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Towards Digital Twins of Small Productive Processes in Microgrids

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Abstract: In microgrids (MGs), energy management systems (EMSs) have been using increasingly detailed models of generation units, loads, and networks to make decisions on the power/energy contribution of each available unit to meet the electrical energy demand. This work aims to investigate the use of digital twins (DT) of small productive processes (SPPs) to regulate endogenous process variables to ensure final product quality, while the expected power consumption is estimated and communicated to the EMS so that it can make its decisions on the participation of each power source in meeting the electrical energy demand. The literature review reveals that this is one of the first attempts, in the context of MGs, to generate DT for SPPs that combine not only the electrical energy consumption, but also link it with the energy/mass balances taking place in the SPPs, highlighting the complexity that SPPs have as electrical loads. The results demonstrate that environmental conditions significantly influence the final electrical consumption of the SPPs. Additionally, the MG exhibits better economic performance when the SPP DT supports EMS decision-making, which is of great importance in MGs due to the special conditions they have for electric power generation, being more challenging in isolated MGs.

Keywords: digital twin; energy management system; microgrids; small productive processes; solar energy

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1. Introduction

Microgrids (MGs) have received significant attention in recent years due to their remarkable characteristics in effectively integrating renewable energy sources to meet the challenges of climate change and decarbonization. The worldwide annual growth rate in megawatts of installed MG capacity is expected to be around 65.19% from 2018 to 2027 [1]. The expectation for MGs is to improve the performance of energy systems in terms of system efficiency, life-cycle cost, quality of services, asset management, and sustainability. As a result, autonomy, reliability, resilience, safety, and environmental friendliness are some of the main characteristics of MG operations [2].

MGs are generally low-voltage energy systems that include distributed energy resources (DERs), energy storage systems (ESSs), and loads that operate in coordination to provide reliable electricity [3]. MGs can operate either connected to the main grid (on-grid) at the distribution level through the point of common coupling, or in an isolated mode (off-grid) (see Figure 1). Since MGs have a large number of controllable DERs, a hierarchical control consisting of three levels is adopted [3]: (i) primary control, (ii) secondary control, and (iii) tertiary control. The primary control refers to the local control or internal control of DERs. The secondary control, also known as the energy management system (EMS), is responsible for the reliable, secure, and economic operation of the MG [3]. The EMS determines optimal (near-optimal) operating set points of the dispatchable units in an MG [3] by solving a unit commitment and/or an economic dispatch problem [4]. The tertiary control manages the operation of multiple MGs that are connected to each other and communicates requirements from the main grid. For example, the overall reactive power management of a main grid that includes several MGs could be accomplished by properly coordinating them through a tertiary control approach [3].

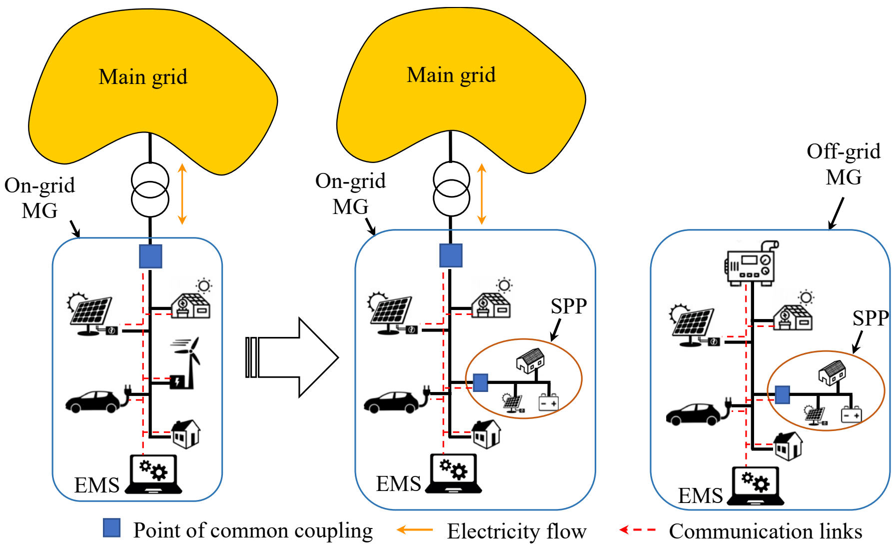

Figure 1. Future MGs including SPPs.

The secondary control can be classified into two approaches: centralized and decentralized. The former involves an MG central controller (MGCC) that receives relevant information from each DER and load in the MG, along with forecast information (e.g., load consumption, and solar and wind resources, among others), to determine the UC and economic dispatch of the DERs considering the selected optimization objectives [3]. Several studies have focused on this approach, including works by [5,6], and a comprehensive analysis of the main research trends of centralized control in MGs can be found in [7]. On the other hand, in the decentralized approach, local controllers make decisions on control variables. In this architecture, the local controllers can communicate with each other and with the MGCC to share information relevant for the MG operation [3].

Decentralized architecture, achieved through multi-agent systems (MAS) [3], employs advanced metering, communication, and control technologies for flexible grid configuration and reliable power supply [8]. In deregulated electricity markets, agents can be independent market participants, leveraging peer-to-peer (P2P) communication and transactive energy. For example, the co-optimization of a multi-microgrid (MG) system coupled with an urban transmission network can be facilitated by P2P communication [8]. Networked MGs (NMGs) have emerged due to the increasing integration of MGs into active distribution networks, and P2P control architecture can take advantage of the flexibility and resilience characteristics of NMGs. [9]. For example, a P2P control architecture for NMGs is presented in [9], which is based on multi-layer and multi-agent algorithms to achieve multiple objectives between MGs.

MGs, similar to bulk power systems and power distribution systems, are evolving. In the near future, they are expected to include not only DERs and conventional loads, but also complex loads, such as power electronic interfaced loads (e.g., electric vehicles, switch-mode power supplies, variable frequency driver motor loads, among others [10]). More recently, small productive processes (SPPs) have been added to the system, as shown in Figure 1, which enable local energy production to benefit the productive economic activities where they are installed [11].

SPPs, primarily located in rural communities, are small manufacturing industries aimed at increasing income and productivity while achieving the United Nations' sustainable development goals [12]. These new complex loads (i.e., the SPPs) have gained interest due to their potential socio-economic benefits, as well as the technical challenges in MG operation, which are voltage-dependent loads, weather-sensitive features, and variable work shifts based on operator scheduling [11,12].

Driven by the Industry 4.0 paradigm, the concept of digital twin (DT) has gained popularity due to its potential benefits in various areas such as industrial applications [13], power systems [14], manufacturing processes [15,16], health services [17], automotive industry [18], chemical industry [19], among others. The definition of DT varies depending on the area of study [20–22]. In electric power systems, it is defined as the virtual image of the physical object in the electrical power system, which makes the provided data usable for various purposes in the control center [23]. In this sense, DT models are being used in a wide area of electric systems, e.g., smart grids, transportation systems, smart cities [24], and MGs [2], among others. However, the development of DT models presents some difficulties and challenges [24] including data analysis and access, connectivity within the DT framework, security, and standardization. A more detailed description of these challenges can be found in [24].

