Optimal Participation of Virtual Power Plants in the Electricity Market Considering Multi-Energy Systems

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***Abstract*—The growth and modernization of the power system are the keys to enabling economic progress. The deregulation, added to the new emerging production technologies, conversion, and storage, triggered a change in the way of managing the power system worldwide. This work analyses the optimal dispatch of a virtual power plant (VPP) with active participation in the electricity market, considering multi-energy systems. The objective is to minimize the total operating cost of the power plant. The power plant is fed by two external networks: electrical and natural gas. The VPP is composed of energy production, conversion, and storage technologies, also considering the integration of a wind turbine and a set of electric vehicles (EVs). In addition to the Grid-to-Vehicle (G2V) charging, the advantage of Vehicle-to-Grid (V2G) technology is also verified, which allows the injection of power into the grid through the vehicles and Vehicle-to-Load (V2L) technology, enabling EVs to contribute to the satisfaction of the electrical load, reducing the costs, showing the advantages as well of EVs' integration in the VPP under analysis.**

Keywords— Electric vehicle; Energy storage system; Multi-energy system; Renewable energy; Virtual power plant

NOMENCLATURE

Indexes

t, Ω^T	Time / Time slot set.
s, Ω^S	Scenario / Scenario set.
n, Ω^N	Electric Vehicle /Set of Electric Vehicles.

Parameters

σ_t^{Elec}	Penalization factor from electricity waste.
$\sigma_t^{Heating}$	Penalization factor from heat waste.
$\sigma_t^{Cooling}$	Penalization factor from cooling waste.
ω_s	Probability of scenario s.
λ_t^{Sell}	Energy selling price.
λ_t^{Buy}	Energy buying price.
$F_{s,t}^{CHP}$	Operational cogeneration cost at time t, scenario s.
$F_{s,t}^{Boiler}$	Operational boiler cost at time t, scenario s.
$F_{s,t}^{Chiller}$	Operational chiller cost at time t, scenario s.
$F_{s,t}^{EHP}$	Operational electric heating pump cost at time t, scenario s.
$P_{s,t}^{Load}$	Power load at time t, scenario s.
$PH_{s,t}^{Load}$	Heat load at time t, scenario s.
$PC_{s,t}^{Load}$	Cooling load at time t, scenario s.
$COP^{Chiller}$	Absorption cooling performance coefficient.
COP^{Heater}	Electric heater performance coefficient.
$COP^{EHP,Heating}$	Heating pump performance coefficient in heating mode.
$COP^{EHP,Cooling}$	Heating pump performance coefficient in cooling mode.
PL^{Max}	Distribution feeder maximum power flow.
$\eta^{EV,Ch}$	Electric vehicle charging efficiency (%).
$\eta^{EV,Dis}$	Electric vehicle discharging efficiency (%).
$\eta^{ESS,Ch}$	Energy storage system charging efficiency (%).
$\eta^{ESS,Dis}$	Energy storage system discharging efficiency (%).
T_c	Electric vehicle plugin time. (h).
T_d	Electric vehicle unplugging time (h).

Variables

$PG_{s,t}^{G2H}$	Transmission power from the grid to the central (kW), at time t, scenario s.
$PG_{s,t}^{H2G}$	Transmission power from the central to the grid (kW), at time t, scenario s.
$PG_{s,t}^{CHP}$	Cogeneration power produced (kW), at time t, scenario s.
$PH_{s,t}^{CHP}$	Cogeneration power heating produced (kW), at time t, scenario s.
$PC_{s,t}^{EHP}$	Heating power pump produced (kW), in cooling mode at time t, scenario s.
$PH_{s,t}^{EHP}$	Heating power pump produced (kW), in heating mode at time t, scenario s.
$PH_{s,t}^{Boiler}$	Boiler heat power produced (kW), at time t, scenario s.
$PH_{s,t}^{Heater}$	Heating power produced (kW), at time t, scenario s.
$PC_{s,t}^{Chiller}$	Absorption heating power pump produced (kW), at time t, scenario s.
$PU_{s,t}^{WT}$	Wind power used (kW), at time t, scenario s.
$PS_{s,t}^{WT}$	Wind power sold (kW), at time t, scenario s.
$PU_{s,t}^{PV}$	Photovoltaic power used (kW), at time t, scenario s.
$PS_{s,t}^{PV}$	Photovoltaic power sold (kW), at time t, scenario s.
$PG_{s,t}^{PV}$	Photovoltaic power generation (kW), at time t, scenario s.

