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The Effect of Non-Coordinated Heating Electrification Alternatives on a Low-Voltage Distribution Network with High PV Penetration

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***Abstract*—The energy transition requires electrical alternatives for domestic heating. Heat pumps are the most common alternatives to gas boilers. However, heat pumps consume a significant amount of electrical power. We simulated an 18-node low voltage network with five buildings with six apartments each to evaluate the effect of deploying heat pumps as part of multi-carrier energy systems at the residential level. We also combined heat pumps with solar collectors and thermal energy storage to quantify whether a more complex system benefits the low-voltage network. Replacing the gas boilers for heat pumps in the majority of the buildings resulted in voltage drops below the limit of the standard EN50160. The voltage drops were significantly improved when we included solar collectors and thermal energy storage in the domestic heating system.**

***Index Terms*—Heating Electrification, Low-Voltage Distribution Networks, Multi-Carrier Systems**

I. Introduction

Policymakers have encouraged the inclusion of distributed renewable energy sources (DRES) at the household level as part of the energy transition toward decarbonization. The effects of DRES on the distribution networks have been investigated and documented, including stability issues, grid congestion, and power plants underused due to power curtailment [1]. For example, in New England [2], the circuits operate near their limits. Germany [3] and China [4] have been obliged to curtail renewable generation plants to address the congestion on the grid. Therefore, distribution system operators actively work to find alternatives to ensure stability on the network.

More recently, strategies to electrify transportation and heat have also been proposed. However, the technologies required to deploy such strategies also affect the grid, adding highly stochastic power demands to an already weather-dependent network. To mention some, [5] and [6] demonstrated that including electric vehicle (EV) chargers in the low voltage (LV) grid, without an aggregated energy management strategy, can cause severe voltage drops, failing to comply the technical standard EN50160. On the other hand, the effect of heating electrification in the LV networks has not been deeply studied. Instead, most research focuses on providing ancillary services with heat pumps (HP), such as demand response and direct load control. For example, [7] concluded that demand response algorithms could avoid voltage drops caused by the high power loads caused by combining HP and EV. Similarly, [8] found that the impact of heat pumps on a low-voltage network is related to their distribution, causing voltage imbalances beyond the allowed limit.

Including energy storage systems on the grid could reduce the adverse effects mentioned above [9], [10]. The techno-economic study done by [11] demonstrated that installing BESS in the LV network can ensure voltage limits above 0.9 pu while representing only 77 % of the costs of upgrading the lines in the network to satisfy the voltage limit. The effect of coordinating strategically located BESS was studied by [12], demonstrating that the power and energy share between the BESS can address voltage issues in real-time while minimizing the size of the batteries and inverters. However, including BESS at the household level not necessarily implies a reduction in the adverse effects on the grid as well [13]. Home energy management systems (HEMS) are configured to reduce the cost for the equipment owner since there are no direct benefits for providing ancillary services at this scale in many energy markets yet. Additionally, the HEMS do not share data with neighboring HEMS; thus, multiple HEMS in the same distribution network work in a non-coordinated fashion.

At the household level, policymakers encourage coupling electric and thermal systems into multi-carrier energy systems (MCES), also known as multi-energy systems. Among the most common technologies that can be coupled are PV, photovoltaic-thermal (PVT) systems, solar thermal collectors, BESS, thermal energy storage systems (TESS), and heat pumps (HP). MCES can result in flexible systems capable of reducing the congestion on the grid if storage is included [14]. Therefore, understanding how HEMS affects the energy exchange between the electric network and prosumers with multi-carrier energy systems is relevant for distribution system operators (DSOs). This way, it would be possible to quantify

The project was carried out with a Top Sector Energy subsidy from the Ministry of Economic Affairs and Climate, carried out by the Netherlands Enterprise Agency (RVO). The specific subsidy for this project concerns the MOOI subsidy round 2020.

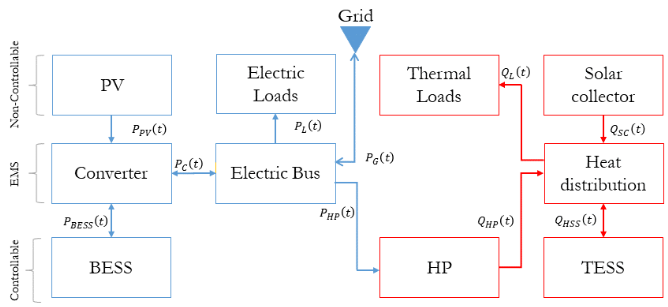


Fig. 1: Considered architecture for the multi-carrier energy system (displaying only the active power flow).

