.06%)	40832 (46.61%)	24463 (27.93%)	1298 (1.48%)
4	14545 (16.6%)	42917 (48.99%)	27867 (31.81%)	2341 (2.67%)
5	25290 (28.87%)	47503 (54.23%)	14874 (16.98%)	3 (0.003%)
6	21064 (24.04%)	42754 (48.8%)	22801 (26.03%)	1051 (1.19%)
7	20710 (23.63%)	45213 (51.61%)	21396 (24.42%)	360 (0.41%)
8	52851 (60.33%)	34819 (39.75%)	0 (0%)	0 (0%)

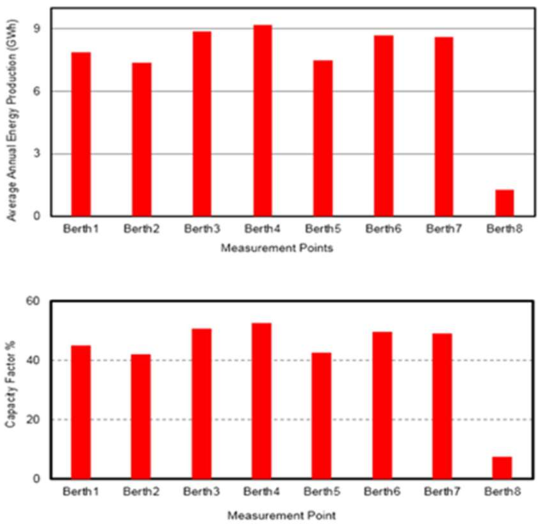

Figure 10: LUSAC UNICAEN analysis of the different berths' energy generation capacities (ITEG deliverable T1.2.2).

Subsequently, the EMR model of Figure 5 is used to validate results in berth 5. In order to reduce the computational burners, the LUSAC UNICAEN laboratory developed a clustering algorithm for regrouping the ten years of tidal speed data of Berth 5 depending on the frequency of repetition, as shown in Figure 11. The proposed algorithm represents the ten years by 27 most frequently repeated daily profiles with a cumulative frequency of repetition of 94%, reducing the initial data-set dimension of 1386720 h to a size of 648 h (27x24h). Finally, the LUSAC UNICAEN EMR model has been launched 27 times for testing the different daily profiles deduced from the clustering algorithm for evaluating the system performance. Results were subsequently integrated based on single profile frequency of repetition to estimate the annual tidal energy production, estimating the TEC energy production at about 6 GWh/year with a capacity factor of about 35% and a utilisation factor of about 70%, as reported in ITEG deliverable T1.2.2.