$PU_{s,t}^{EV}$	Electric vehicle power used (kW), at time t, scenario s.
$PS_{s,t}^{EV}$	Electric vehicle power sold (kW), at time t, scenario s.
$PG_{n,s,t}^{EV,Ch}$	Electric vehicle charging power (kW) of vehicle n, at time t, scenario s.
$PG_{n,s,t}^{EV,Dis}$	Electric vehicle discharging power (kW) of vehicle n, at time t, scenario s.
$Eng_{s,t}^{ESS}$	Energy stored by the energy storage system (kWh), at time t, scenario s.

I. INTRODUCTION

A. Motivation

Smart Grids (SGs) are advanced electrical systems that use digital technologies to monitor, control, and manage the production, distribution, and consumption of electricity. This technology enables the efficient integration of renewable energy sources, such as solar and wind power, into the electrical grid. Integrating renewable energy sources into the conventional grid is challenging because they are highly dependent on weather variation. However, SG utilizes sensors, communication, control, and artificial intelligence to monitor and manage energy production and use in real-time, which allows adaptation to varying energy supply and demand [1]. In addition, SGs enable active consumer participation in energy production and consumption through energy efficiency measures and distributed generation sources, such as solar power production systems in homes and businesses. This increases the efficiency and flexibility of the power system and improves grid reliability, enabling the penetration of renewable energy in power generation [2]. A virtual power plant (VPP) is a network of power-generating units as well as flexible consumers and storage systems. The main objective of a virtual power plant is the coordination of its components, robustly providing the necessary electricity, and actively participating in the electricity market.

B. Literature Review

In [3] a division of VPPs in service regions is presented whose main differentiation factors are the region space and the administrative level, followed by the load diversity and the type of users. To facilitate the integration of distributed energy resources (DERs) while ensuring local system security, the concept of a VPP capacity curve is presented in [4]. In [5], different types and scales of electric vehicles (EVs) are considered, and it is found that they have a significant and positive effect on the bidding strategy of the power plant.

In [6], a demand response scheme based on incentives is presented, guided by data mining that models the energy exchanges between the plant and its participants. In [7] a double-layer scheduling model is established for power plants with intermittent renewable energy and thermostatically controlled distributed loads, with the focus on reducing the deviations in the exchanges with the grid.

In [8], an operation strategy of energy hubs in the presence of electrical, heating, and cooling demand as well as renewable power generation uncertainties is presented. In [9], an analysis not only of the benefits of utilizing the prosumer's flexibility but also of the problems associated with the operation and optimization of the network is provided. In [10], a robust chance-constrained optimization framework is presented for the optimal operation management of an energy hub in the presence of electrical, heating, and cooling demands and renewable power generation.

The proposed strategy can be used for optimal decision-making of operators of energy hubs or energy providers. In [11], the aim is to develop a technical VPP operational model to optimize the scheduling of a diverse set of DERs operating in a day-ahead energy market, considering grid constraints.

C. Contributions

Although several studies have already been conducted for the ideal participation of VPP in the electricity market, there are still only a few works that study these VPPs in multi-energy systems, where several energy sectors are coupled together to provide more economical energy services to final consumers. Hence, the main objective of this work is to model the operation of a virtual power plant considering multi-energy systems, and to optimize the total cost reduction of the power plant operation, due to active participation in the electricity market. To achieve the objective, the optimization method used to solve the proposed model is Mixed-Integer Non-Linear Programming (MINLP). It can be achieved through optimal asset management, not only considering technical limitations but also the unpredictability that the power plant is subject to in real life, such as renewable energy production. This coupled with the emerging electric mobility market, adds a considerable number of flexible loads to the power grid, making it essential to have an optimal real-time management that maximizes the good use of all resources and, above all, satisfies the imposed loads.