In MGs, the use of DT models is highly beneficial for various purposes, such as planning, operation, maintenance, expansions and reinforcements, control and operation management, operator training, state-of-health monitoring, and fault diagnosis, among others [2]. An MGDT can, for instance, be employed to optimize its design and sizing to achieve a more cost-effective and environmentally friendly solution prior to construction [2]. Several potential applications of DT in the context of MGs are discussed in the literature and are extensively covered in [2], for example:

- MG design and development: DT models can help in the early design and planning phases of MGs by providing information on their performance under different conditions. This helps designers identify necessary design changes and potential application risks and mitigation strategies. By subjecting the MGDT model to an environment similar to the expected operating conditions, taking into account the uncertainty of local resources such as wind speed and solar radiation, the model can provide more accurate design plans. This reduces uncertainty for investors and operators of variable resources.
- Control and operation management: The MGDT model serves as a parallel tool for the control and management of the MG [25], enabling evaluation, detection of critical operating conditions, and making operating decisions for MG operators. For instance, the MGDT model can assist EMS in the adjustment of operating constraints for battery operation based on the remaining useful life to reduce the battery's stress.
- Operator training: The MGDT platform is a low-risk and advanced training environment for human operators of MGs at a low cost. Training operators in a dynamic environment expands their experience in monitoring MGs, particularly in adverse and emergency operating conditions. The MGDT also trains operators in MG maintenance services. To facilitate interaction between MGDT and human operators, an efficient human–machine interface is necessary. Virtual reality and augmented reality are potential technologies for the development of such an interface.

Furthermore, as experienced during the COVID-19 pandemic, the education sector globally was forced to transition to a predominantly virtual learning environment to maintain the educational process despite the confinement restrictions [26]. In this context, MGDT models present an efficient and modern alternative for teaching students involved in this field of study, especially graduate students who could gain a more comprehensive understanding of the operation of MGs and their components and validate their developments.

In recent years, several studies have focused on investigating different applications of DT models in the MG context. In [27], an MGDT for optimal ESS scheduling is proposed to minimize electricity bills. The optimal ESS charging/discharging scheduling is established to minimize electricity bills and implemented using supervised learning techniques instead of optimization strategies. The model's suitability is evaluated through a comparative analysis with the optimization-based ESS charging/discharging scheduling pattern. The results show that the proposed digital model achieves greater electricity bill savings compared to actual ESS operation. In [28], a DT for cyber–physical system security is proposed to improve the security of critical and noncritical MG infrastructure. The DT is a real-time, physics-based simulation that runs alongside the physical system, providing constant monitoring and control. The primary objective of the DT is to assist operators in assessing the health of the physical system and overall performance under a range of operating conditions. The results show that the DT model is able to collect system data and present anomalies to the operator. Moreover, DT models have recently emerged as attractive alternatives for evaluating ancillary services and protection mechanisms in the context of NMGs. For example, in [29], a DT is proposed for the energy management of NMGs in the distribution system. The NMGs are virtually represented using an artificial neural network (ANN) by training the data from the different optimal results of UC. The proposed DT model can interact with the physical model (NMGs) in real time depending on its operational mode. In other words, the virtual model can provide real-time dispatch updates on the schedule of conventional generators, fuel cells, and battery ESS. The mathematical formulation and implementation of an IoT-based DT for the resiliency of NMGs are presented in [30]. The proposed DT is validated using a practical setup of the distributed control system and Amazon Web Services. The results show that the proposed framework can quickly detect and mitigate different types of attacks, such as false data injection, denial of service, and coordinated attacks.

DT models can also improve the performance of remote control systems for MGs by providing highly dynamic real-time remote monitoring and control. This enables the tuning of the control strategy to ensure optimal performance [2]. For example, in a space MG where maintenance and component replacement is difficult, a DT model can be particularly useful [31].

Although investigating the role of DT as a new tool for improving MG performance is a fairly new research area [2], there has been a rising trend in using DT models to improve developments, deployments, and various applications in the context of MGs. However, none of the aforementioned works, and to the best of our knowledge, no works in the literature, have investigated the complexities in production processes such as voltage dependence and weather sensitivity of SPPs to develop DT models. Therefore, to fill this research gap, this work combines not only the energy and mass balances that take place in the SPPs, but also links them with the electric energy consumption to demonstrate the complexity that SPPs have as electric loads when developing DT models.

To advance with DT developments for future MGs, it is also necessary to consider new complex loads, such as SPPs, as part of the MGDT development. The use of emerging technologies can optimize production, efficiency, precision, loss reduction, and consumption, among others [32]. For example, having a DT library of SPPs can be useful for the development of sophisticated EMS, supervisory control, and data acquisition (SCADA) systems, and protection systems in MGs.

The SPP DT model was developed in MATLAB/Simulink, considering the actual characteristics and complexities of a solar drying SPP. More specifically, the voltage dependence characteristic of the SPP electrical loads is addressed through ZIP models [33], and the sensitivity to weather (i.e., ambient temperature and solar radiation) is handled using mass and energy balance equations. It should be noted that although the variable work shifts of SPPs are challenging for the operation of MGs, their study is beyond the scope of this work. To validate the proposed SPP DT model, actual measurements of solar radiation and ambient temperature were taken from [34] for the Vítor settlement located near the city of Arica. The results obtained reinforce the previously reported statements [11,12], in which the dependence of the electrical consumption of SPPs on the voltage supply was posited, and further extend them by showing that environmental conditions play an important role in the final electrical consumption of the SPPs.

The remainder of this paper is organized as follows. Section 2 provides a further description of the SPPs that are deployed worldwide and in Chile. Section 3 presents the description of the general framework for the MG-SPP DT, focusing on its three main elements: physical system, virtual system, and management layer. The methodology considered to develop the SPP DT model in the MG context is described in Section 4. Section 5 introduces the case study used to validate the methodology. The results obtained and the discussion after applying the methodology to the case study are presented in Section 6. Finally, Section 7 highlights the main conclusions and future work of this study.

2. Small Productive Processes

2.1. Small Productive Processes Worldwide

Due to the potential benefits of the SPPs, several projects have been installed to support the socio-economic development of communities. Some examples of SPP projects are described below [35].

- Ice making: This SPP produces ice for preserving food and cooling drinks, especially in remote and hot locations. The devices responsible for ice production are either small stand-alone ice freezers or large commercial ice makers.
- Milling: Communities often use milling to produce flour by processing different products, such as corn and cassava, among others. Due to the lack of electricity in some remote areas, small mills powered by diesel generators are usually used. However, in some regions, photovoltaic (PV) panels are used to supply this type of SPP.
- Carpentry: This SPP is commonly performed in rural locations. The machinery used in this process, such as drills, electric cutters, among others, can have significant electrical consumption.
- Water treatment: Access to drinking water is fundamental for people's development, especially in remote areas. The methods used for water treatment usually require electrical energy, for example, electrochemical treatments, filtration, and reverse osmosis.
- Other productive uses: Several SPPs commonly performed in developing countries are described in [36]. For example, irrigation, cooling, food processing, etc.

2.2. Solar-Based Small Productive Processes in Chile

Chile has enormous potential for solar energy, especially in the northern part of the country. The Atacama Desert, for instance, has exceptional conditions with 2556 kWh/m^2 and a clear sky with an annual average clearness index of 0.72, which is close to the world maximum of 0.8 [37].