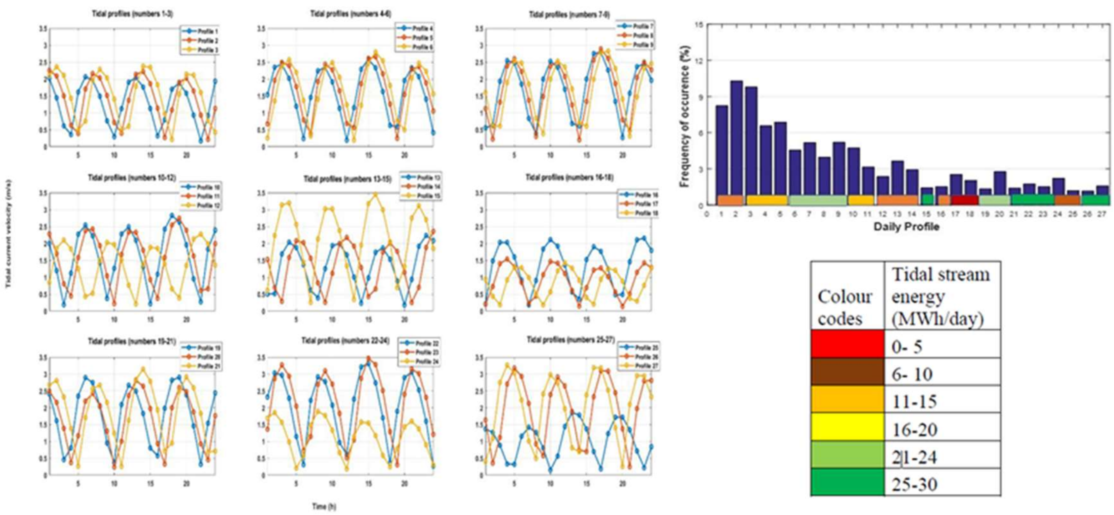

Figure 11: LUSAC UNICAEN results in tidal current data-set reduction and energy production estimation (ITEG deliverable T1.2.2).

The off-line estimations are mainly dressed to give recommendations for dimensioning to validate the plant microgrid actual configuration and suggest possible extensions. Concerning the EMS development, a day-ahead scheduling of the energy and hydrogen production is required (strongly recommended). For this purpose, the forecasting models are developed. Based on the timescale of the electricity market, the day-ahead and real-time energy generation, load demand and prices are usually accounted for forecasting purposes. Particularly, it is recommended to forecast the power generation and load demand to schedule the operation of RESs, ESSs and grid power from the utility grid in a day advance to maximize the revenue. However, due to intermittent and stochastic characteristics of environmental factors and load usages, the uncertainty of day-ahead scheduling is unavoidable. Therefore, real-time corrective dispatching is necessary. In this case, the firstly day-ahead scheduling is corrected through a subsequent real-time predictive control model. The main difference is the time sampling reduced from hours to few minutes. The EMS forecasting unit must be consequently designed as two layers: the day-ahead scheduling and the real-time dispatching. In this framework, the LUSAC UNICAEN laboratory developed a multi-time scale forecasting framework based on deep recurrent neural network to forecast the tidal current profile. Tidal current profiles are subsequently used to evaluate the power generation from TEC; models for extended wind turbine plant scenario are also developed. LSTM methods are used for day-ahead predictions. LSTM replaces the conventional neuron in the RNN with an internal memory cell and three multiplicative gates including the input gate, the forget gate and the output gate. When the LSTM neuron receives the input, the forget gate discards some information from the transient cell state. The input gate decides what new information will be created and updated to the cell state. The final output is decided by an updated state. Temporal dependencies of the sequence are then captured (memorized). On the contrary, the real-time estimation belongs to the joint state-parameter estimation problem, which is typically solved through the usage of a state observer or filter to estimate the changeable state parameters. Kalman filter as the most well-known filter is used for prognostic problems. But Kalman filter can only be used in linear systems, which is not the case of most prognostic problems. Approximate filters like extended Kalman filter (EKF) and unscented Kalman filter (UKF), and another nonlinear filter such as particle filter (PF) are widely used in the nonlinear prognostic problem. UKF is chosen to estimate real-time degradation because it has not only higher accuracy than EKF but also lower computational costs. Results of prediction are proposed in Figure 12 for both tidal and wind speed profiles; the day-ahead prediction results are proposed on the left, while real time predictions are shown on the right, the gain in accuracy can be easily noted. The obtained results are directly exploited in decision-making optimisation approaches.