D. Paper Organization

The remaining work is as follows: Section II shows the main mathematical information that models the problem, while Section III shows the study case and main results. Section IV shows the main findings and perspective for future works.

II. MATHEMATICAL MODELING

A. Objective Function.

The objective function described in Eq. (1) seeks to minimize the operating costs of the VPP's assets. The VPP is connected to the electricity grid and exchanges energy with it, which includes the purchase costs and the revenues from selling energy to the grid [10], [11].

$$\sum_{s=1}^{N_s} w_s \left[\sum_{t=1}^{N_t} \left[\begin{gathered} \left(PG_{s,t}^{G2H} . \lambda_t^{Buy} - PG_{s,t}^{H2G} . \lambda_t^{Sell} \right) + \\ + F_{s,t}^{CHP} + F_{s,t}^{Boiler} + F_{s,t}^{Chiller} + F_{s,t}^{EHP} + \\ + \sigma_t^{Elec.} . W_{s,t}^{Elec.} + \sigma_t^{Heating} . W_{s,t}^{Heating} + \\ + \sigma_t^{Cooling} . W_{s,t}^{Cooling} \end{gathered} \right] \right] \tag{1}$$

B. Problem Restriction.

The assets' operating costs are represented by Eqs (2)-(5). In the following equations, a, b, c, d, and f, represent the different cost coefficients of the units considering different days and seasons of the year.

Eq. (2) expresses the CHP operation cost, while Eqs. (3) and (4) describe the operating costs of the boiler and absorption chillers, respectively, both expressed by linear equations as a function of natural gas consumption. Eq (5) is dealing with the electric heat pump operating cost which only operates in one of the modes, producing heat, $PH_{s,t}^{EHP}$, or cooling, $PC_{s,t}^{EHP}$, power.

$$\begin{aligned} F_{s,t}^{CHP} = a_{NG}^{CHP} \left(PG_{s,t}^{CHP} \right)^2 + b_{NG}^{CHP} \left(PG_{s,t}^{CHP} \right) + c_{NG}^{CHP} \left(PH_{s,t}^{CHP} \right)^2 \\ + d_{NG}^{CHP} \left(PH_{s,t}^{CHP} \right) \\ + e_{NG}^{CHP} \left(PG_{s,t}^{CHP} \right) \left(PH_{s,t}^{CHP} \right) + f_{NG}^{CHP} \end{aligned} \tag{2}$$

$$F_{s,t}^{Boiler} = a_{NG}^{CHP}\left(PH_{s,t}^{Boiler}\right) + b_{NG}^{Boiler} \tag{3}$$

$$F_{s,t}^{Chiller} = a_{NG}^{Chiller}\left(PC_{s,t}^{Chiller}\right) + b_{NG}^{Chiller} \tag{4}$$

$$F_{s,t}^{EHP} = a^{EHP}\left(PH_{s,t}^{EHP} + PC_{s,t}^{EHP}\right)^2 + b^{EHP}\left(PH_{s,t}^{EHP} + PC_{s,t}^{EHP}\right) + c^{EHP} \tag{5}$$

Constraint (6) is part of the mathematical modeling formulation for the cogeneration unit, where the feasible operational region of this asset is characterized by a convex quadrilateral region. Hence the binary variable binary $I_{s,t}^{CHP}$ ensures that this asset operates within this region when it is in operation.

Also, like Eq. (6), Eq (7) expresses the boiler operation with its respective binary variable, while Eq (8) describes the absorption chiller operation restricted as well to the machinery performance. Eqs (9) and (10) represent the operational restrictions for the electric heat pump Eq. (9), the electrical heater Eq. (10), with their respective machinery performances, and binary variables $I_{s,t}^{asset}$.