The Ayllu solar project was established in 2017 to take advantage of the solar resource of the Arica Region in northern Chile [38]. The main objective of the Ayllu Solar project is to create cost-effective, replicable, and scalable solar energy solutions in key areas for community development [38]. The Ayllu Solar initiative consists of different SPPs, as shown in Figure 2. Nevertheless, only three of the reference projects are further described below:

- Processing of agricultural products with solar energy [38]: This SPP involves the installation of a solar drying process and packing and storage facilities for agricultural products (e.g., fruits and vegetables) produced by farmers in Caleta Vítor and Valle del Chaca. The project includes a PV system, an office, a meeting room, a processing, sorting, and calibration line, and a drying process.
- River shrimp farming [40]: The objective of this SPP is to support the socio-economic development of the inhabitants of the villages of Camarones, Maquita, and Taltape through the intensive use of solar energy in river shrimp farming. The project includes a water treatment system and a water recirculation system powered by a PV plant.
- Camelids fiber processing center [40]: This SPP involves the installation of machinery powered by solar energy to add value to the raw camelid fiber produced in General

Lagos and Visviri commune. The processing center includes a PV generation system and a thermo-solar system that is used to heat water for washing camelids fiber.

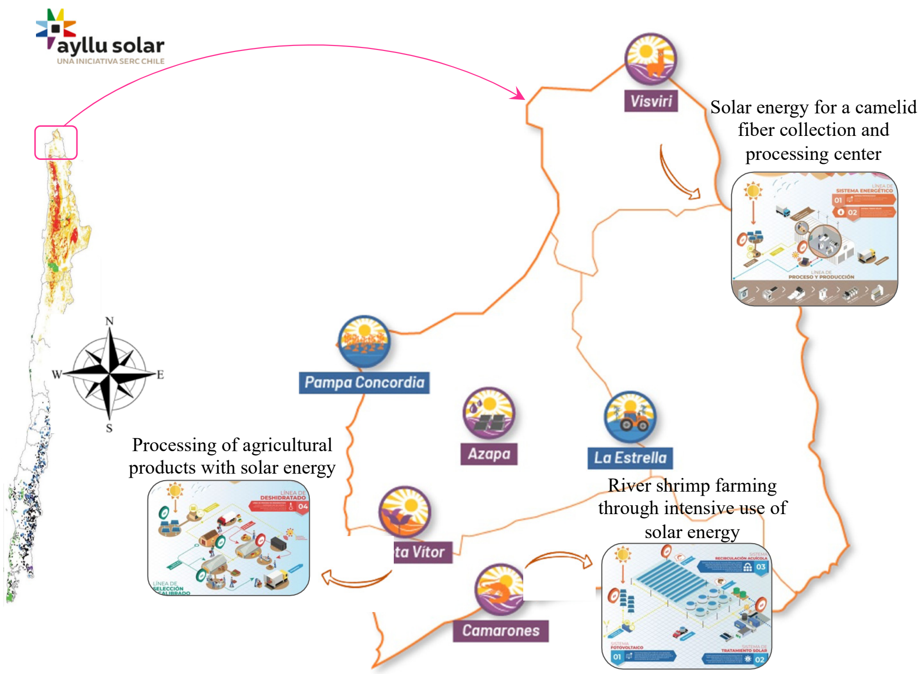

Figure 2. Ayllu Solar SPPs installed in the Arica and Parinacota regions, Chile (adapted from [39]).

3. MG-SPP DT General Framework

The MG-SPP DT framework comprises three main elements: the physical system, the virtual system, and the data management layer that facilitates exchange between them. On the top of this structure, DT services can be developed to establish interaction between the physical and virtual systems [2], as illustrated in Figure 3.

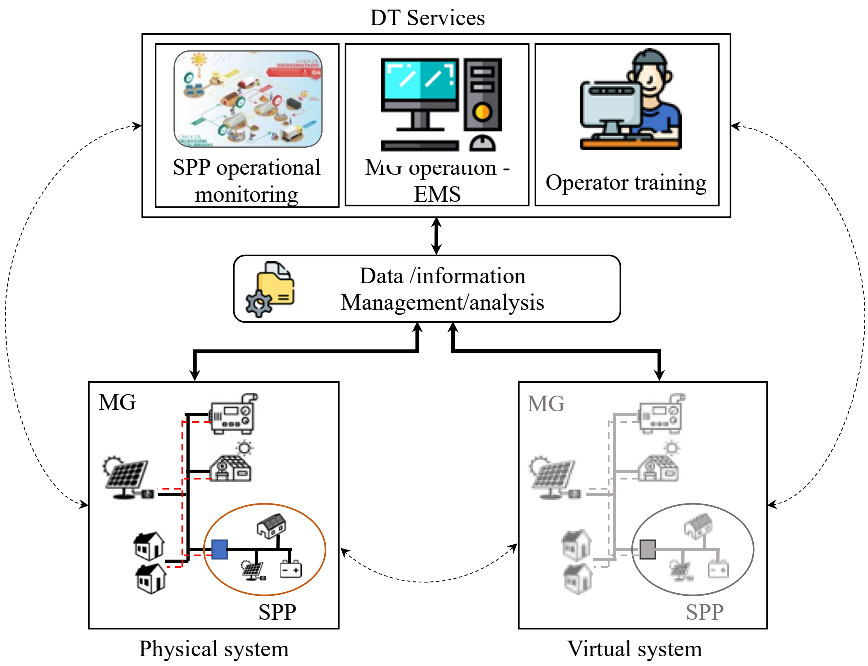

Figure 3. Overview of the MG-SPP DT framework.

3.1. Physical System

The physical system describes any system built in the real world. It is important to note that the physical system is the basis for building the virtual system. As shown in Figure 3, in this case, the physical system comprises an MG and its main components, such as generation units, energy storage, distribution network, sensors, and communication networks, as well as conventional and complex loads, i.e., the SPPs (see Section 2). SPPs generally involve the consumption of electricity for productive activities. However, when they rely on solar energy, SPPs connect thermal processes with electrical energy consumption. This is one of the main characteristics of these complex loads and will depend on the type of SPP under study (see Section 2.2). Therefore, it is essential to address the complexity of SPPs when developing DT models for MGs that include these types of loads.

3.2. Virtual System

The virtual system emulates the behavior of the physical system through simulation platforms. To build the virtual environment, the best available knowledge of the physical system dynamics and historical data obtained from the real system are required [2]. Different modeling approaches, such as physics-based models, data-driven models, and hybrid models, can be used to build the virtual system [2]. The virtual system can be built on a platform suitable for this type of development, such as MATLAB/Simulink and PSCAD, among others. Finally, the resulting virtual system models can be validated and tuned using the knowledge and historical data collected from the physical system. In the case of MGs, creating a DT model requires virtually representing the main components of the MG under study (i.e., DERs, loads, etc.). When MGs include SPPs, their complex characteristics can be represented through physics-based models that reflect the mass/energy balances and power consumption in the SPPs.

3.3. Data Management

The data/information management/analysis layer systematically processes the data collected from the physical system and the virtual system, and shares the data (converted into useful information) with each other to achieve proper operation of the DT model and services. The data flow is often in real time, and it is essential to preserve data integrity and privacy [2]. As can be seen in Figure 3, the virtual MG system shares information with the physical system to support energy management, for example, through sending operation commands or delivering estimations of expected energy consumption for MG operation.

3.4. DT Services

Defining the purposes or services of the DT model and its modeling requirements is crucial. This step allows for verification of the available data and simulation tools needed to analyze the feasibility of building the desired DT model. It also determines the granularity of the models and the resolution of the data. For example, in the context of MGs, services such as operation, operator training, prediction, and security analysis, among others can be established. Moreover, DT models for SPPs can be useful for managing their operation, monitoring services, operator training, and education through advanced teaching tools. A DT containing SPPs can also provide valuable insights into the dynamics of MGs, that integrate these processes, and their impact on the MG operation and EMS.