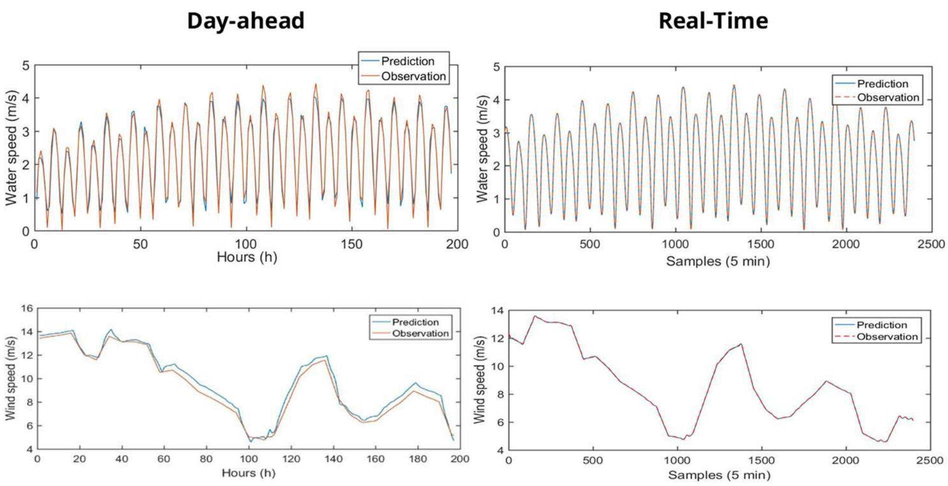

Figure 12: Results of forecasting models for input tidal current and wind speed profiles.

4.5 Recommendation in decision-making

The decision-making unit is the core of the EMS. It is responsible for meeting the forecasted results with real-time measurements and ensuring the microgrid safe operations. Usually located in the tertiary control level, it calibrates the single components set-points for low-levels controllers. Several strategies can be used for energy management, mainly grouped in two main categories: rules-based and optimised approaches.

Rule based approaches ensure the ability of the system to give solution in limited calculation times. This strategy is also termed as a deterministic approach as the solutions remains the same for each run. The decision logic is based on the available/generated power calculation. In this case the reaction principle is adopted: monitoring the actual generation levels and adjust the output power. For this reason, rules-based are able to ensure a good reactivity at low computational burdens. The controller collects data from the monitoring unit to calculate the amount of active and reactive power available for load devices requirements. If the suited condition for power demand is filled, the single unit (sub-system) is switched on; conditions on energy price can be also accounted. The rules-based strategies are consequently, the simplest ones to be implemented in case of small microgrid structures, which are usually asking for few energies flows management. If the microgrid management requirements (in terms of systems priorities and costs) are well defined, simple logic rules can be defined for power dispatching.

On the contrary, in case of complex microgrid structures requiring several objectives, the *optimised approaches* are the most suitable. To optimise the microgrid operations, an objective function, also named cost function, is commonly defined with components accounting for all single device costs and revenues; constraints and penalties (when required) are also considered. Costs are evaluated per each device operation by multiplying the accounted energy for the related unitary cost. In case of contractors, the unitary costs are directly referred to the energy price (i.e., the cost of the electricity for the grid). While system plant (capital expendable), operational and maintenance costs are commonly accounted for in the so named levelized cost of energy (LCOE). In general, techno-economic problems are treated, but it is possible to add other objective criteria, such as carbon emission, power quality and system performance. The problem variables are the operational set-points of each sub-system composing the microgrid. Depending on their nature, the optimisation to solve is classed in real, mixed or integer problems. The aim of the problem solver is to minimize the cost function (or find the mathematical zero) depending on the objective function definition. Among the different problem solvers artificial intelligence reasoning systems, genetic / evolutionary algorithms and heuristics methods are currently employed in optimisation processes [2]. As for forecasting, the timeframe of the optimisation can vary from 24h to few minutes, depending if the problem is referred to the unit commitment or to the economic dispatch, respectively [8].

