Hierarchical Control of Space Closed Ecosystems

Expanding Microgrid Concepts to Bioastronautics

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ne of the main challenges of human space exploration is the development of artificial ecosystems, which can be used as life support systems (LSSs) to enable longduration human space missions. In an open LSS, no food generation or waste treatment is provided in space, and supplies from Earth are necessary. According to Figure 1, considering the approximate metabolic consumables and hygiene water as well as the number of crewmembers [1], a huge mass would be required to be transported from Earth, which brings the necessity of a regenerative or closed LSS [2]-[4]. Closed ecological systems (CESs)

are ecosystems without any matter exchange with the outside environment [2]. The most advanced humanmade CESs include Advanced Life Support System Test Bed (ALSSTB) (the NASA Johnson Space Research Center, Houston, Texas), Biosphere 2 (Oracle, Arizona), BIOS-3 (Krasnoyarsk, Russia-no longer operative), the Closed Ecology Experiment Facility (CEEF) complex (Rokkasho, Japan), the Micro-Ecological Life Support System Alternative (MELiSSA) Pilot Plant (MPP) (Universitat Autònoma de Barcelona, Spain), and the Concordia Antarctica Station, which are different from one another with respect to their complexity, size, and degree of closure [2]. CESs are necessary for long-term

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FIGURE 1 – The human consumables and throughput values in kilograms per crewmember per day. O2: oxygen; CO2: carbon dioxide; H2O: water.

manned space missions, which aim to minimize support from Earth. They are composed of several specific compartments that, together, reproduce the main functionalities of an ecological system in a continuous mode of operation and under controlled conditions. Figure 2 is an illustration of one of the leading CESs, named *MELiSSA*, which is composed of six microbiological compartments. As illustrated in Figure 2, these compartments are connected to each other through gas, liquid, and solid interfaces, and each of them has a specific role in

the overall process [5]–[7]. The main objectives of CESs are to regenerate the atmosphere, provide and recycle water, supply the required amount of food to sustain human life, and process the waste generated in the loop to provide self-sustainability. To this end, individual compartments must



FIGURE 2 – An illustration of a CES: MELISSA. O2: oxygen; CO2: carbon dioxide; H2O: water; VFAs: volatile fatty acids.

be efficiently integrated to close the loop and serve as a regenerative LSS. A significant concern in integrating complete compartments and developing a closed operational loop is related to designing an efficient, reliable, and dynamic control system that can fulfill system requirements and guarantee its long-term performance.

From a systemic view point, CESs are autonomous systems integrating various generation, recycling, and consumption subsystems with the storing capability to solve potential unbalances of key elements in the loop. Accordingly, CESs share many similarities with other autonomous systems, like islanded microgrids (MGs), which opens up new opportunities to benefit from recent advances in the remodeling and control of such complex structures. In this regard, this article aims to explore the similarities of the islanded MGs with CESs and benefit from MGs' highly developed control structures to cope with the complex control tasks of closed ecosystems.

CESs: State of the Art

The Russian project BIOS-3 is one of the first closed ecosystem experiments to rely on both microalgae and higher plant crops to convert the carbon dioxide (CO₂) released by the crew into O₂ with a negligible leak and degrees of closure of 100, 85, 40, and 20% for O₂, water, nitrogen, and minerals, respectively [3]. Most of the successful results of BIOS-3 inspired Biosphere-2, which is the biggest closed ecosystem facility ever focused on the study of human-environment relationships to be used for future outer space habitat designs. It contained aquatic and terrestrial ecosystems colonized with model organisms mimicking Earth. A totally sealed environment, it used only external energy from the sun. Biosphere-2 experiments in 1991 proved the importance and challenges of the controllability of closed ecosystems, as microorganisms grown in the soil released CO2 into the atmosphere in an uncontrolled way, thus exceeding the capacity of plants to revitalize the air, while making the atmosphere unbreathable for the crew. Hence, the expected degree of closure of 100% could not be guaranteed by controllability and leakage issues [8].

One of the longest runs of a closed LSS, which was promoted by NASA in 1998, is the Lunar-Mars Life Support Test, which involved air revitalization coupled to the food supply from crop cultures, and waste processing in a 90-day test. One of the outcomes of this project was to boost an integrated control system design to take into account the overall operation to reduce crew and ground personnel intervention time [9].

