

Virtual Power Plant Solution for Future Smart Energy Communities

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First published 2023

ISBN: 978-1-032-18978-9 (hbk)

ISBN: 978-1-032-18979-6 (pbk)

ISBN: 978-1-003-25720-2 (ebk)

Chapter 11

Complementarity and Flexibility Indexes of an Interoperable VPP

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DOI: 10.1201/9781003257202-12

The funder for this chapter is
H2020



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

11 Complementarity and Flexibility Indexes of an Interoperable VPP

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CONTENTS

11.1	Introduction	210
11.2	Complementarity	210
11.2.1	Overview.....	210
11.2.2	Proposed Method.....	212
11.3	Flexibility.....	213
11.3.1	Overview.....	213
11.3.2	Proposed Method.....	214
11.4	Case Study	215
11.4.1	Complementarity	216
11.4.2	Flexibility.....	217
11.5	Conclusion and Future Work	218
	Acknowledgment	219
	References.....	219

NOMENCLATURE

API	application programming interface
CI	complementarity index
CL	controllable loads
DER	distributed energy resource
ES	energy source
FI	flexibility index
RES	renewable energy source
S	energy storage
VPP	virtual power plant
VRE	variable renewable energy

11.1 INTRODUCTION

The field of energy systems has received special attention in this decade from the scientific community around the world. This is due to the urgent need for a sustainable transition to a fossil-free energy system with low greenhouse gas emission which will ensure a safe environment. Renewable energy systems are the main component of this energy source (ES) transition. So most proposed studies for the transition are based on how to integrate renewable ESs (RESs) to existing grid systems and then reduce the use of fossil ESs. As a result, during this decade, RES has gained an increasing penetration over fossil ESs [1]. But wind and solar have a high share of RES integration [1] with both being VRE (variable renewable energy) generators, and this results in a huge challenge in planning, transmission and distribution of energy. It then becomes more obvious to think about a better way of analyzing the entire grid composition and its behaviors. Analyzing the flexibility of the grid and the complementarity of virtual power plant (VPP) components can provide a better understanding of its behaviors from intraday to years.

In our study and according to [2], a VPP is a practical concept that combines various distributed energy resources (DERs) to improve energy management efficiency and facilitate energy trading. The main purposes of a VPP are to enhance and optimize power generation, as well as trading or selling power on the electricity market. A VPP can be considered to be performant in one hand if its components form together an optimal combination based on a defined criteria, and on the other hand, it has the ability to handle the variability or fluctuation and uncertainty on both generation and consumption side. This chapter will propose two metrics called complementarity index (CI) and flexibility index (FI) to determine, respectively, the level of complementarity and flexibility of a given standalone and interoperable VPP.

As VPP can be composed of RES and non-RES energy generators, this study will focus on VPP composed of only RES as energy generators, storage systems and controllable loads (CLs).

We also assume that the VPP is installed in a standalone manner, which allows it to fully control the system and provide better management in transmission and distribution. These kinds of VPP are useful for island cities.

In the next sections, we will first present an overview of CI in the literature, then the proposed metric for CI calculation. After that, similar study will be carried out for the FI and then will present a case study in order to experiment with these indexes and assess preliminary results, and finally, future work and conclusion are described.

11.2 COMPLEMENTARITY

11.2.1 OVERVIEW

The choice of VPP energy resources and other components is a critical investment decision for managers. This task needs proper information that states the context and gives better understanding of the current need of the VPP. The evaluation of VPP

resources complementarity between each other and especially the complementarity between ESs allow one to make an appropriate decision. The CI is a popular evaluation metric that determines how much complementary VPP resources or components provide.