It is now evidence that independently on the strategy, the energy price has a primary role in decision-making activities. It can be assumed as additional condition in rules-based power dispatching and it is mandatory in cost function definition in optimised approaches. For these reasons, the system monitoring is also collecting information on energy price variation. It is strongly recommended that the forecasting unit takes into account its prediction. In ITEG project, a contract for difference (CfD) support scheme is considered for the economic analysis of the tidal plant operation to regulate exchanges with the grid. When the CfD strike price is higher than the market price, the contract supplier has to pay the difference amount to the tidal plant operator. Accordingly, the tidal plant operator has to pay back to the contract supplier the difference amount in case, the strike price is lower than the electricity price [13,14]. Consequently, the day ahead hourly public sale prices for the electricity export to the grid is monitored and compared to the

CfD reference value for decision-making. In case of rules-based approaches, the difference between the CfD and the actual price of energy is directly assumed as switching condition for tidal generated power injection to the grid or to the hydrogen production unit. In this analogy, the variation of the difference between the CfD and the actual price of energy will represent a variation in costs and revenues in the objective function of the optimisation problem. Consequently, depending if its value is assumed as cost or as revenue it will force the energy injection into the grid or into the hydrogen production unit.

Based on these considerations, the ITEG microgrid initial configuration is tested by using the models' simulations. In case of tidal-grid-electrolyser configuration, the optimised results converged with the outcomes obtained with the rule-based approach. This is expected because the rules-based strategies are finalised to give priority to hydrogen production from tidal generation by considering the energy price. That in case of optimised approaches, it is equivalent to define an objective function for cost minimisation by limiting hydrogen production with the energy imported from the grid. In order to simplify the EMS decision-making process and reduce computational burden, the rules-based approach is suggested for this scenario; results of which are presented in deliverable T1.3.1. Difference in rules-based and optimised approaches are more observable if compared with their application in complex scenarios. In case of new scenarios development, the optimised approaches are recommended, as discussed in the following.

4.5.1 Decision-making in developing new scenarios: a case study

According with the results of ITEG deliverable T1.3.2, a new scenario is proposed as case study to compare the microgrid operations with different decision-making approaches. Simulations are performed by adapting the LUSAC UNICAEN model of Figure 6 for the microgrid configuration presented in Figure 13. The system comprises of a horizontal axis floating TECrated at 2 MW and two PEM electrolyser units rated at 500kW units. Both units for hydrogen production are located onshore. This integrated system is owned by the plant operator. Additionally, an onshore wind energy system and grid connection with import/export capabilities are considered from external operators.

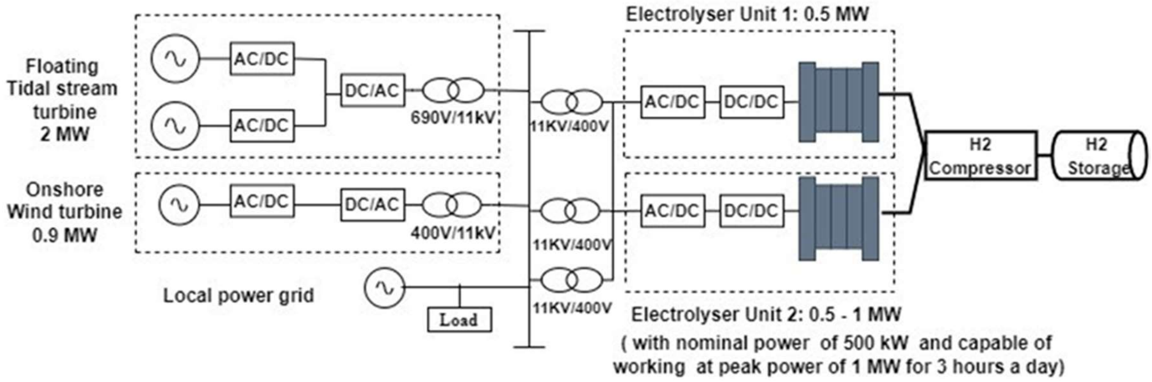

Figure 13: Case study: Combine tidal and wind turbines plants to power grid and hydrogen production [13].