The recent promising integration results in the MPP connecting the gas phase of the crew chamber and the cyanobacteria bioreactor through a cascade controller serve as a platform to build an advanced control structure for the entire loop [6]. Table 1 provides an overview of the most advanced projects for space applications, pointing out their differences in waste management strategies and photosynthetic organisms used.

From a control viewpoint, previous attempts to close an ecological system reported the importance of controllability in such complex systems. Even though there are different CESs strategies with advanced control structures, to the best of our knowledge, there are no hierarchical control structures (HCSs) designed for the integrated operation management of CESs. In [5], an HCS that controls the biomass production in one of the compartments of the MPP by adjusting the light intensity is developed, but it is not extended to more compartments of the loop. Hence, this article focuses on proposing a hierarchical control framework for CESs, including several generation, consumption, and storage subsystems aimed at serving as a regenerative LSS based on the advanced HCS of MGs.

From MGs to CESs

MGs are the local aggregation of distributed energy resources (DERs), energy storage systems (ESSs), and loads, with the capability of operating in either grid-connected or islanded modes [11]. Islanded MGs, MGs without power exchange with the main grid or adjacent MGs, have been implemented in many applications, including geographical islands and rural areas as well as automotive, avionic, and marine industries [12]. The main characteristics of an islanded MG include 1) the capability of locally solving energy balance problems; 2) performing several multitime-scale control tasks allied with different operational and technical requirements at the system and component levels; 3) scheduling several microgeneration units, characterizing different dynamical behavior; 4) supplying MG consumers with reliable, clean, and sustainable energy, taking into account the uncertainty involved with generated and demanded power; and 5) managing storage possibilities to cope with energy balance and enhancing system reliability and performance. MGs are beneficial for both the main grid and

TABLE 1 – CES PROJECTS: THE MAIN TECHNOLOGIES FOR WASTE MANAGEMENT, PHOTOSYNTHETIC REACTIONS, AND DEVELOPERS.

PROJECT	WASTE MANAGEMENT	PHOTOSYNTHESIS	DEVELOPER
BIOS-3	Incineration	Microalgae and plant crops	Institute of Biophysics, Russia [3]
Biosphere 2	Biological conversion	Microorganisms consortia, coral reefs, and tropical rainforests	University of Arizona [8]
CEEF	Incineration	Plant crops	Institute for Environmental Sciences, Japan [10]
ALSSTB	Biological and physical- chemical conversions	Plant crops	NASA [9]
MELISSA	Biological conversion	Cyanobacteria and plant crops	ESA [7]
ESA: European Space Agency.			

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MGs users. From the viewpoint of the main grid, an MG is regarded as a controllable entity, which can support the upstream network by providing ancillary services, while from the MGs participants' point of view, it can be seen as a highly reliable source of power, which can enhance the quality of life of its participants.

On the other hand, CESs are smallscale islanded systems that aim to distribute matter through the loop in the form of mass flow. Hence, the system's operation requires coordination between the energy resources, namely, photosynthetic compartments that receive solar energy and convert it into chemical energy, matter-storing systems (MSSs), and matter sinks represented by different compartments, including the crew compartment in the system.

DERs

DERs in MGs include small on-site generation units called microsources; they entail diesel generators, microturbines, wind turbines, photovoltaic (PV) systems, and so on, which, in comparison to conventional power generation systems, enhance the reliability of energy systems while reducing investment costs [13]. DERs in CESs are more limited due to the poor environment in terms of the resources found in space. However, sunlight is the most abundant energy source on Earth and in outer space, and it plays a crucial role in both renewable-based MGs and CESs. PV systems and photosynthetic complexes harness sunlight energy to produce electrical- and chemical-potential energy, respectively. Although there are differences in their methods of operation, the final product (electrical energy in PVs and energy carrier molecules in photosynthetic cells), and energy conversion efficiency, they share many similarities [14], [15].

In a PV cell, the sunlight photon is absorbed by the semiconductor material (e.g., silicon) and results in the generation of an electron-hole pair. The energized electrons flow through the conductor as electrical current, and the resulting electrical output power can be used immediately or stored for later use. In natural photosynthesis, the energy of the absorbed photon results in an excited state of chlorophyll. These high-energy electrons are used to produce the energy-storing molecules nicotinamide adenine dinucleotide phosphate hydrogen and adenosine triphosphate in a series of light-driven reactions. The water molecule as a donor of the electron is broken, and O_2 is produced as an important byproduct [15], [16]. Figure 3 shows both processes. It is worth mentioning that in CESs, it is not only important to be able to capture solar energy and distribute electrical energy, but to achieve high efficiency in the conversion of electrical energy to chemical potential as well.