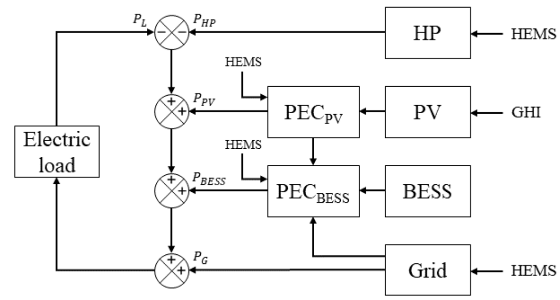


Fig. 2: Model considered for a building with a PV system and a BESS, interconnected to the electric bus by a power electronics converter (PEC) each. The HP and the grid are connected directly to the electric bus, as well as the house electric load P_{L}.

the effect of the deployments of electrical alternatives for heat and mobility at the residential level to prevent worsening the congestion in the grid.

In this work, we studied the effect of different strategies for residential heating decarbonization on the low-voltage distribution network. Three scenarios were simulated in the CIGRE 18-node residential network [15]: 1) a traditional system with electric loads and a gas boiler to cover heat demand, 2) adding PV to scenario 1, and 3) adding a BESS and replacing the boiler in scenario 2 with a combination of a heat pump, a solar collector and a TESS (resulting in the MCES shown in Fig. 1). For scenario 3, we analyzed different operation conditions of the heat sources: only the HP, the HP and the solar collectors, and the three components. The scenarios were evaluated during environmental and load conditions typical for the winter and summer in The Netherlands. The contributions of this paper are towards analyzing the effect of non-coordinated household-level MCES in the voltage level of an LV, as most papers focus on the optimal placement of assets within the network for controlled compensation managed by the DSOs. Additionally, we studied how adding thermal energy storage to households affects their electrical power demand.

II. House Demand Model

For this work, we considered an MCES with the architecture shown in Fig. 1 because all its components are commercially available. Different cases without specific components will be studied under different scenarios. Note that Fig. 1 shows the active power flow between the components; however, we considered the apparent power for the model, thus considering the reactive power. This way, to study the influence of coupling the multi-carrier components from the electrical perspective, one can use

$$I_j^h = \frac{S_j^D + S_j^{HP} - S_j^{DRES} - S_j^{BESS}}{V_j}, \tag{1}$$

to model the interaction between the power demanded by the load in the *j-th* house, S_j^D, the power consumed by the heat pump, S_j^{HP}, the available power from DRES, S_j^{DRES}, and the power delivered or consumed by the BESS, S_j^{BESS}.

Despite the complex HEMS strategies proposed in the literature, most commercially available household products use scheduling algorithms to charge and discharge the batteries. Because of the small effect a single household has on the grid in terms of power, prosumers cannot participate in most wholesale energy markets. Therefore, the energy management strategy used for this work is based on fixed pricing schedules. For the electric load, during the high price period (7:00 am to 11:00 pm), the EMS will prioritize the power from the DRES (a PV system), then the BESS, and finally, will buy from the grid if their combined power is not enough to fulfill the demand. On the other hand, during the low-price period (11:00 pm to 7:00 am), the battery will charge at a constant rate during the whole period, prioritizing the energy from the DRES, if any, and buying from the grid the remaining. Fig 2 shows the house's electric architecture.

For the thermal system, the algorithm implemented is also based on schedule, as used by current HEMS technologies. This way, the heat available from the solar collectors (SC) will be prioritized. If the heat demand is still not satisfied, the TESS will be used as the second option if the temperature in the working fluid is between 50 °C and 95 °C. At 50 °C, the tank is considered fully discharged; above 95 °C, it would be assumed fully charged. In between, it can discharge to supply thermal power or be charged if the solar collectors are producing thermal power and the house is not demanding a thermal load. The HP will be the last resource if the TESS is fully discharged and the solar collector thermal power is insufficient. For this work, we only considered spatial heating as a thermal load. The model's architecture for the thermal network in the house and the heating system is presented in Fig 3. The details of the model can be found in [16], [17].

III. Network model

To compare the behavior of the distribution network under the proposed scenarios, one needs a model for the network itself. In this paper, we proposed a scalable model based on the generic network architecture shown in Fig. 4. This model allows us to obtain the voltage at any node, the line current between two consecutive nodes, and, thus, the power

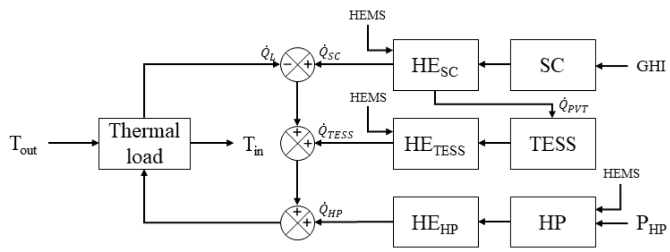


Fig. 3: Model considered for a building with SC, TESS, and HP, interconnected to the thermal network by a heat exchanger (HE) each, to supply the thermal load $\dot{Q}_{\mathrm{L}}$.