According to [3], complementarity should be considered as the capability of energy components of working in a complementary way, and it can be observed in time, space and jointly in both domains. ES complementarity can be mainly divided into spatial, temporal and spatiotemporal complementarity. One or more ESs are considered to be spatially complementary when their production complements each other in different space or regions. And two or more ESs are considered to be temporarily complementary when their production complements each other at different periods of time in the same region or space. Spatiotemporal complementarity consists of using both temporal and space complementarity during the analysis. Beluco et al. in [4] defined complementarity in the energy field as the capacity of two or more ESs to be complementary available between them. And then propose a CI K defined by equation (11.1), where K_t , K_e and K_a are partial indexes measuring complementary based on time, energy and amplitude, respectively.

$$K = K_t \times K_e \times K_a \quad (11.1)$$

Time-complementarity K_t is defined by equation (11.2), where D and d are, respectively, the number of maximum and minimum days of availability of a given ES.

$$K_t = \frac{|d_1 - d_2|}{\sqrt{|D_1 - d_1| |D_2 - d_2|}} \quad (11.2)$$

Energy-complementarity K_e is defined by equation (11.3) where E represents the total energy produced by a given source during the year.

$$K_e = 1 - \frac{|E_1 - E_2|}{|E_1 + E_2|} \quad (11.3)$$

Amplitude-complementarity K_a is defined by equation (11.4), where δ_1 and δ_2 represent a score resulting from equation (11.5), where E_{max} , E_{min} and E_{av} represent, respectively, in equation (11.5) maximum, minimum and average value of energy availability for a given source.

$$K_a = \begin{cases} 1 - \frac{(\delta_1 - \delta_2)^2}{(1 - \delta_2)^2}, & \text{if } \delta_1 \leq \delta_2 \\ \frac{(1 - \delta_2)^2}{(1 - \delta_2)^2 + (\delta_1 - \delta_2)^2}, & \text{if } \delta_1 \geq \delta_2 \end{cases} \quad (11.4)$$

$$\delta = 1 + \frac{E_{max} - E_{min}}{E_{av}} \quad (11.5)$$

Beluco et al. used CI in [4] to develop a complementarity map of wind and solar energy based on Rio Grande do Sul energy data. Also in [5], it was used to evaluate complementarity between wind, hydropower and solar energy based on Rio Grande do Sul energy data. In [6], maps of correlation between wind and water were used to evaluate the complementarity between both ESs based on Brazilian territory energy data.

In this chapter, we will propose a novel evaluation metric to calculate the CI of a VPP that will take into account ES, available storage, CL capacity and consumption loads. The methodology presented is based on the assumption that the VPP is or will work in a standalone environment where it handles all the processes from energy generation to consumption without any outside influence.

11.2.2 PROPOSED METHOD

Given a VPP, V , with a set of ESs, $ES = es_1, es_2, \dots, es_n$, a set of energy storage, $S = s_1, s_2, \dots, s_n$ and a set of CL, $CL = cl_1, cl_2, \dots, cl_n$. V is defined as complementary VPP if for each element es_i of ES , there is another element es_j in ES that can compensate the energy loss or excess of es_i while responding to the VPP fluctuation or variation in both generation and consumption, and also if its CL and storages can be used to regulate the network when total generation and total consumption do not match in a single point of time. CI allows us to determine this degree or level of complementarity.

This index is divided into three different parts: journey CI between ESs, seasonal CI between ESs and the index of tolerance of the VPP that represents the usability of the storage systems and CL to mitigate the gaps between demand-response. So the complementarity index, CI , is defined by equation (11.6), where $Card(ES)$ is a number of active ESs of the VPP.

$$CI = \begin{cases} \frac{1}{3}(CI_{journey} + CI_{seasonal} + CI_{tolerance}) \\ 0 \text{ if } Card(ES) \leq 1 \end{cases} \quad (11.6)$$

The journey complementarity index, $CI_{journey}$, is defined by equation (11.7), where we iteratively look for highest negative correlation between es_h that represents the hourly energy production of a single ES of the VPP and the u_h which characterizes the hourly production of all ESs along a full day.

$$CI_{journey} = \sum_{es_h \in ES} \frac{\min(0, \text{argmin}(\text{corr}(es_h, u_h)))}{Card(ES)} \quad \forall u_h \in ES \quad (11.7)$$

The seasonal complementarity index, $CI_{seasonal}$, is defined by equation (11.8), where es_d and u_d are similar to es_h and u_h in $CI_{journey}$ but with daily data along the full year.

$$CI_{seasonal} = \sum_{es_d \in ES} \frac{\min(0, \text{argmin}(\text{corr}(es_d, u_d)))}{\text{Card}(ES)} \quad \forall u_d \in ES \quad (11.8)$$