4. Methodology

This section describes the methodology used in this study to establish SPP DT in an MG context, based on the main stages presented in [2] for developing DTs for MGs. Nevertheless, the methodology described in that work covers the development of DTs for MGs broadly. Therefore, only the stages required for developing SPP DTs are considered in this work and are described in the following subsections. Finally, it is essential to define the system boundary between the SPP DT model and MG to ensure that the SPP DT accurately reflects the real-world system's behavior.

4.1. Definition of the Scope and Modeling Requirements for the SPP DT

This stage focuses on clearly defining the scope and objectives of the DT model. This includes identifying the SPP to be converted into a DT, along with its operating characteristics and the components of the MG system to be considered. Performance metrics to be evaluated are also determined at this stage, along with the desired services of the SPP DT model and the requirements for their modeling. Depending on the complexity of the SPP and MG system components, the level of detail required for the SPP DT model is defined. This may involve deciding whether to model individual components or subsystems and the level of accuracy needed for the model.

4.2. Gathering of Data and Technical Parameters of SPP

The next stage is to collect data and technical parameters on the SPP system, including technical specifications, energy consumption, production, storage, and environmental data such as solar radiation, wind speed, temperature, and humidity. Depending on the specific devices and data sources, this may require installing sensors or meters, gathering data from existing monitoring systems and public databases, and experimental data. For example, in the Chilean case, solar and wind resource measurements can be obtained from [34] and [41], respectively, while technical parameters for actual SPPs can be found in [39]. Once data, especially measurements, are gathered, cleaning and preprocessing may be necessary to ensure accuracy and consistency, such as removing outliers, filling in missing data, or converting data into a standard format. After cleaning and preprocessing, the resulting data can be stored in a suitable database or data management, which could include a cloud-based database or a local server [2], depending on the size and complexity of the data. It should be noted that the database will be the main source of information for subsequent stages. Finally, it is crucial to ensure that the data are stored and transmitted securely, and that any sensitive information is protected.

4.3. Development and Implementation of SPP DT

Once the technical data and parameters are available, the development and implementation of the DT model can begin. This involves creating a virtual representation of the SPP and its components and integrating them into a simulation environment. It should be noted that modeling and simulation form the basis of implementing DTs in practice [13]. The first step in creating an SPP DT is to develop precise models that accurately replicate the behavior of the actual system or asset. To achieve this, the most reliable information on the system dynamics should be utilized and merged with the accessible data, such as historical data obtained under different operational circumstances [2]. Combining the models of all subsystems and their interconnections results in a comprehensive system model.

To create suitable SPP DT models, physics-based, data-driven, or hybrid approaches can be utilized. Physics-based models rely on first-principle physical models and precise mathematical representations of the system dynamics to explain system behavior. The choice of modeling approach depends on the context, the type of SPP under study, and the technical information available and accessible. When information on some parameters is unknown, the model can be adaptively identified based on the most recent data that reflect the current operating conditions of the system [2]. The resulting SPP DT model can be implemented on a simulation platform suitable for this type of development (e.g., MATLAB/Simulink and PSCAD, among others). When selecting a simulation platform, it is important to consider factors such as model complexity, availability of modeling components, programming expertise required, and cost. Once the platform is selected, the SPP DT model can be built by choosing appropriate components and configuring them to represent the SPP in the MG context.

4.4. Tuning and Validation of SPP DT

The SPP DT needs to be validated against real-world data to ensure accuracy. Thus, tuning and validation are critical steps in the development of the SPP DT model in the MG context. Tuning involves adjusting the model parameters such as the simulation time-step, accuracy of the model's physical representation, and sensitivity of the model's controls to ensure that it accurately reflects the real-world system. On the other hand, validation involves comparing the DT model's output against real-world data, including energy consumption, solar radiation, temperature, and humidity, to ensure that it accurately reflects the actual SPP's behavior. The validation process may also involve simulating different scenarios using the SPP DT and identifying opportunities for improvement. Both tuning and validation can be performed using historical data collected from the physical system under various operating conditions [2]. As more data are collected and additional information about system performance is obtained, this information can be used to continually improve the DT model. By tuning and validating the DT model, it is feasible to ensure that it accurately represents the real-world system and provides valuable insights into system operation and performance.

5. Case Study

This section presents the application of the methodology described in Section 4 to a case study. This consists of an actual SPP for agricultural processing installed in Caleta Vítor near the city of Arica, in northern Chile [39].

5.1. Definition of the Scope and Modeling Requirements for the Caleta Vítor SPP DT

The SPP to be transformed into a DT model is a solar drying process used for agricultural products (see Section 2.2), which is connected to an MG (see Figure 4). The EMS is responsible for minimizing the operating costs and determining the operating setpoints for the MG. It should be noted that the EMS is formulated as presented in [12]. The solar dryer mainly comprises an electric heater, an electric fan, and auxiliary equipment for lighting and office devices. The drying period depends primarily on the temperature of the drying air, the type of product, and external variables such as ambient temperature, relative humidity, and solar radiation. On the one hand, the solar drying process primarily uses solar radiation to increase the internal temperature of the dryer, and, in this case, the electric fan is responsible for regulating the working temperature. Alternatively, during periods of the day when there is not enough solar radiation, the electric heater is used to maintain the drying temperature. In addition, the administrative activities of the SPP usually take place from 9:00 to 18:00. Given that the quality of the final product highly depends on keeping the inner temperature and the relative humidity of the solar dryer homogeneous and within the desired ranges to adequately carry out the drying process of the products, the SPP DT is used to operate the solar dryer in a way that leverages the available solar radiation in the drying process as much as possible, while reducing the negative effects of changes in the weather conditions on the inner temperature and relative humidity. To achieve this, the fan and heater are switched on/off accordingly. Importantly, the use of the SPP DT, as mentioned above, also helped to regulate the energy consumption of the solar dryer. In fact, the operation of these elements solely takes place when the SPP DT indicates that the temperature might exceed the limits of the desired range for the drying process.

5.2. Gathering of Data and Technical Parameters of SPP

The SPP physical system is a solar drying process. Figure 5a displays a picture of the actual solar dryer SPP installed in Caleta Vítor. Solar radiation and ambient temperature are the primary weather variables that influence the behavior of the solar dryer. Therefore, actual measurements of these variables, taken every 10 min, were obtained from [34] for the geographical location of the SPP. Additionally, the technical parameters of the solar dryer SPP required for the development and implementation of the DT model were obtained from [28].

Table 1 lists the main technical characteristics and thermal parameters of the solar dryer SPP. A more detailed description of the design, construction, and operating characteristics of the solar dryer can be found in [42]. It should be noted that this paper employed mass and energy balances to derive the DT for the case study. The parameters were acquired from the description of the solar dryer used, and the well-known ZIP model was utilized to interface the heat transfer equations with the electrical energy consumption. The ZIP model was chosen because the power consumption of the solar dryer depends not only on the weather conditions, but also on the voltage supply, specifically the power consumed by the fan and the heater to regulate the inner temperature and relative humidity of the dryer. The parameters of the ZIP model were obtained from actual measurements and using the identification procedure proposed in [11].