This scenario is proposed to avoid both the underutilisation of the electrolyser units and the repeated transitions in their operating modes, which were observed by simulating the tidal-grid-hydrogen production system when import from the grid was limited. In the given system configuration, the wind energy system is proposed to be connected to the tidal-hydrogen system, allowing grid exchanges if required. However, power import from the grid is limited to enhance the green hydrogen production. Consequently, this scenario aims to increase the hydrogen production unit utilisation and reduce its multiple switches between on/off and stand-by conditions modes by reducing energy consumption during transitions and electrolysers' degradations in the long run [14]. For these purposes, the electrolysers different operating modes and transitions (on/off and stand-by conditions) are considered, accounting for energy production forecasting and grid limitations. At the same time, energy price variations, CfD contracts, devices LCOE and carbon credits for CO_2 saving are also introduced; as presented in ITEG T1.3.2 deliverable.

To give an idea of the increased logic rules introduced for the new scenario, the simplified flowchart modifications for operating the electrolyser units is proposed in Figure 14. It is evidence, that if this approach has still low computational burdens, its simplicity is reduced with the increasing of the connected devices. Moreover, objectives and constraints related to the new scenario also introduce two opposed criteria: make the system operation economic and maximise the green hydrogen production. Because the wind plant is owned by an external contractor, the objective of minimising the cost will suggest to reduce the energy provided by the wind plant. On the contrary, the condition related to the green hydrogen production to save carbon emissions will give priority to the wind energy use instead of the grid electricity. It is worth noting that, based on [16], the UK grid carbon intensity can be estimated in average at 209 gCO2e/kWh. A compromise is found, as shown by results of Figure 15. Anyway, with the rules-based approach no information is given on the optimal solution. Although, the start/stop and stand-by conditions are reduced for one electrolyser, this is not the case for the second one. This point is solved and guarantee with using the optimised approach.