$$PG_C^{CHP}.I_{s,t}^{CHP} \leq PG_{s,t}^{CHP} \leq PG_A^{CHP}.I_{s,t}^{CHP} \tag{6}$$

$$PH_{s,t}^{Boiler,Min}.I_{s,t}^{Boiler} \leq PH_{s,t}^{Boiler} \leq PH_{s,t}^{Boiler,Max}.I_{s,t}^{Boiler} \tag{7}$$

$$PC^{Chiller,Max}.I_{s,t}^{Chiller} \leq PC_{s,t}^{Chiller} \leq PC^{Chiller,Max}.I_{s,t}^{Chiller} \tag{8}$$

$$PC^{EHP,Min}.I_{s,t}^{EHP,Cooling} \leq PC_{s,t}^{EHP} \leq PC^{EHP,Max}.I_{s,t}^{EHP,Cooling} \tag{9}$$

$$0 \leq PH_{s,t}^{Heater} \leq PH_{s,t}^{Heater,Max}.I_{s,t}^{Heater} \tag{10}$$

The following constraints are related to the energy storage system, and renewable energy operation, while addressing the integration of EVs as well.

$$Eng_{s,t}^{EES} = Eng_{s,t-1}^{EES} + PG_{s,t}^{EES,Ch.}.\eta^{EES,Ch.} - PG_{s,t}^{EES,Dis.}/\eta^{EES,Dis.} \tag{11}$$

$$0 \leq PG_{s,t}^{EES,Ch.} \leq PG_{s,t}^{EES,Ch.,Max}.I_{s,t}^{EES,Ch.} \tag{12}$$

$$0 \leq PG_{s,t}^{EES,Dis.} \leq PG_{s,t}^{EES,Dis.,Max}.I_{s,t}^{EES,Dis.} \tag{13}$$

$$PU_{s,t}^{WT} + PS_{s,t}^{WT} = PG_{s,t}^{WT} \tag{14}$$

$$PU_{s,t}^{PV} + PS_{s,t}^{PV} = PG_{s,t}^{PV} \tag{15}$$

$$Eng_{n,s,t}^{EV} = Eng_{n,s,t-1}^{EV} + PG_{n,s,t}^{EV,Ch.}.\eta^{EV,Ch.} - \frac{PG_{n,s,t}^{EV,Dis..}}{\eta^{EV,Dis.}} \quad \forall t \in [1,T_d] \wedge]T_c,24] \tag{16}$$

$$0 \leq PG_{n,s,t}^{EV,Ch.} \leq PG_{n,s,t}^{EV,Ch.,Max}.I_{n,s,t}^{EV,Ch.} \tag{17}$$

$$0 \leq PG_{n,s,t}^{EV,Dis.} \leq PG_{n,s,t}^{EV,Dis.,Max}.I_{n,s,t}^{EV,Dis.} \tag{18}$$

C. Transactions with the Electricity and Natural Gas Network.

Constraints (19) and (20) limit energy transactions between the power plant and the electrical grid, considering the maximum power flow, PL^{Max} of the distribution feeder that connects both networks in the VPP.

Constraint (21) guarantees the power exchanges' unidirectionality described by the binary variables [10], [11]. Connection to the natural gas network is not subject to any limitation.

$$0 \leq PG_{s,t}^{G2H} \leq PL^{Max}.I_{s,t}^{G2H} \tag{19}$$

$$0 \leq PG_{s,t}^{H2G} \leq PL^{Max}.I_{s,t}^{H2G} \tag{20}$$

$$0 \leq I_{s,t}^{G2H} + I_{s,t}^{H2G} \leq 1 \tag{21}$$

D. Virtual Power Plant Power Balance.

The following equations represent the critical balance for electricity, heat, and cooling. Thus, the possible load curtailment is modeled by adding the corresponding positive variable on the left-hand side of the associated constraints. It should be noted that the corresponding load curtailment has been penalized in the objective function.

The electrical load (22) is satisfied by the grid, cogeneration, EES, photovoltaic panels, wind turbine, and EVs. The boiler, electric heater, cogeneration, and electric heat pump ensure the heat production expressed in Eq. (23). The cooling process (24) is ensured by the electric heat pump and the absorption cooler installed on the VPP [10], [11].