The tolerance complementarity index, $CI_{tolerance}$, is defined by equation (11.9), where $load_t$ and $prod_t$ represent, respectively, the total energy production and consumption at a given time, N defines the number of observations, $storage$ and cl represent, respectively, the total number of storage and CL capacity. ϵ_1 and ϵ_2 represent, respectively, the degree of consideration of the capacity of storage and CL over their total values. The $CI_{tolerance}$ is very important to distinguish the complementarity between VPPs with and without storage systems. Also, the capacity of storage will have an impact on the CI index of any VPP. The higher the capacity, the more complementarity weight will increase.

$$CI_{tolerance} = \sum_{t=1}^N \frac{1 - \min\left(1, \frac{|load_t - prod_t|}{storage \times \epsilon_1 + cl \times \epsilon_2}\right)}{N} \quad (11.9)$$

11.3 FLEXIBILITY

11.3.1 OVERVIEW

With the increasing penetration of RESs (especially wind and solar) in power systems, the planning and control of the power system are becoming a huge challenge due to their uncertainty and variability. The capacity of the VPP to handle these uncertainty and variation during time is called flexibility. In [7], the term flexibility was defined as the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost over different time horizons. Another definition of the term in [8] was the ability of a power system to maintain continuous service in face of rapid and large swings in supply and demand.

FI is a metric to determine the level of flexibility of a power system. It can be used by VPP managers to monitor and improve the power system. Different metrics were proposed in the literature for its calculation. Berahmandpour, Montaser Kouhsari and Rastegar introduce in [9] a new FI for real-time operation incorporating wind farms. This index is based on up and down generation constraints and ramp rate limitations of each unit of the power system. The insufficient ramping resource expectation (IRRE) metric was proposed to measure power system flexibility for use in long-term planning [10]. Zhao, Zheng and Litvinov introduce a Boolean-based index indicating whether or not a power system's largest variation range is within a given target range [11].

In this chapter, we propose an FI that takes into account VPP historical or forecasted ES production, available free and full storage capacity, ramping capacity and loads data in a given time horizon. A detailed explanation of the methodology will be presented in the next section.

11.3.2 PROPOSED METHOD

Consider a given VPP, V , composed of a $ES = es_1, es_2, \dots, es_n$ and $S = s_1, s_2, \dots, s_n$, which are, respectively, a set of energy generation sources that can be dispatchable (provide ramping capabilities) or intermittent and energy storage. V is said to be flexible at a given time t if the difference between generation and loads can be covered by the storage capacity or by ramping up or down some of its energy generation source even with some unexpected variations from loads or generations (mainly intermittent sources). The proposed FI is based on seeking for V deficiency to provide flexibility over time. The final FI of V in a specific interval is the mean FI of V at each time and defined by equation (11.10).

$$FI = \frac{1}{N} \sum_{t=1}^N Flex(t) \quad (11.10)$$

where $Flex(t)$ is the FI at time t . It is defined by equation (11.11). In order to quantify the level of the flexibility at a given time, consider a $E = \{(i_1, j_1), (i_2, j_2), \dots, (i_n, j_n)\}$ a set of couples of random variations from loads and generations, $Flex(t)$ given by equation (11.11) is the mean of the FI at time t with every couple of variations. This index shows how well V handles uncertainty and variability from both generation and loads.

$$Flex(t) = \frac{1}{Card(E)} \sum_{(i,j) \in E} Flex(t, i, j) \quad (11.11)$$

where $Flex(t, i, j)$ determines the FI at time t according to i and j that represent, respectively, the variation generated from productions and loads. This index has a float basis, so its value can only be between 1 if flexible and 0 otherwise. $Flex(t, i, j)$ is then defined by equation (11.12) where we assume that the ramping up and down are superior to zero and the difference between production and consumption is never equal to zero.

$$Flex(t, i, j) = \begin{cases} \min\left(1, \frac{full_storage_t + ramp_up_t}{|prod_t * i - load_t * j|}\right) & \text{if } prod_t * i - load_t * j < 0 \\ \min\left(1, \frac{free_storage_t + ramp_down_t}{|prod_t * i - load_t * j|}\right) & \text{if } prod_t * i - load_t * j > 0 \end{cases} \quad (11.12)$$

where $full_storage_t$ and $free_storage_t$ determine, respectively, the total stored energy that can be consumed the available storage capacity at time t , $ramp_up_t$ and $ramp_down_t$,

represent, respectively, the total ramping up and down capacity at time t , and $prod_t$ and $load_t$ are, respectively, total energy production and consumption at time t .