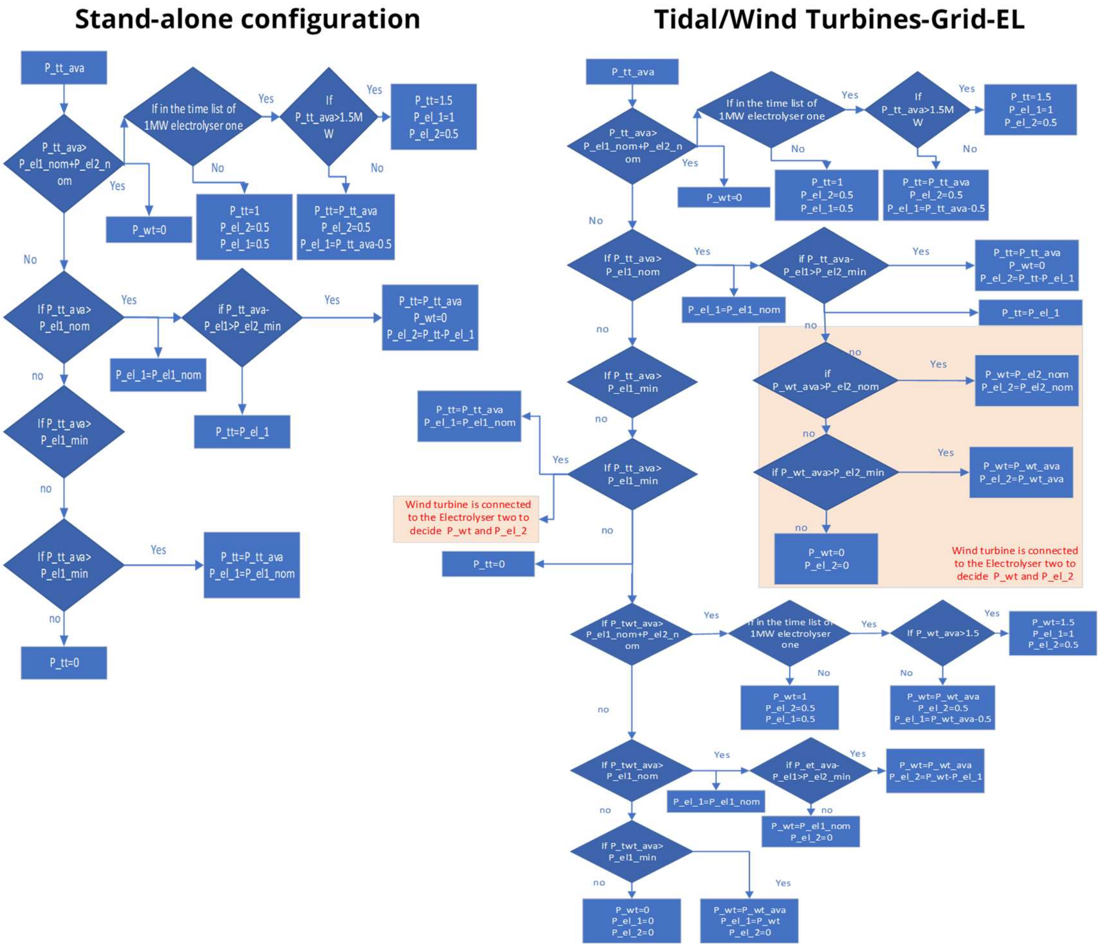

Figure 14: Rules-based approach: Electrolyser unit 2 operational flowchart.