$$P_{s,t}^{Load} + W_{s,t}^{Elec.} = PG_{s,t}^{G2H} + PG_{s,t}^{CHP} + PG_{s,t}^{EES} + PG_{s,t}^{PV} + PG_{s,t}^{WT} + PG_{s,t}^{EV} \tag{22}$$

$$PH_{s,t}^{Load} + W_{s,t}^{Heating} = PH_{s,t}^{Boiler} + PH_{s,t}^{Heater} + PH_{s,t}^{CHP} + PH_{s,t}^{EHP,Heating} \tag{23}$$

$$C_{s,t}^{Load} + W_{s,t}^{Coohng} = PC_{s,t}^{Chiller} + PC_{s,t}^{EHP,Cooling} \tag{24}$$

III. CASE STUDY AND MAIN RESULTS

The VPP is externally powered by an electrical and natural gas network. The surplus of energy is sold to the electrical grid. Internally, VPP comprises three groups of assets: production, conversion, and storage. Production includes photovoltaic panels and wind turbines.

Energy conversion devices involve CHP, boiler, electric heater, electric heat pump (EHP), and absorption chiller. Electrical energy storage is carried out by the EES and the EVs, which also act as a load. The main operating objective of the VPP is to respond to the different imposed loads: electrical, heat, and cooling.

Fig. 1 shows the operational region of the cogeneration unit, with a nominal capacity of 375 kW. Electricity production is limited to the range of 50 kW and 375 kW, while thermal energy is limited to the range of 0 kW and 125 kW [12]. The boiler capacity is 400 kW, and it has an efficiency of 0.5. The absorption refrigerator has a capacity of 75 kW and cannot use the thermal energy produced by the cogeneration unit, the electric heater, or the boiler, which must burn natural gas to provide the thermal energy necessary for its operation. The capacity of the electric heat pump is 200 kW, operating in both modes of heating and cooling production. The minimum capacity for each operation mode is 10 kW.

The electric heater has a maximum capacity of 300 kW. The ESS has a capacity of 300 kWh, with a charge and discharge power of 10 kW. A minimum state of charge (SoC) of 50 kWh is defined, which works as an operational reserve in case of power cuts. The SoC at the end of each day must match the SoC at the beginning of the day, being settled to 200 kWh. The installed capacity of the photovoltaic system is 30 kW, considering 10 different scenarios for the summer, and winter seasons, respectively. The wind turbine represents 50 kW of installed capacity, where was considered 10 different scenarios as well for the summer and winter seasons, respectively.

Additionally, 10 different electric vehicles, common nowadays in European countries, were considered, described in Table I [13]. It was assumed that the charging/discharging efficiency is 95% for all the vehicles, with $SoC^{min} = 0.2$ and $SoC^{max} = 0.8$.

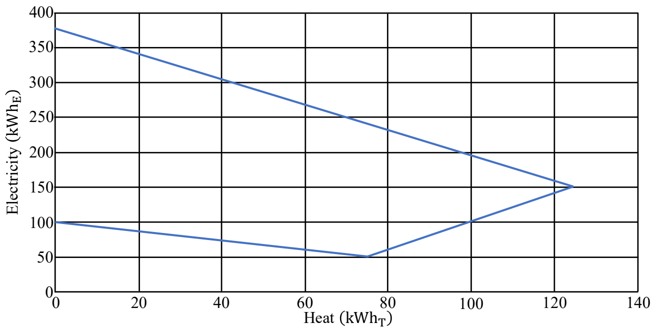

Fig. 1. Feasible operational region of the cogeneration unit.

TABLE I. Main Features of the EVs considered in the VPP.

EV Model	Battery Capacity (kWh)	Charging/ Discharging Power (kW)
Tesla Model Y	60	11
Fiat 500e Hatchback 24 kWh	23.8	11
Audi Q4 e-tron 40	82	11
Nissan Leaf	40	3.6
VW e-UP!	36.8	7.2
Opel Corsa-e	50	7.4
Smart EQ ForTwo Coupe	17.6	4.6
Mini Cooper SE	32.6	11
Hyundai Kona Electric 39 kWh	42	7.2
Volvo XC40 Recharge Single Motor	69	11

Also, the disconnection period was settled to 6:00-10:00 am and connection to VPP from 5:00-9:00 pm with a certain SoC due to the daily use. Electricity exchanges with the grid are carried out through a 300-kW line that allows unidirectional energy exchanges. The VPP demand can be met by purchasing energy from the grid and in case of excess production the energy can be sold to the grid. Again, the import of natural gas is not limited.