11.4 CASE STUDY

To test and assess these factors, an interoperable API was developed to facilitate the future demonstration in real-settings conditions. The API will have many modules (see Figure 11.1) in order to provide a tailored solution based on the requirements. One of these modules is responsible for data transfer or ingestion between the API and other external data providers. This module supports three main data transfer protocols such as Http(s), WebSocket and MQTT. Http protocol is used by API clients to send or retrieve data from the module where a new connection is established for each request. WebSocket protocol is used by clients to establish a connection with the module one time and then can send or receive data in real time without establishing new connection. The MQTT protocol is used to communicate with a shared MQTT server that does not belong to the API, but our module uses this server to listen for new data and also broadcast data to clients through this protocol. By providing these multiple communication protocols, any VPP including this API will be interoperable with different modules and paradigms.

In this case study, we use the “Île-de-France” region energy generation in 2020 dataset [12] to provide a real-world usage of the proposed CI and FI. For the sake of simplicity, only wind, solar and bioenergy are used in this study as clean energy

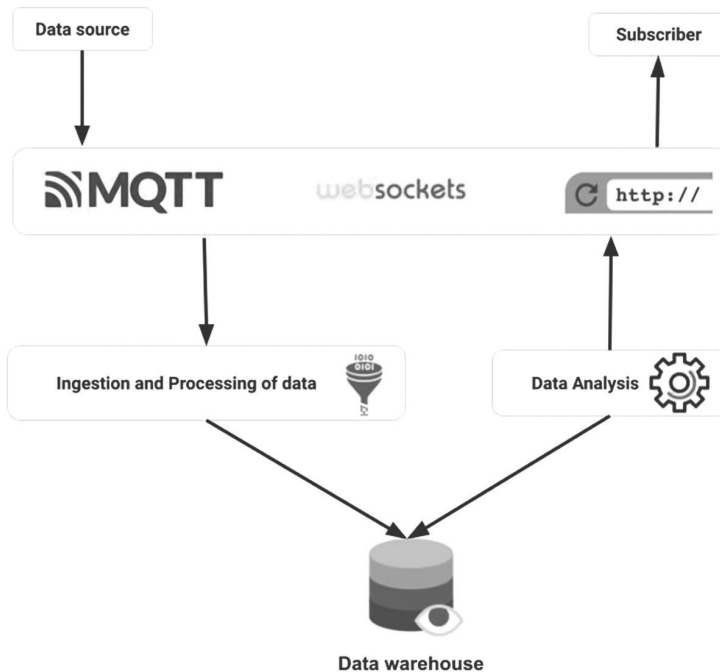


FIGURE 11.1 Interoperable cloud-based application.