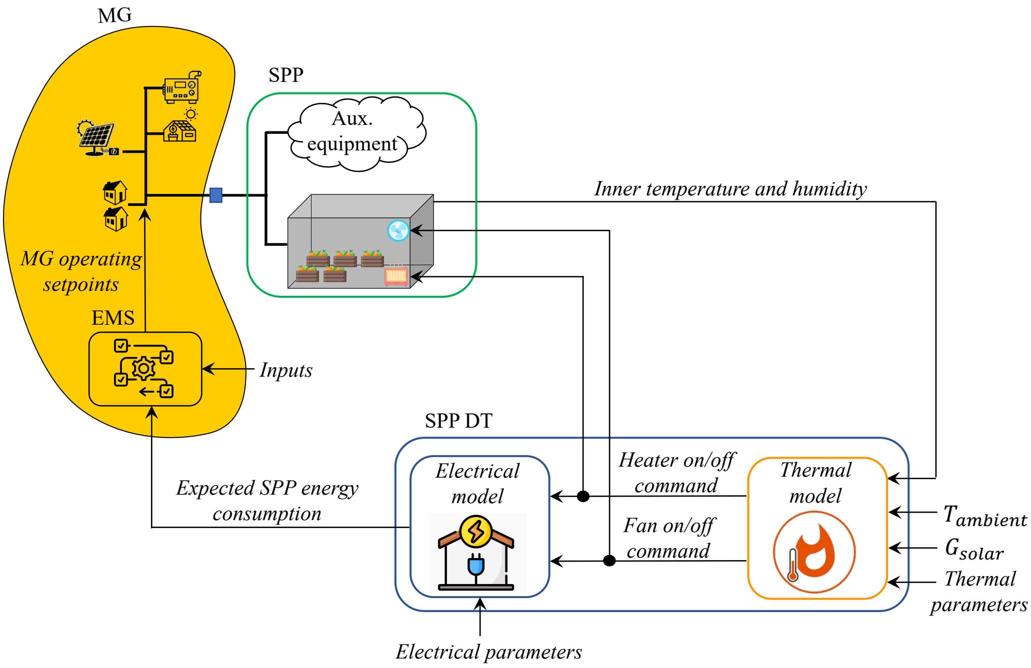

Figure 4. System topology including the physical part (i.e., MG, EMS, and SPP) and the SPP DT.

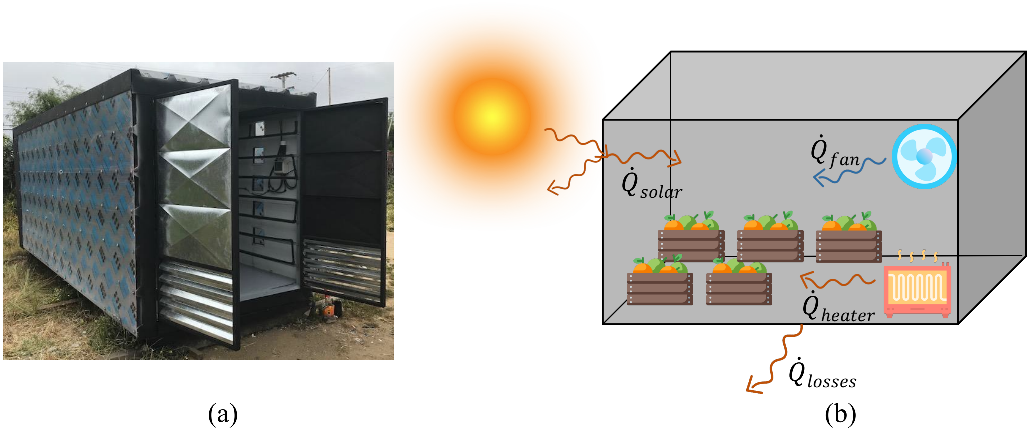

Figure 5. (**a**) Actual solar dryer SPP, (**b**) simplified overview of the solar dryer SPP and its heat flows.

5.3. Development and Implementation of the DT for the Caleta Vítor SPP

The SPP physical system is a thermoelectric system; therefore, a physical model-based approach is considered to build the virtual system. Figure 4b depicts a simplified overview of the physical system (i.e., the solar dryer) and its heat flows. The heat flows are represented by different variables, where $\dot{Q}_{solar}$ is the heat flow from solar radiation, $\dot{Q}_{heater}$ represents the heat flow from the electric heater, $\dot{Q}_{fan}$ is the heat flow removed by the electric fan, and $\dot{Q}_{losses}$ represent the heat flow lost through the dryer walls. The physical phenomena of the solar dryer are represented through heat transfer equations [43] as follows, with the heat flow from solar radiation expressed mathematically as Equation (1).

$$\dot{Q}_{solar} = A_{dryer}\left(\alpha G + \varepsilon\sigma\left(T_{sky}^4 - T_s^4\right)\right) \quad (1)$$

where A_{dryer} is the total area of dryer's walls exposed to the solar radiation G, α and ε represent the absorbance and emissivity coefficient of the wall, respectively, σ is the Boltzmann constant, T_{sky} is the temperature of the sky, and T_s is the temperature of the surface of the dryer's wall.

Table 1. Main technical characteristics and thermal parameters of the solar dryer.

Description	Technical Characteristics (Units)
Working temperature	~60 (°C) to 70 (°C)
Capacity	1400 (kg)–1800 (kg)
Container	Length = 5.4 (m)
	Width = 2.2 (m)
	Height = 2.1 (m)
	Material: zinc
Thermal insulation	High-density polyurethane film
	Thickness = 0.04 (m)
Electric fan	Nominal active power = 610 (W)
	Frequency = 50 (Hz)
	Diameter = 0.45 (m) Operating velocity = 0.45 (m/s) ZIP coefficients: Z = 0.26, I = 0.9, P = −0.16
Electric heater	Nominal active power = 2000 (W)
	Frequency = 50 (Hz) ZIP coefficients: Z = 0.92, I = 0.1, P = −0.02
Auxiliary equipment	Active power = 420–800 (W) Frequency = 50 Hz ZIP coefficients: - Lighting: Z = 0.52, I = 0.45, P = 0.03 - Office devices: Z = 0.08, I = 0.07, P = 0.85
Thermal parameters	Specific heat capacities: - Air = 1005.4 (J/kg·°K) - Banana = 3350 (J/kg·°K) Absorbance coefficient = 0.76 Emissivity coefficient = 0.6 Convective heat transfer coefficient = 17 (W/m^2·°C)

Equation (2) expresses a constant air flow rate provided by the i-th electric device ($i = \{heater, fan\}$) into the dryer.

$$\dot{Q}_i = \left(T_i - T_{dryer}\right)\dot{M}_i c \quad (2)$$

where T_i denotes the temperature of the air from the i-th electric device, $\dot{M}_i$ is the air mass flow rate through the i-th electric device ($i = \{heater, fan\}$), T_{dryer} represents the current inner temperature of the dryer, and c is the heat capacity of air at constant pressure.

The heat losses through the dryer's walls are represented in Equation (3).

$$\dot{Q}_{losses} = \left(T_{dryer} - T_{ambient}\right)/R_{eq} \tag{3}$$

where T_{out} denotes the ambient temperature, and R_{eq} is the equivalent thermal resistance of the dryer walls.