The electrical loads, considering the summer and winter seasons have some differences. During the summer the loads are much higher, exceeding 400 kW, never dropping below 200 kW. In winter, the loads are much lower, reaching only 250 kW, dropping to 50 kW at some periods. Fig. 2 shows the prices of electricity and natural gas for the summer and winter seasons. Hence Figs. 3-5 shows the electricity load in summer, the thermal load in winter, and the refrigeration load in winter seasons, respectively. As noticed it is possible to observe the different behavior needed by the different assets to guarantee the profitable and reliable operation of the VPP.

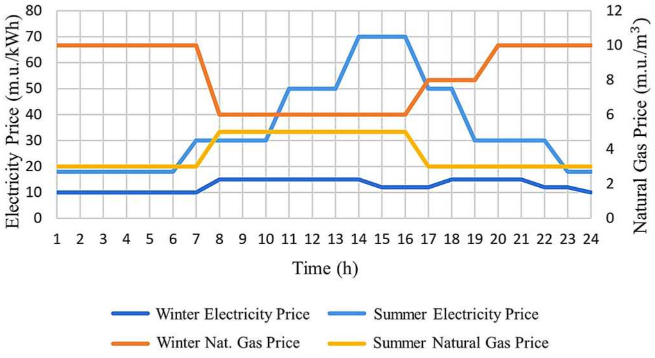

Fig. 2. Electricity and natural gas daily prices in the different seasons.

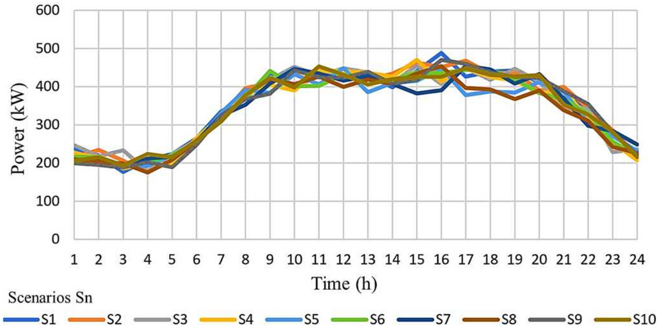

Fig. 3. Electricity load in the summer season [10]

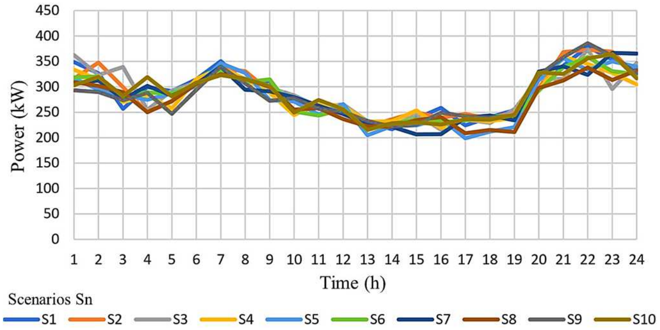

Fig. 4. Heating load during the winter season [10]

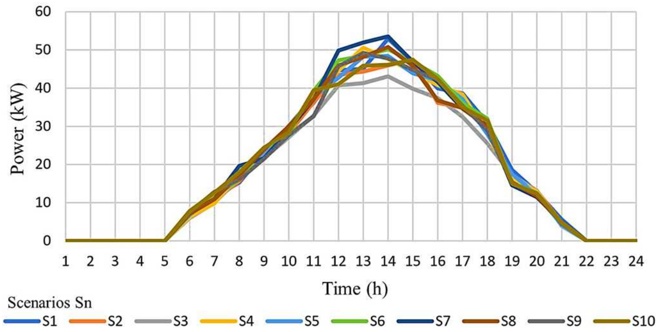

Fig. 5. Cooling load during the winter season [10]

Fig 6. shows a component of the power injected into the grid, the electric vehicles, over the total injected power. The export derived from the vehicles follows the total export of the plant, increasing and decreasing simultaneously, as shown for the four peaks of injection into the grid. The figure also shows the balance of exchanges between the grid and the power plant, before and after V2G. A positive balance indicates that the power plant is exporting, otherwise, it is importing.