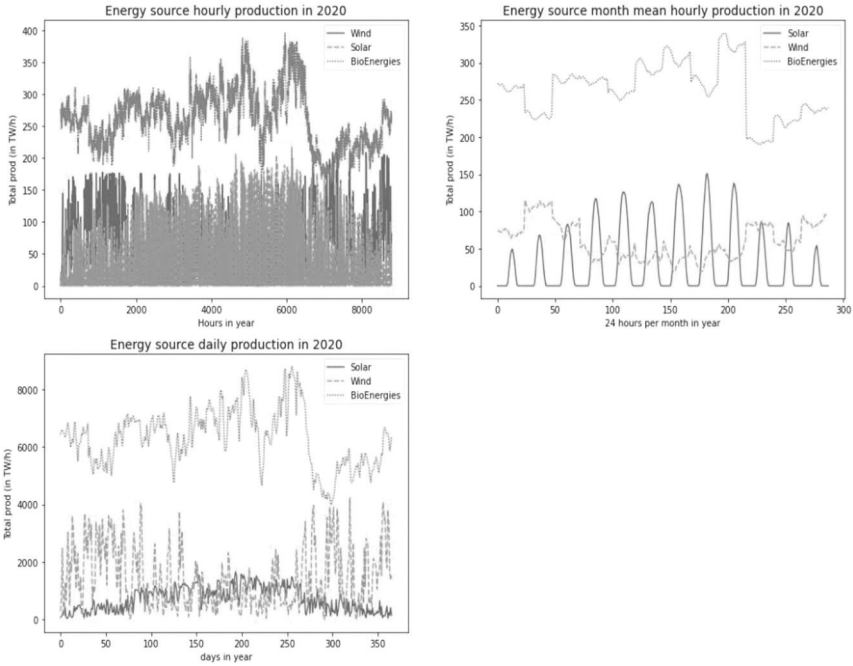


FIGURE 11.2 Energy source generations in 2020.

generation sources. Bioenergy is dispatchable and provides a ramping capacity that can be used to regulate the energy network. We also fine tune the load consumption according to the used ES as we did not use all ESs.

Figure 11.2 depicts different ways of visualizing each ES production capacity during the year of 2020, where the first column shows the total energy produced by each source per hour. We can see that a high share of the production is ensured by the bioenergy source. The second column shows the mean hourly total production of a given month of each source. We can notice the expected behaviors of the solar source which is only available at some hours during a day. Then the third column shows the total daily energy production per source, also wind sources decrease in spring and summer, whereas solar increase which can be considered as a kind of potential complementarity.

Figure 11.3 depicts the total energy generation resulting from aggregation of three sources and total energy consumption (loads). The first column displays, respectively, total generation and consumption per hours, whereas the second column the per day. We can notice that variations of consumption are more important than the production fluctuation.

11.4.1 COMPLEMENTARITY

In order to evaluate the level of complementarity of this power system in “Île-de-France”, we computed the CI with different values of storage CL capacity. Table 11.1 describes the obtained results.

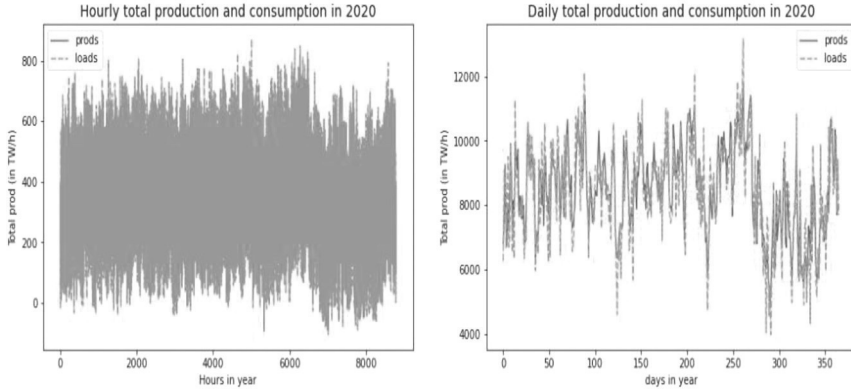


FIGURE 11.3 Energy total production and consumption in 2020.

As shown in Table 11.1, we can see that the couple (wind-solar) is more complementary than the couple (bioenergy-wind) which confirms that the VPP components have real impact on the complementarity. Moreover, we note that the power system provides a highly seasonal complementarity than journey, which can be seen in Figure 11.2. Also, the CI decreases with low-level storage and CL capacities decreases. One thing to remember is that the storage and CL are crucial to this power system, because if wind and solar variations exceed the ramping capacity, the entire system will go down.