Similar to biogas-generation technology in MGs, which can provide heat and energy cogeneration, CESs might also include an anaerobic digester to process the generated waste and produce CO₂ [17]. Analogous to microgeneration units in MGs, operational constraints such as minimum uptime/downtime limitations, ramprate constraints, and mass flow-generation capacity are required to be respected in the control of CESs. As an example, the optimal higher plants growth rate in C4b in the MPP (see Figure 2) is strongly conditioned by its activation time, which is related to the plants circadian rhythm [18] (being the 16-h daylight time when the maximum plants growth rate takes place in the current operational conditions used in the MPP). The minimum deactivation time of this compartment is also required to be longer than eight hours for a proper functioning of the plants' metabolism.

Energy and Mass Storing Systems

Storing systems are essential elements in both MGs and CESs. They can increase a system's reliability and flexibility by providing the system with a backup source of energy and offer the ability to shift energy production and consumption intervals. In MGs, the uncertain nature of the power produced by renewable energy sources (RESs) and asynchronism between the peak interval of power generation and consumption as well as the different dynamical responses of various elements are among the main motivations for incorporating ESSs. In this sense, ESS management is a significant control task in renewable-based MGs [19], [20]. In CESs, due to the day-night cycles of plants and the different dynamics of loop elements, storage systems are used for buffering purposes. Increasing the number of cells or the plant population results in producing more O_2 , water, and food, which can be stored for later consumption.

However, it is important to optimize the size of storing tanks to keep the system weight at its minimum, a requirement stated by the European Space Agency's (ESA's) Advanced Life Support System Evaluator (ALISSE) criteria [21], which is also a main concern in isolated mobile MGs, such as ships and space MGs. Besides, considering technical issues such as accumulation limitations and the technical constraints of storage tanks (e.g., flowrate limitations, minimum and maximum storing capacity, and so on), including MSSs will complicate the CES control process.

Hybridization is another efficient way to cope with the different dynamics of system components and benefit from advances in various technologies. As an example, in a hybrid MG that includes a fuel cell, battery, and ultracapacitors, the dynamic response of the system to power demand variations can be improved by utilizing the stored energy. This concept can be also applied to CESs where the two photosynthetic compartments based on cyanobacteria and higher plants feature different dynamic-response characteristics. Additionally, stored materials can be used to respond to sudden changes in the system.

Energy/Mass Consumers

In a CES, the crew consumption rate drives the entire operating loop. The survival of the crew is ensured by satisfying specific conditions for the availability of water, food, and gas concentration. Similar to MGs, consumers are considered one of the



FIGURE 3 – An illustration of the comparison of MGs and CESs.

main sources of uncertainty in addition to sunlight, as their activities can considerably affect the supply of matter. Although we can have an estimate of the average O_2 consumption rate of the whole loop, many factors can affect this rate, such as crew activity, the elemental composition of feces and urine, and the consumption and generation rates of microbial communities.

MGs should be able to operate autonomously and interact with other MGs and the main grid, while the state of the art of LSSs are still not in a developed-enough stage to consider interconnections among different CESs. In both MGs and CESs, DERs and ESSs/ MSSs spread over the system and are connected to each other and to loads.

As in MGs, the design and planning of a CES is an important field of study that needs to take into account different considerations such as the system scale, degree of closure (the variable accounting for the degree of internal regeneration), efficiency of individual compartments and of the whole system, and the safety and weight of the system. All of the considerations affecting the design and operation of a CES are well described in the ALISSE criteria [21], which is out of the scope of this article. This research is focused mainly on the control and operation management of CESs.

Although there are striking similarities between both systems, some of the specific characteristics of CESs make their design and operation more challenging than renewable-based MGs. As an example, aside from light, which comes from an external source of energy, other energy sources are generated inside the loop. Hence, the generation capacity of different matter resources cannot be predetermined and are specified based on the current state of the dynamic system. However, existing similarities offer the possibility to use the advanced control methodologies developed for MGs for CESs as well, an aerospace application of increasing interest.