Since EVs are the main addition to the system, it is crucial to analyze the origin of the energy that allows their charging. According to Figs. 7 and 8, it can be assumed that it is possible to significantly reduce the dependence on the grid for charging since the power plant's internal units take on most of it. In this way, it is possible to mitigate a current problem, the possible overload that electric vehicles can cause in electrical networks.

During the summer season, cogeneration dominates the electric load, a result of high electricity tariffs and low natural gas prices (Fig. 9). Renewable energy, despite reasonable production, does not make a significant contribution because the electrical load is high. If the load is high, and cogeneration is producing at the limit of its capacity throughout the day, it is necessary to use the grid to meet demand, even at times when the highest electricity tariffs are charged. The contribution of EVs is also low.

During the winter, with lower electricity tariffs and higher natural gas prices, the purchase of energy from the grid becomes favorable compared to the summer. Even so, the variation of these tariffs throughout the day, makes cogeneration preferential to import energy from the grid, during the morning and early afternoon. In this season, electric vehicles have a considerable contribution, at the end of the day.

Table II shows the initial costs of VPP considering the summer and winter seasons, showing incomes and costs between VPP to the grid (VPP2G) and grid to VPP (G2VPP). Tables III, IV, and V show the VPP cost in G2V, V2G, and V2L modes, respectively. Even considering a predefined period where EVs are connected to the grid, benefits to absorb or sell energy are possible to the VPP or the external grid.

The simulation was implemented considering the Generic Algebraic Modelling Systems (GAMS) considering the MINLP solver [14], installed on a normal PC dotted with Intel i7 2.7GHz and 8GB of RAM and Windows 10 environment. Also Excel sheets were used to create the tables and figures from the results obtained from GAMS.

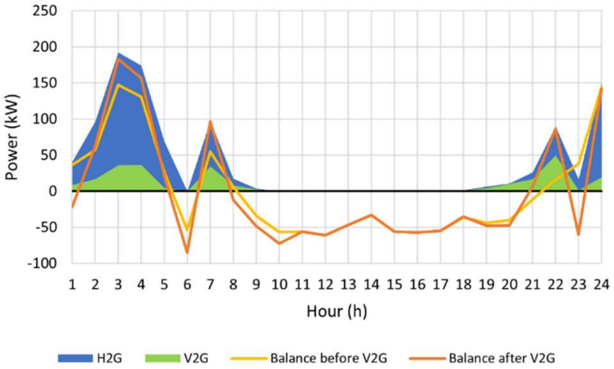

Fig. 6. V2G exchanges (summer).

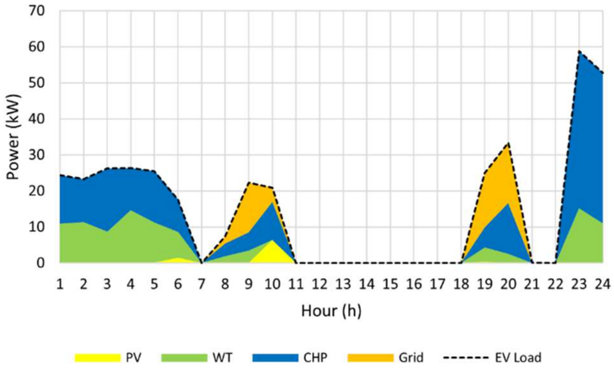

Fig. 7. Electric vehicle supply distribution (summer).

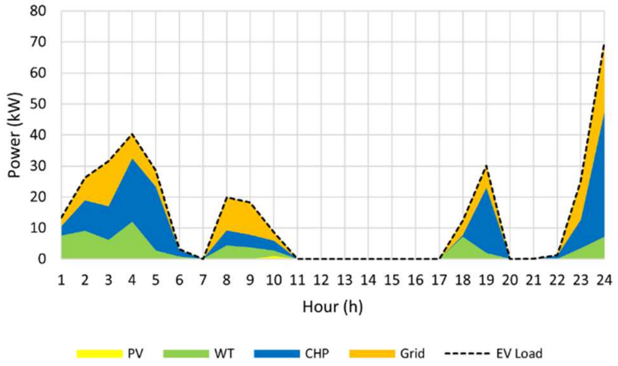

Fig. 8. Electric vehicle supply distribution (winter).