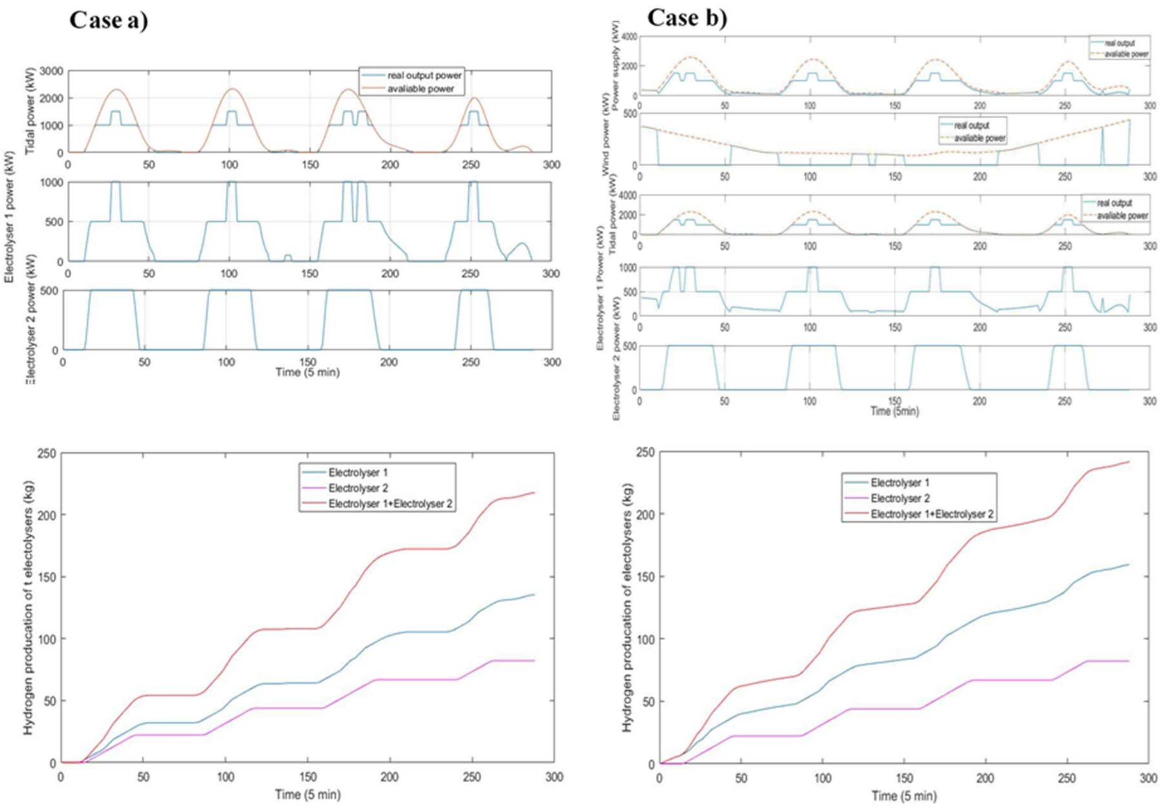

Figure 15: Simulation results of power generations and dispatching in the two electrolysers and hydrogen daily production for rules-based approach: case a) Stand-alone configuration involving only tidal turbine power generation; case b) considers both tidal and wind turbine power generation.

In order to meet the new scenario requirements, the optimisation approach is formulated as a mixed-integer nonlinear problem. A probabilistic evolutionary genetic algorithm (GA), is selected as optimisation method. This tool is largely used to solve the nonlinear mixed integer problems ensuring robust and efficient control strategies design [15]. For more details in methods implementation, the reader can refer to the ITEG deliverable T1.3.2. In the following the main results are summed-up. As shown in Figure 16, the operations of both electrolyser units 1 (green dashed line) and 2 (violet line) are optimised for the new scenario, avoiding start-stop and stand-by conditions. About 33% of the tidal energy generation is exported to the grid, the remaining is used to maximise the green hydrogen production. Concerning import from the grid, only 5% of the required energy for hydrogen production is imported. This low percentage demonstrates that the grid is only solicited to ensure a continuous and reliable operation of the electrolysers' units during transients in RES energy generation. While concerning the wind turbine, only the 30% of the required energy for hydrogen production is imported. The hydrogen production load factor is consequently increased by about 25% and the utilisation factor of about 35% with respect to the stand-alone configuration (maintenance periods excluded). Finally, the new optimised scenario allows an improvement of 28% of the hydrogen production under optimal operation of the electrolysers; opposed to about the 15% of hydrogen production improvement observed in case of rules-based approach. As expected, best performance in system production and operations are obtained in case of optimised approach.