Control and Operation Managements of CESs

In Figure 2, the integrated system of a CES contains both the dynamics of the individual compartments as well as the interacting parts. The integrated system is very complex, with a large number of state and manipulated variables, nonlinear interacting dynamics, and several varying operational and technical limitations. Additionally, the dynamic-response time of the processes in the various compartments are noticeably different. The impact of the dynamics of the different phenomena that takes place in each compartment in the whole loop is strongly affected by the volume, the residence time, and the nominal concentration of the compounds in each compartment.

The multiobjective control process requires meeting mainly two control objectives, namely, balancing the consumption and production of oxygen, water, and food to guarantee life support and process the loop waste to achieve high levels of recycling.

Due to the multiple time scales of CESs and the different time resolutions of the objectives, an integrated control structure may not be successful. The combination of the need of a long prediction horizon, in the order of several weeks, with short, controlled time steps, in the order of a few minutes or seconds, results in a highdimension control problem, which cannot be handled in real time. Hence, a multitime frame organization of the controller is required.

Furthermore, developing appropriate models to be used in different layers and sublayers of the control hierarchy with different levels of abstraction is of vital importance. Although nonlinear mechanistic models provide a good representation of the real process behavior, they should be adapted for control purposes with a small time resolution. Hence, developed models should provide a satisfactory compromise between the accuracy in their operating range and complexity.

Hierarchical Control of MGs

To accommodate different time scales, MG control is organized in an HCS [22], [23]. The significant objectives of MG missions, including voltage and frequency regulation, power sharing, synchronization, resilient and economic operation, feature different time scales in the range of milliseconds to several days [24]. There exist several standards related to MG operation and control, including IEC 62898-1, IEC/TS 62898-2, IEC 62898-3-1, and IEEE Standard 2030.7-2017 [25]-[28]. ANSI/ISA-95 or ISA-95 is an international standard for automation system design and implementation for enterprise-control system integration in all industries, which is general enough to be applied in chemical processes. In an HCS based on ISA-95, the control tasks are distributed in several levels following a functional and temporal decomposition. The standard multilevel HCS based on ISA-95 and its adaptation to the control strategy of MGs is presented in Figure 4 [23].

In this scheme, the control levels are different from each other with respect to the functionality, speed of response, and operation period as well as the communication requirements [29]. Moreover, the complexity of the required models differs in various layers. In an HCS, different control levels interact with each other by adjusting reference trajectories and constraint boundaries. To preserve the stability and robust performance of the system, the timeframe management of the reference signals and control commands of one level to the lower levels is of vital importance. Hence, the bandwidth is decreased with the increase of the control levels.

Expanding the HCS of MGs to Control CESs

The parallelisms between CESs and isolated MGs show the great potential of benefiting from the highly developed HCS of the islanded MGs to cope with the complex control tasks of CESs. Organizing the control strategy in several layers is also consistent with the variety of the control tasks and the different time scales of CESs. The significance of adopting a generic



FIGURE 4 - A multilevel HCS of MGs and CESs.

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system-model approach containing several layers is represented in [5] for different purposes of control, management, test, and optimization.

Adopting the HCS of MGs to deal with the complexity of the optimization and control of the entire loop of a CES, the control process of the integrated system can be distributed in several levels as follows. The adaptation of the HCS of MGs to CESs is also outlined in Figure 4, according to the following levels.

Level 0 (Device-Level Control)

The controllers at this level are responsible for sensing and manipulating the actuators of the biochemical process to regulate the behavior of the associated compartment. These controllers follow control-command signals.

Level 1 (Primary Control)

At this level, a local controller is responsible for devising appropriate control actions to follow the mass flow references received from higher-level controllers. In addition, control agents at this level are responsible of sharing information about the dynamic compartment constraints so that higherlevel controllers can have a global view of the whole process to optimally distribute resources [30]. The strong coupling of variables and the interdependency of compartments may require the dynamic adjustment of constraints.

Level 2 (Secondary Control)

To compensate for the set points' deviations and to improve the tracking performance of primary controllers, a secondary controller is required to provide local controllers with corrective actions. The corrective actions are obtained based on feedback signals and the desired operating references and sent to the local controllers. To preserve the stability of the system, the secondary controller is required to be faster than the tertiary controller but slower than the primary controllers.

Level 3 (Tertiary Control)

The responsibility of this level is to guarantee the long-term performance of the process and provide optimal operating set points based on the predicted evolution of the demand and supply of matter by different compartments while taking into account their dynamic operating constraints and technical limitations. In case a matter exchange between different ecosystems is desired, flow management can be also scheduled at this level.