The current inner temperature of the solar dryer is obtained through Equation (4).

$$\frac{dT_{dryer}}{dt} = \frac{1}{\sum_{j \in \mathcal{J}} M_j c_j}\left(\dot{Q}_{solar} + \dot{Q}_{heater} - \dot{Q}_{fan} - \dot{Q}_{losses}\right) \tag{4}$$

where $\mathcal{J}$ is the set of products inside the dryer (including air), M_j and c_j are the mass and the heat capacity constant of each product, respectively.

The solar dryer is equipped with a thermostat that controls the operation of the fan or heater. When the temperature inside the dryer drops below 60 °C, the thermostat turns on the heater, while it turns on the fan when the temperature rises above 70 °C. The thermal and electrical components of the solar dryer DT model are coupled through the thermostat. The electrical representation of the heater and fan is performed using the well-known ZIP load model [33]. Note that expert knowledge of the actual solar dryer operation and historical active power consumption over two weeks of dryer operation [11] were used to validate and tune the models.

The SPP DT model has been primarily developed for the MG operation and the monitoring of the SPP. Figure 4 illustrates that each controllable load on the SPP (i.e., fan and heater) can be switched on/off based on the SPP DT's suggestions to use of the available solar radiation as much as possible. Moreover, the expected SPP energy consumption is sent to the EMS to decide on the MG's operating setpoints. The virtual system's data are also useful to validate EMS developments [12] and SPP load models [11].

The data preprocessing and virtual system implementation were developed in MATLAB/Simulink, while the electrical part was modeled and implemented using Simscape$^{\text{TM}}$ Electrical$^{\text{TM}}$ Specialized Power Systems blocks. The data management layer was implemented in MATLAB, where measurements and the best available knowledge obtained from the physical system were processed and shared with the virtual system. The computational experiments were conducted on an HP ENVY 27 All-in-One with an IntelR Core$^{\text{TM}}$ i7-4790T @2.70 GHz processor and 12.0 GB RAM.

Finally, it should be noted that the resulting SPP DT was tuned and validated by running several operating scenarios, considering the input data contained in the Supplementary Material Database available for this work.

6. Results and Discussion

This section presents the results obtained after developing the SPP DT model and applying the methodology to the case study. To analyze the performance of the model, actual data on solar radiation and outdoor temperature from two seasons (summer and winter), two types of days expected in practice (clear, and cloudy), and performance indicators (e.g., internal dryer temperature, active power consumption) were considered. In addition, to show the benefits of using the SPP DT model as decision-making support for EMS in the MG, one day of operation (24 h) was simulated, and a comparison of performance in terms of MG operating costs (in Chilean pesos or CLP) was performed. Figure 6 displays the actual solar radiation and outdoor temperature profiles, as well as the internal temperature of the solar dryer and active power consumption of the DT for clear days. Figure 7 shows the same profiles, but for cloudy days, with both figures corresponding to the summer and winter.

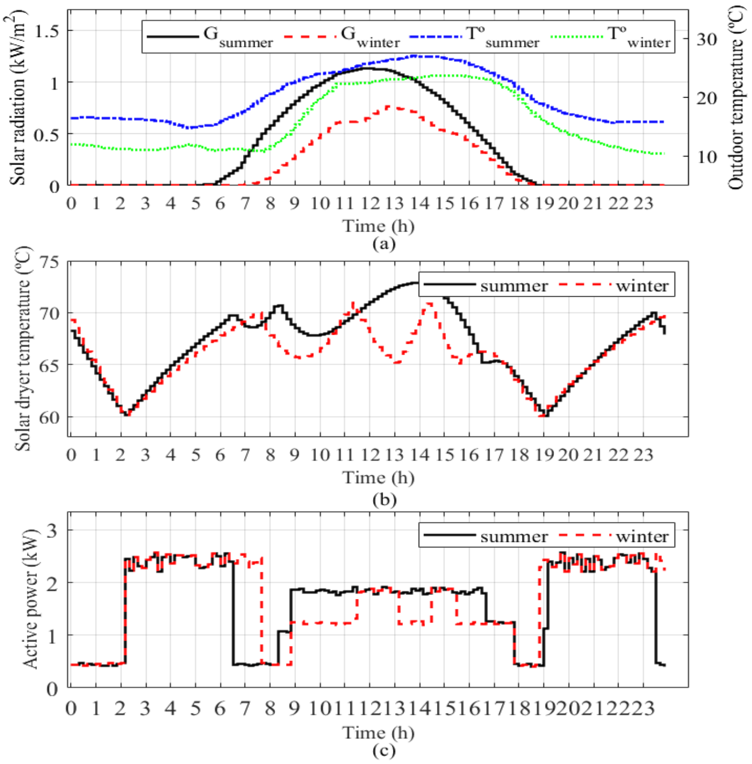

Figure 6. (**a**) Solar radiation and outdoor temperature, (**b**) solar dryer temperature, and (**c**) SPP active power consumption for clear days.

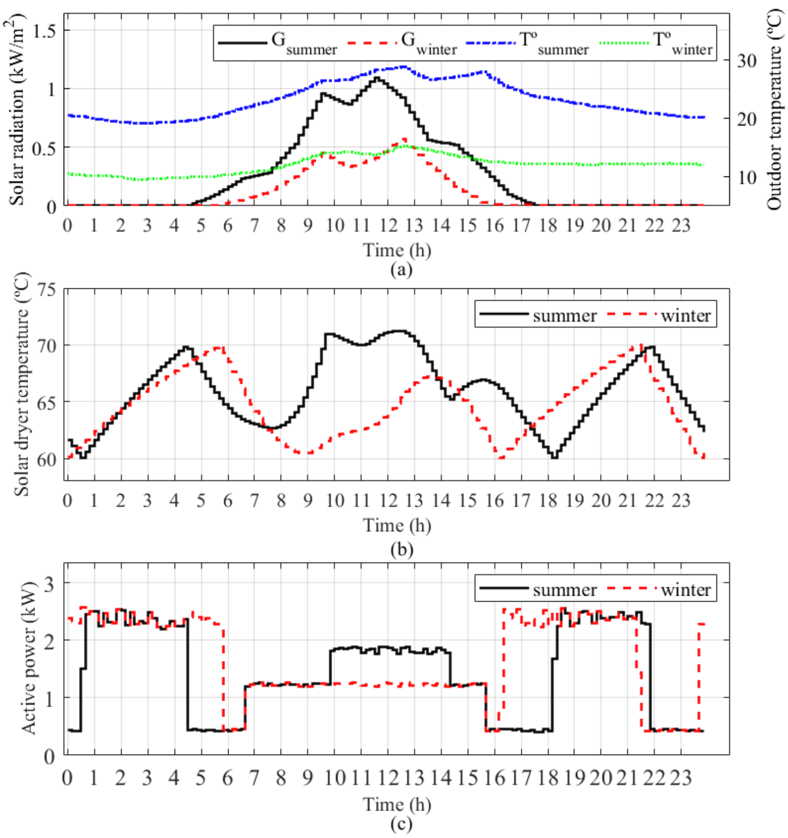

Figure 7. (**a**) Solar radiation and outdoor temperature, (**b**) solar dryer temperature, and (**c**) SPP active power consumption for cloudy days.

Table 2 summarizes the results of MG operation, including total MG operating cost (Total), minimum MG operating cost (Min), maximum MG operating cost (Max), average total MG operating cost for the evaluation day (Avg.), and the average operating cost reduction considering the EMS without SPP DT as the base case (Avg. red.).