11.4.2 FLEXIBILITY

To evaluate the flexibility of the system, we introduced various values of available storage capacities (0, 50, 100 MWh). This can be used as backup when the ramping capacity of the bioenergy is not able to balance the network. The normal production capacity of the installed bioenergy is 120 MW/h with a ramping up capacity of 60%

TABLE 11.1
Complementarity Index with Different Storage and CL Capacity

ESs	Controllable		Journey CI	Season CI	Tolerance CI	CI
	Storage	loads				
0 Wind, Solar	500	200	0.223689	0.445353	0.784346	0.484463
1 Wind, Solar	500	10	0.223690	0.445354	0.704162	0.457735
2 Wind, Solar	100	250	0.223691	0.445355	0.569307	0.412783
3 Wind, Solar	0	0	0.223692	0.445356	0.002277	0.223773
4 BioEnergy, Wind	500	200	0.209926	0.266876	0.786136	0.420979
5 BioEnergy, Wind	500	10	0.209927	0.266877	0.706618	0.394473
6 BioEnergy, Wind	100	250	0.209928	0.266878	0.572882	0.349895
7 BioEnergy, Wind	0	0	0.209929	0.266879	0.002049	0.159617

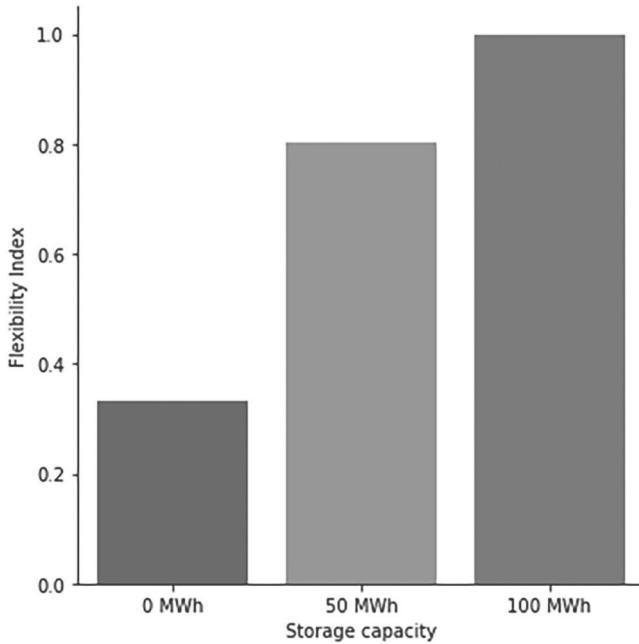


FIGURE 11.4 Flexibility index with different level of storage.

and ramping down capacity of 40%. Figure 11.4 shows the obtained result of the FI with different storage capacities.

As presented in Figure 11.4, we can notice that the actual ramping capacity (where the storage capacity is null and with only the ramping up [30% of 120 MWh] or down [15% of 120 MWh] capacities) did not provide enough flexibility to balance the power system when there are unexpected variations in energy production or consumption, however when the capacity of the storage increased, the FI rises significantly. Therefore, a VPP with a high share of variable renewable energy sources and low ramping capacities will require a high capacity of storage system to become flexible.

11.5 CONCLUSION AND FUTURE WORK

Recent years have been marked by an increasing penetration of renewable energy systems in power systems due to the desire to move from fossil ES to fossil-free ES as soon as possible. The integration of RESs comes with planning and control challenges, as the high share of renewable sources actually integrated are wind and solar that are both variable and nondispatchable. Defining key metrics that help power system (VPP) managers to make proper planning and control very accurately will allow RES to be easily integrated among existing grids. In this chapter, we propose methodology beyond the state of the art to calculate the level of complementarity (CI) and flexibility indexes (FI) of a power system. The preliminary results show that the combination of energy sources impact the complementarity of VPP. Regarding

the flexibility index, the ramping and especially the storage systems are crucial to improve the flexibility of a green power system.

CI calculates how complementary are the power system components such as ES, storage capacity and CL capacity. The methodology defines two ESs as complementary if they have a negative correlation over time. FI determines how well the power system handles unexpected behaviors from both generation and consumption side. This index is calculated by determining a set of variabilities in generation and consumption over time and then seeking where the power system failed.

The provided FI and CI do not consider the price fluctuation and the configuration of the different used RESs in their equations. In future research, we intend to adapt the equation to one that use these parameters and also integrate fossil ESs in order to make tools to handle this transition phase.

ACKNOWLEDGMENT

This work was carried out by the H2020 VPP4ISLANDS Project co-funded by the European Commission under the agreement GA No. 957852.

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