Level 4 (Supervisory Control)

The supervisory controller is devoted to establishing the operating strategies of the system following a set of main criteria such as ESA's ALISSE criteria [21]. Monitoring the state of health (SoH) of the system and projecting its states in the future using high-fidelity models and simulating the system in a fasterthan-reality environment, the supervisory controller will be able to support the reliable operation of the system by adjusting its operating strategies and predictive maintenance.

Accommodating the multiple time scales of the system, a temporal decomposition is also required at some levels [31], [32]. As a result, the control levels might consist of several sublayers, which act on different time scales while handling the corresponding objective function and relevant constraints. The number of sublayers and associated prediction and control horizons as well as the required sampling rate are determined based on the time-scale properties of the system and the desired control tasks. Furthermore, the interactions between different layers and sublayers are required to be clearly defined to consider the functionality of a sublayer in determining reference trajectories or adjusting the constraints of other sublayers [32]. By applying the proposed HCS, different subsystems are integrated, and the system's operation can be controlled in a coordinated manner. Figure 5 depicts the proposed HCS for an exemplary pilot plant (the MPP).

Control Methodology

In the HCS for CESs, appropriate control methods are developed at each level bearing in mind the control requirements (such as the control functionality or the speed of controller response) and system characteristics among others. The capability of model predictive control (MPC) in considering system constraints and taking into account future predictions of the system behavior as well as its closed-loop control approximation makes it a good candidate for deriving the control strategy in higher control levels, specifically, tertiary and secondary levels. While at the lower levels, faster controllers such as proportional-integral, proportional-integral-derivative, or predictive functional control (PFC) are highly preferred. PFC is a variation of MPC, which is characterized by its simple calculation algorithm and easy implementation. Using the two main characteristics of coincidence points (h steps later than the current step, where the reference trajectory and predicted process output will coincide) and basic functions distinguishes the PFC method from other predictive controllers [33]. In the proposed control structure, MPC is used at tertiary and secondary levels while PFC is deployed for controlling the light intensity in compartment C4a and the input gas flow in C3.

Prediction System and Data Exchange

To implement the HCS, the required information (the state of the system, system parameters, prediction of disturbances, updated trajectories, constraint boundaries, and so forth) at each control level and sublevel should be provided.

Data gathering is conducted through reliable monitoring systems, and relevant information is exchanged with the controllers through designated communication systems. Advanced estimation and prediction methods are required to find the latest values of unmeasurable state variables and system dynamics evolution during the prediction horizon. The estimation and prediction methodologies should be fast enough for online implementation. In this article, a model-based prediction system is deployed at the tertiary level using high-fidelity models of the pilot plant and the data obtained through the monitoring system.

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FIGURE 5 – An HCS for oxygen management. PI: proportional-integral; PFC: predictive functional control.

Simulation Analysis

In this section, the performance of the proposed HCS will be evaluated using the MPP as a test case. The MPP was built in 2009 to integrate the individual compartments to have a complete operational loop in a testing facility with high-quality standards. The demonstration scenario of the MPP is to achieve a closed-liquid and gas loop fulfilling 100% of the O_2 requirements and at least 20% of the food requirements for one person. Figure 6 shows the four compartments of the MPP.



FIGURE 6 – The MELISSA Pilot Plant. (a) Compartment C3, (b) compartment C4a, (c) compartment C4b, and (d) compartment C5.

Simulation analyses are based on a 25-day simulation period implemented in the MATLAB environment using the proposed HCS for the aggregation of three compartments and a gasstoring system (see Figure 5) and the nominal operating conditions used in the MPP [6]. The goal is to assess the long-term operation of the MPP using the proposed HCS with an O_2 reference of 21% in the crew compartment.

The prediction horizon of the MPC at the tertiary and secondary levels are set to six and 1 h, respectively, while the sampling times of the controller are equal to 1 h, 6 min, and 36 s, for the controllers at tertiary, secondary, and primary levels, respectively. According to the simulation results presented in Figure 7, the dynamics of the crew compartment correspond to a circadian rhythm of high O₂ consumption during the day and low O2 consumption at night [Figure 7(a)]. The secondary control is responsible for maintaining the O₂ concentration in the crew compartment within a specified boundary (19-24%) while following the references received from the tertiary controller regarding the storage tank charge/discharge rate and the O₂ supply rate of C4a. The scope of the tertiary control is to determine the optimal operating

conditions for the plant, taking into account the overall predicted O_2 consumption and production rates and certain operating criteria determined by the supervisory control.