Table 2. Summary of MG operating costs.

Approach	Total (CLP)	Min (CLP)	Max (CLP)	Avg. (CLP)	Avg. Red. (%)
EMS without SPP DT	3.93×10^6	1.29×10^3	8.89×10^3	5.84×10^3	-
EMS with SPP DT	3.74×10^6	1.18×10^3	8.89×10^3	5.60×10^3	5.06

As can be seen in Figure 6a, as expected, solar radiation is considerably lower in winter. Nevertheless, the maximum and minimum temperatures in the two seasons are not significantly different. Due to the higher solar contribution in summer, the solar dryer considerably increases its internal temperature between 12:00 and 14:00 (see Figure 6b). The highest solar contribution in winter occurs around 13:00. In Figure 6c, it can be observed that a greater use of the electric fan is made in summer due to the high solar contribution and the need to regulate the working temperature of the dryer. In contrast, in winter, the fan is turned on only twice, around 11:30 and 14:30. Moreover, in winter, the use of heaters is extended between 6:30 and 8:00 due to the low solar contribution in the morning compared to summer. These results are expected because there is less solar contribution in winter than in summer. Therefore, the productive process primarily uses the heater to reach and maintain the temperature during the entire drying period.

Cloudy days are expected in practice, and during these days, the solar radiation decreases considerably in both seasons (see Figure 7a). Additionally, cloudiness has a significant impact on the ambient temperature in winter, causing it to decrease considerably throughout the day compared to a clear day. These conditions drastically change the operation of the SPP compared to the previous case. For instance, as shown in Figure 7c, in summer, the decrease in solar contribution leads to practically no electric fan operation during the day, resulting in a decrease in SPP power consumption. On the other hand, during winter, the opposite effect is observed: the electric heater is active for a longer time due to the low contribution of solar radiation and the low ambient temperature caused by cloudiness, as shown in Figure 7b, to maintain the working temperature.

Table 2 presents the actual operating costs of the MG, and the results show that using the SPP DT model as a decision-making support for EMS leads to a significant reduction in total MG operating costs by approximately 5%. This outcome can be attributed to the fact that when operating the solar dryer using the SPP DT model, available solar radiation is leveraged to the fullest extent possible, thereby mitigating the negative effects of changes in weather conditions on the internal temperature and relative humidity. As a result, the EMS has more accurate information on the expected power consumption of the SPP. Finally, it should be noted that the proposed SPP DT model, particularly the active power consumption profiles, can be used to validate SPP load models, as demonstrated in previous studies conducted by the authors [11,12] in the context of MG analysis.

7. Conclusions

In this work, a methodological framework for developing DT models for SPPs was presented. A key novel feature is the incorporation of the actual technical characteristics and complexities of SPPs as part of a DT application for MGs. The methodology was validated in a case study consisting of a solar drying SPP. The SPP DT model was developed in MATLAB/Simulink, with actual summer and winter measurements of weather variables for clear and cloudy days used to evaluate the performance of the SPP DT model. The results demonstrated that using the SPP DT model as decision-making support for EMS can lead to a considerable reduction in the total MG operating costs (by around 5%). Moreover, the SPP DT model's performance is consistent with the expected results in the practical operation of the actual solar drying SPP. To provide further valuable evidence, future work should consider new case studies with different SPPs. Finally, MG DTs offer new opportunities for better engagement of communities in decentralized energy solutions, following the idea of Social SCADA presented in [44].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16114324/s1, File S1: Database.xlsx.

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References

1. Wood, E. What's Driving Microgrids toward a $30.9B Market? Available online: https://www.microgridknowledge.com/editors-choice/article/11430269/what8217s-driving-microgrids-toward-a-309b-market (accessed on 3 November 2022).
2. Bazmohammadi, N.; Madary, A.; Vasquez, J.C.; Mohammadi, H.B.; Khan, B.; Wu, Y.; Guerrero, J.M. Microgrid Digital Twins: Concepts, Applications, and Future Trends. *IEEE Access* **2022**, *10*, 2284–2302. [CrossRef]
3. Olivares, D.E.; Mehrizi-Sani, A.; Etemadi, A.H.; Cañizares, C.A.; Iravani, R.; Kazerani, M.; Hajimiragha, A.H.; Gomis-Bellmunt, O.; Saeedifard, M.; Palma-Behnke, R.; et al. Trends in Microgrid Control. IEEE Trans. *Smart Grid* **2014**, *5*, 1905–1919. [CrossRef]
4. Liu, G.; Ollis, T.B.; Xiao, B.; Zhang, X.; Tomsovic, K. Community Microgrid Scheduling Considering Network Operational Constraints and Building Thermal Dynamics. *Energies* **2017**, *10*, 1554. [CrossRef]
5. Olivares, D.E.; Cañizares, C.A.; Kazerani, M. A centralized optimal energy management system for microgrids. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–6.
6. Palma-Behnke, R.; Benavides, C.; Lanas, F.; Severino, B.; Reyes, L.; Llanos, J.; Sáez, D. A Microgrid Energy Management System Based on the Rolling Horizon Strategy. *IEEE Trans. Smart Grid* **2013**, *4*, 996–1006. [CrossRef]
7. Espín-Sarzosa, D.; Palma-Behnke, R.; Núñez-Mata, O. Energy Management Systems for Microgrids: Main Existing Trends in Centralized Control Architectures. *Energies* **2020**, *13*, 547. [CrossRef]
8. Liu, Y.; Wang, Y.; Li, Y.; Gooi, H.B.; Xin, H. Multi-Agent Based Optimal Scheduling and Trading for Multi-Microgrids Integrated with Urban Transportation Networks. *IEEE Trans. Power Syst.* **2021**, *36*, 2197–2210. [CrossRef]
9. Wang, Y.; Nguyen, T.-L.; Xu, Y.; Tran, Q.-T.; Caire, R. Peer-to-Peer Control for Networked Microgrids: Multi-Layer and Multi-Agent Architecture Design. *IEEE Trans. Smart Grid* **2020**, *11*, 4688–4699. [CrossRef]
10. IEEE PES Task Force on Microgrid Dynamic Modeling. *Trends in Microgrid Modeling for Stability Analysis*; Technical Report (PES-TR106); IEEE Power & Energy Society: Piscataway, NJ, USA, 2022.
11. Espín-Sarzosa, D.; Palma-Behnke, R.; Valencia, F. Modeling of Small Productive Processes for the Operation of a Microgrid. *Energies* **2021**, *14*, 4162. [CrossRef]
12. Espin-Sarzosa, D.; Palma-Behnke, R.; Valencia, F. Integration of Small Productive Processes into an Energy Management System for Microgrids. *IEEE Access* **2022**, *10*, 69010–69030. [CrossRef]
13. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. IEEE Trans. *Ind. Inform.* **2019**, *15*, 2405–2415. [CrossRef]
14. Zhou, M.; Yan, J.; Feng, D. Digital twin framework and its application to power grid online analysis. *CSEE J. Power Energy Syst.* **2019**, *5*, 391–398. [CrossRef]
15. Qi, Q.; Tao, F. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access* **2018**, *6*, 3585–3593. [CrossRef]