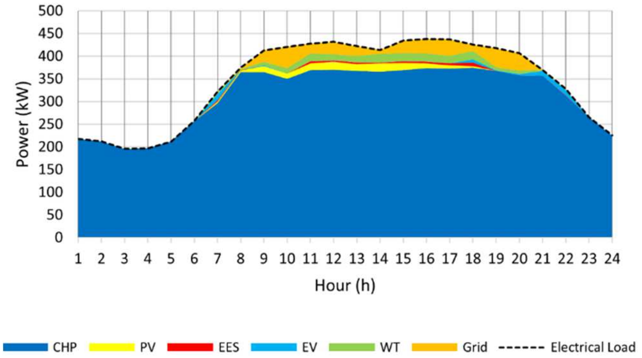

Fig. 9. Distribution of supply to the electrical load (summer).

TABLE II. INITIAL VPP COST.

	Assets	Summer	Winter
Benefits	*H2G*	313451.61	12979.18
Costs	*G2H*	291437.63	550770.19
	EHP	68336.31	48000.00
	Boiler	67465.11	149793.16
	Cooler	48094.57	29963.01
	Cogeneration	1079367.08	503054.42
	Total	1241249.08	1268601.61

TABLE III. VPP COST AFTER G2V INTEGRATION.

	Assets	Summer	Winter
Benefits	*H2G*	192050.59	12995.12
Costs	*G2H*	319245.29	558437.00
	EHP	68336.31	48000.00
	Boiler	61164.12	160062.82
	Cooler	48094.57	29963.01
	Cogeneration	1022895.02	503978.45
	Total	1327684.71	1287446.17

TABLE IV. VPP COST AFTER V2G INTEGRATION & DIFFERENCE WITH G2V.

	Assets	Summer	Diff. (%)	Winter	Diff. (%)
Benefits	*H2G*	260309.95	35.34	12995.12	32.40
Costs	*G2H*	377914.88	18.38	558437.00	0.48
	EHP	68336.31	0.00	48000.00	0.00
	Boiler	68.656.05	-0.50	160062.82	0.62
	Cooler	48094.57	0.00	29963.01	0.00
	Cogener.	1017087.28	-0.57	503978.45	0.08
	Total	1311979.15	-1.18	1287446.17	-0.01

TABLE V. VPP COST AFTER V2L INTEGRATION & DIFFERENCE WITH G2V.

	Assets	Summer	Diff. (%)	Winter	Diff. (%)
Benefits	*H2G*	261024.64	0.27	14487.58	-15.80
Costs	*G2H*	377229.65	-0.18	575090.16	2.49
	EHP	68336.31	0.00	48000.00	0.00
	Boiler	60904.55	0.08	147770.58	-8.25
	Cooler	48094.57	0.00	29963.01	0.00
	Cogener.	1016127.99	-0.09	493457.99	-2.16
	Total	1309668.43	-0.176	1279794.16	-0.58

IV. CONCLUSION

In this work, a VPP with active participation in the electricity market was modeled, considering multi-energy systems, in which the objective is to reduce the total cost of operation of the VPP, always satisfying demand and restrictions. For this, the MINLP method was successfully implemented. The VPP is made up of energy production, conversion, and storage units and is fed by two external networks, electricity, and natural gas, whose priorities are the satisfaction of electrical loads for heating and cooling. The integration of EVs was analyzed, involving different implementations: G2V, V2G, V2L, and charging through VPP units. It was possible to observe that V2G and V2L technology can be beneficial for the VPP at critical moments, and still provide benefits for the VPP at critical moments of the network, selling part of the stored potential and recharging again in more opportune periods, resulting in a costs reduction. As future research, the trend will pass by the implementation and analysis of new renewable energy sources in the VPP, for example, offshore wind, due to its high potential, or even the integration of green hydrogen, and further analysis of the installed renewable potential. It would also be interesting to optimize the randomness of the EVs, through the Monte Carlo method, bringing the results closer to reality.

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