In the simulation presented, the supervisory control aims to keep the pressure of the storage gas tank around a reference level of 50% of the rated value and to use two nominal levels of light intensity in C4a operation, namely, 225 and 84 W/m² for day and night shifts, respectively. In Figure 7(b) and (c), it can be observed how the secondary control generates a conciliatory response between the references received from the tertiary level and the boundaries imposed on the O₂ concentration in the crew compartment. At the primary control level, the light intensity in C4a fluctuates around the two nominal points for day and night shifts [see Figure 7(d)], and the O2 tank pressure level remains close to the reference level [Figure 7(e)].

Looking to the Future

Adapting the well-developed hierarchical control strategy of MGs to the control of CESs is a promising approach to deal with their complex control tasks. In this article, a hierarchical control strategy for CESs was introduced based on the multilevel control structure of MGs, pointing out the similarities between both systems. The control structure can be extended for controlling other CESs; not only terrestrial LSSs, but also Mars- or Lunar-based LSSs in the future. Moreover, the hierarchical structure can be effectively scaled-up to include the interconnection of several ecosystems. To design the HCS of CESs, hardware-in-the-loop (HIL) simulation and digital twinning provide unique opportunities, which are explored in the following sections.

HIL

To validate controller performance and reduce the implementation risk, HIL simulations can be deployed. Using an HIL simulation, the real-time response of the designed controller to the stimuli from the real plant model can be observed and utilized for evaluating and improving the controller performance in early developmental stages. It can also be used for validating the developed model of the plant. Taking advantage of efficient digital platforms, flexible and high-performance controllers can be designed for implementing complex control methodologies. In this sense, a field-programmable gate array (FPGA) is an attractive solution to design



FIGURE 7 – (a) A concentration of O_2 in the crew compartment. (b) The scheduled storage charging (–)/discharging (+) rate of the storage tank by tertiary control and the realized rate. (c) The scheduled O_2 supply assigned to C4a by tertiary control and the realized rate. d) Light intensity in C4a determined by the C4a primary controller. (e) The O_2 tank's pressure level.

a customized digital system, which substantially reduces the execution time of the controller, exploiting wide parallelization. Including FPGA in the loop, other control functionalities such as SoH monitoring and predictive maintenance can be implemented during the remaining time from the end of the control task and the next sampling time [34].

Digital Twinning

Digital twinning is the virtual representation of a system that mirrors the operating conditions of its corresponding twin in the real world. The digital twin (DT) allows the system designers and decision makers to assess the dynamic behavior of the system during developmental stages, as well as during the implementation, operation, and service phases, for making well-informed decisions. DT is based on high-fidelity models of the physical system and is connected to the physical counterpart through bidirectional communication links. In this way, the real-time data obtained from the physical system will help improve the accuracy of the DT, while the DT can support the optimal control and operation of the physical system by providing an advanced decision-support system and facilitating efficient in-house and remote monitoring. Considering the complexity involved in designing the control system of CESs, DTs can provide an unprecedented, advanced platform to enhance controller system performance during the CESs' lifetime.

Conclusion

Considering the recent advances in space exploration knowledge and technologies and the increasing tendency toward long-term missions on Mars and on the Moon, developing efficient and reliable LSSs is of vital importance. The design of efficient LSSs necessitates advanced control strategies with the capability of managing a highly complex process.

From a systemic point of view, CESs are autonomous systems integrating various generation, recycling, and consumption subsystems with the storage capability to locally solve potential matter and energy imbalance problems. From this perspective, CESs share striking similarities with isolated MGs developed for solving energy balance problems in an autonomous and independent manner. In this regard, a hierarchical control strategy for CESs was proposed based on the multilevel control structure of MGs. A supervisory controller at the top of the hierarchy decides the operating policy of the plant through a human-machine interface. Strategic decisions related to operating priorities, predictive maintenance, SoH monitoring, and standard CES criteria are performed at this level. Tertiary, secondary, and primary controllers at lower levels determine the optimal operating points of the system considering specific requirements and operating goals at different time scales.

The simulation results of applying the proposed method to the MPP proved the effectiveness of the proposed control structure in achieving a desired performance while meeting the system's technical and operational requirements. Future works are related to enhancing the controllers' performance in the presence of different kinds of disturbances in addition to aggregating other compartments in the loop.

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