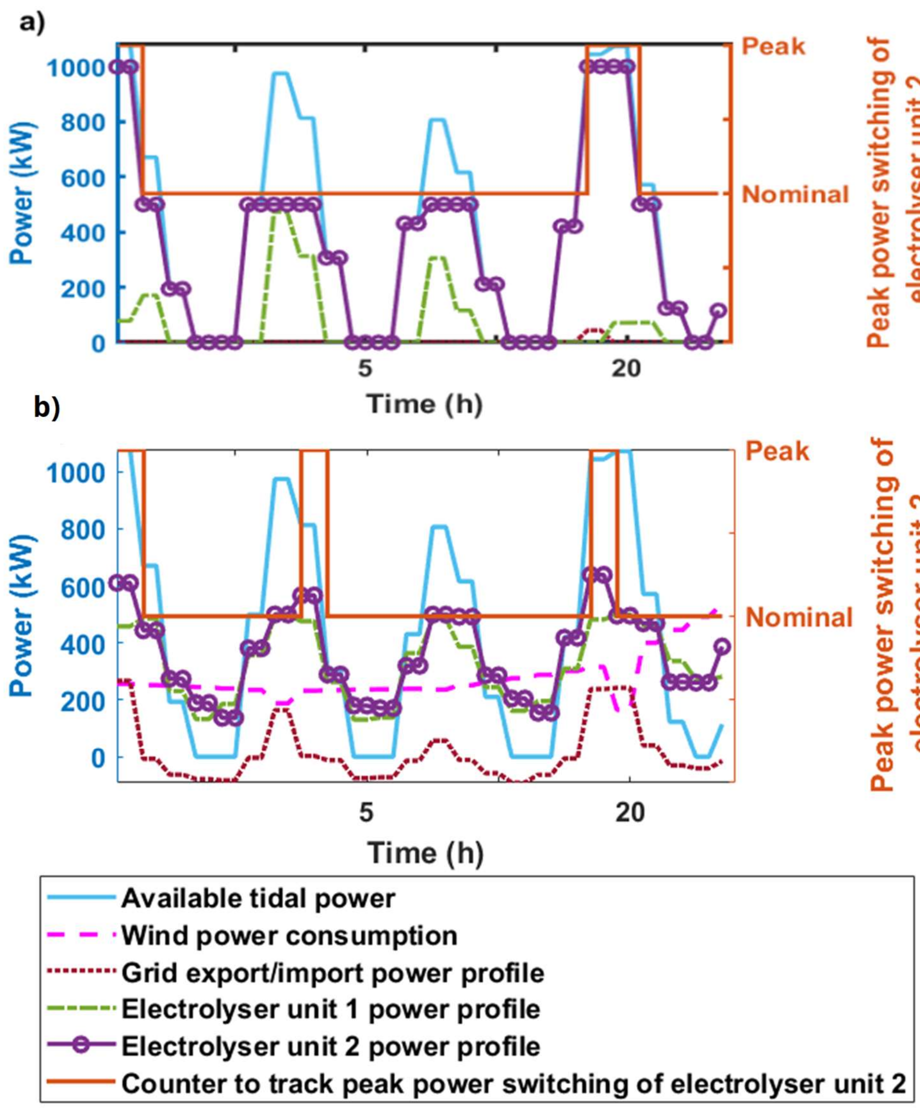

Figure 16: Simulation results of power generations and dispatching in the two electrolysers for optimised approach: case a) Stand-alone configuration involving only tidal turbine power generation; case b) considers both tidal and wind turbine power generation [13].

5 Conclusion

Several EMS solutions are presented. The deliverable is based on results of simulations to study EMS structure and operations. The EMS structure, the forecasting and the decision-making units are analysed. Per each task, suggestions are given based on results of models' simulations. Main recommendations are summed-up in the following. Several methods can be used in case of EMS centralised and decentralised structures to solve forecasting and decision-making problems. Their applications will mainly depend on the purposes of the microgrid case study, but the following points can be assumed as a common short guideline for the different configurations.

1. The first step is the microgrid configuration and objectives analysis. Depending on possible constraints and applications objectives of the connected devices, the complexity of the microgrid EMS structure must be defined.
2. For simplest microgrid and EMS problems a centralised structure can be used.
3. For complex microgrid including several actors and requiring several optimisation criteria for EMS, the decentralised structures are suggested for their higher flexibility and reliability.
4. The EMS is responsible for setting the operational points of the different devices. For this purpose, both day-ahead scheduler (unit commitment) and real-time (economic dispatch) units must be developed. Their specifics must be considered in modelling, forecasting and decision-making activities.
5. Modelling is a useful tool; however, care must be taken in the model timeframe, in the level of details in component modelling and resulting computational burden.
6. Forecasting activities must be applied in RES generated power, load demand and energy price variation predictions. Prediction timeframes will vary from 24h to few minutes, depending if the information is exploited for unit commitment or economic dispatch, respectively.
7. Decision-making activities, will be responsible for operating conditions and power dispatching. For simplest microgrid with minor optimisation criteria, rules-based approaches can be sufficient to offers accurate and robust results reducing the computational burden. On the contrary, when problem constraints and optimisation criteria are higher, optimised approaches are recommended. Two levels of optimisation processes must be planned, the day-ahead scheduler for 24h energy balance and the real-time controller for power dispatching.
8. Although the low-levels controls are not detailed in this deliverable, power quality, active/reactive power, voltage and frequency balances must be considered and added to the optimised criteria if possible.
9. Finally, the ageing behaviour of the different devices composing the microgrid must be considered in decision-making activities for predictive maintenance and adaptative control purposes.

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