16. Leng, J.; Wang, D.; Shen, W.; Li, X.; Liu, Q.; Chen, X. Digital twins-based smart manufacturing system design in Industry 4.0: A review. *J. Manuf. Syst.* **2021**, *60*, 119–137. [CrossRef]
17. Liu, Y.; Zhang, L.; Yang, Y.; Zhou, L.; Ren, L.; Wang, F.; Liu, R.; Pang, Z.; Deen, M.J. A Novel Cloud-Based Framework for the Elderly Healthcare Services Using Digital Twin. *IEEE Access* **2019**, *7*, 49088–49101. [CrossRef]
18. Damjanovic-Behrendt, V. A Digital Twin-based Privacy Enhancement Mechanism for the Automotive Industry. In Proceedings of the 2018 International Conference on Intelligent Systems (IS), Funchal-Madeira, Portugal, 25–27 September 2018; pp. 272–279.
19. Min, Q.; Lu, Y.; Liu, Z.; Su, C.; Wang, B. Machine Learning based Digital Twin Framework for Production Optimization in Petrochemical Industry. *Int. J. Inf. Manage* **2019**, *49*, 502–519. [CrossRef]
20. Brosinsky, C.; Westermann, D.; Krebs, R. Recent and prospective developments in power system control centers: Adapting the digital twin technology for application in power system control centers. In Proceedings of the 2018 IEEE International Energy Conference (ENERGYCON), Limassol, Cyprus, 3–7 June 2018; pp. 1–6.
21. Boschert, S.; Rosen, R. *Digital Twin—The Simulation Aspect BT—Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers;* Hehenberger, P., Bradley, D., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 59–74; ISBN 978-3-319-32156-1.
22. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*; Kahlen, F.-J., Flumerfelt, S., Alves, A., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 85–113; ISBN 978-3-319-38756-7.
23. Brosinsky, C.; Song, X.; Westermann, D. Digital Twin—Concept of a Continuously Adaptive Power System Mirror. In Proceedings of the International ETG-Congress, Esslingen, Germany, 8–9 May 2019; pp. 1–6.
24. Jafari, M.; Kavousi-Fard, A.; Chen, T.; Karimi, M. A Review on Digital Twin Technology in Smart Grid, Transportation System and Smart City: Challenges and Future. *IEEE Access* **2023**, *11*, 17471–17484. [CrossRef]
25. Shafto, M.; Conroy, M.; Doyle, R.; Glaessgenn, E.; Kemp, C.; LeMoigne, J.; Wang, L. NASA technology roadmap: Modeling, simulation, information technology and processing roadmap technology area 11. *Nat. Aeronaut. Sp. Admin.* **2012**, *32*, 1–38.
26. Mashaly, M. Connecting the Twins: A Review on Digital Twin Technology & its Networking Requirements. *Procedia Comput. Sci.* **2021**, *184*, 299–305. [CrossRef]
27. Park, H.-A.; Byeon, G.; Son, W.; Jo, H.-C.; Kim, J.; Kim, S. Digital Twin for Operation of Microgrid: Optimal Scheduling in Virtual Space of Digital Twin. *Energies* **2020**, *13*, 5504. [CrossRef]
28. Danilczyk, W.; Sun, Y.; He, H. ANGEL: An Intelligent Digital Twin Framework for Microgrid Security. In Proceedings of the 2019 North American Power Symposium (NAPS), Wichita, KS, USA, 13–15 October 2019; pp. 1–6.
29. Hong, Y.-Y.; Apolinario, G.F.D. Ancillary Services and Risk Assessment of Networked Microgrids using Digital Twin. *IEEE Trans. Power Syst.* **2022**, 1–15. [CrossRef]
30. Saad, A.; Faddel, S.; Youssef, T.; Mohammed, O.A. On the Implementation of IoT-Based Digital Twin for Networked Microgrids Resiliency Against Cyber Attacks. IEEE Trans. *Smart Grid* **2020**, *11*, 5138–5150. [CrossRef]
31. Saha, D.; Bazmohammadi, N.; Raya-Armenta, J.M.; Bintoudi, A.D.; Lashab, A.; Vasquez, J.C.; Guerrero, J.M. Space Microgrids for Future Manned Lunar Bases: A Review. *IEEE Open Access J. Power Energy* **2021**, *8*, 570–583. [CrossRef]
32. Qian, C.; Liu, X.; Ripley, C.; Qian, M.; Liang, F.; Yu, W. Digital Twin—Cyber Replica of Physical Things: Architecture, Applications and Future Research Directions. *Futur. Internet* **2022**, *14*, 64. [CrossRef]
33. Arif, A.; Wang, Z.; Wang, J.; Mather, B.; Bashualdo, H.; Zhao, D. Load Modeling—A Review. *IEEE Trans. Smart Grid* **2018**, *9*, 5986–5999. [CrossRef]
34. Molina, A.; Falvey, M.; Rondanelli, R. A solar radiation database for Chile. *Sci. Rep.* **2017**, *7*, 14823. [CrossRef] [PubMed]
35. Booth, S.; Li, X.; Baring-Gould, I.; Kollanyi, D.; Bharadwaj, A.; Weston, P. *Productive Use of Energy in African Micro-Grids: Technical and Business Considerations*; National Renewable Energy Lab: Golden, CO, USA, 2018.
36. Terrapon-Pfaff, J.; Gröne, M.-C.; Dienst, C.; Ortiz, W. Productive use of energy—Pathway to development? Reviewing the outcomes and impacts of small-scale energy projects in the global south. *Renew. Sustain. Energy Rev.* **2018**, *96*, 198–209. [CrossRef]
37. Jimenez-Estevez, G.; Palma-Behnke, R.; Latorre, R.R.; Moran, L. Heat and Dust: The Solar Energy Challenge in Chile. *IEEE Power Energy Mag.* **2015**, *13*, 71–77. [CrossRef]
38. Ramirez-Del-Barrio, P.; Mendoza-Araya, P.; Valencia, F.; León, G.; Cornejo-Ponce, L.; Montedonico, M.; Jiménez-Estévez, G. Sustainable development through the use of solar energy for productive processes: The Ayllu Solar Project. In Proceedings of the 2017 IEEE Global Humanitarian Technology Conference (GHTC), San Jose, CA, USA, 19–22 October 2017; pp. 1–8.
39. SERC-Chile Ayllu Solar. Available online: https://ayllusolar.cl/en/iniciative/ (accessed on 10 December 2021).
40. Ayllu-Solar. *Solar Energy: Sustainable Development for Arica & Parinacota Semi-Annual Y4Q2 Report*; Ayllu-Solar: Santiago, Chile, 2018.
41. Muñoz, R.C.; Falvey, M.J.; Arancibia, M.; Astudillo, V.I.; Elgueta, J.; Ibarra, M.; Santana, C.; Vásquez, C. Wind Energy Exploration over the Atacama Desert: A Numerical Model–Guided Observational Program. *Bull. Am. Meteorol. Soc.* **2018**, *99*, 2079–2092. [CrossRef]
42. Espinoza, J. Innovación en el deshidratado solar. *Ingeniare. Rev. Chil. Ing.* **2016**, *24*, 72–80. [CrossRef]

43. Yunus, A.; Cengel, D.; Ghajar, A.J. *Heat and Mass Transfer: Fundamentals and Applications*; McGraw-Hill Education: New York, NY, USA, 2014; ISBN 9780073398181.
44. Palma-Behnke, R.; Ortiz, D.; Reyes, L.; Jiménez-Estévez, G.; Garrido, N. A social SCADA approach for a renewable based microgrid—The Huatacondo project. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–7.