at any node. To obtain those parameters, we start with a nodal analysis on node 1, so the node voltage V_1 results in:

$$V_1 = V_0 - I^L_{0,1} Z_{0,1}\,, \tag{2}$$

where I^L_{0-1} and Z_{0-1} are the current and impedance between the nodes 0 and 1. Similarly, for node 2, the voltage would result in

$$V_2 = V_1 - I^L_{1,2} Z_{1,2}\,. \tag{3}$$

Note that one can replace (3) in (2) to obtain an expression dependent only on the voltage of the bulk source. A general expression for the voltage at any node j can be obtained as

$$V_j = V_0 - \sum_{i=1}^{j} I^L_{i-1,i} Z_{i-1,i}\,. \tag{4}$$

Likewise, if the procedure is repeated for the current, but starting from the last node n, the current in the line between the nodes n and *n-1* is

$$I^L_{n-1,n} = I^h_n\,, \tag{5}$$

where I^h_n is the current flowing in or out of the *n-th* house. For the previous node, the expression would be

$$I^L_{n-2,n-1} = I^L_{n-1,n} - I^h_{n-1}\,. \tag{6}$$

This way, we can replace (6) in (5) to obtain an expression dependent only on the demand and the generation of the nodes towards the end of the branch. Thus, a general expression for the current between two consecutive nodes can be written as

$$I^L_{j-1,j} = \sum_{i=j}^{n} I^h_i\,. \tag{7}$$

Finally, substituting (7) in (4) results in

$$V_j = V_0 - \sum_{i=1}^{j} \left(Z_{i-1,i} \sum_{k=i}^{n} I^h_k \right), \tag{8}$$

which is an expression for the voltage at any node. This expression depends only on the current exchange at each node, the line impedances, and the bulk source voltage.

This model can be extrapolated to more complex circuit configurations. If the circuit has several branches, those branches need to be solved first, reducing the branch to a node. Then, the method can be applied again to the resulting circuit, considering the voltage at the transformer as 1 pu and a stiff medium voltage grid.

IV. Results

To evaluate the effect of deploying multi-carrier energy systems at households on an urban secondary distribution system, we simulated the CIGRE 18-node test network shown in Fig. 5, with the parameters indicated in Table I, for one year. The neighborhood simulated consists of similar six-apartment buildings located in nodes 11, 15, 16, 17, and 18. The load conditions presented in Table II for each building are based on typical power consumptions [18]. Fig 6 and Fig 7 show a representative week of the electric load and the yearly thermal losses, respectively. On the other hand, different sizes of PV systems (combinations of 2.4 kWp and 3.2 kWp), BESS (combinations of 2.4 kW and 4 kW, all with 5 kWh), and heat pumps (2.7 kW) were assigned to each building to add variability. To each apartment, we added a 1.62 m^2 solar collector, with an efficiency of 70 %, and a perfectly isolated 4 m^3 water tank as TESS (based on commercially available volumes for the Dutch market), with an initial SoC of 50 % for all TESS on January 1st. We selected the days and hours with worse voltage conditions to compare each case scenario.

TABLE I: Parameters considered for the CIGRE test network

Nodes	Distance [m]	Impedance per distance [Ω/km]
1-10	9 segments of 35	0.162 + 0.07j
3-11	30	1.539 + 0.076j
4-14	3 segments of 35	0.265 + 0.07065
14-15	30	0.265 + 0.07065
6-16	30	0.229 + 0.0719j
9-17	30	1.539 + 0.076j
10-18	30	1.113 + 0.0735j

TABLE II: Maximum power for the load, PV, BESS, and heat pump per node

Node	Load (kVA)	Power factor	PV (kW)	BESS (kW)	BESS (kWh)	HP (kW)
11	12	0.85	6.4	8	10	5.4
15	12	0.85	9.6	9.6	15	8.1
16	12	0.85	14.4	14.4	30	16.2
17	12	0.85	19.2	19.2	30	16.2
18	12	0.85	19.2	24	30	16.2

A. Case 1: Buildings without DRES or MCES

To define the base case, we studied how the voltage in the network behaves when the buildings have a typical residential power demand. As seen in Fig. 8, during the periods of highest demand, most of the nodes have a voltage above 0.95 pu, satisfying the voltage limits of EN50160, as expected.

B. Case 2: Buildings with PV

In this case, we incorporated a PV system into each building. The peak power for each building is indicated in Table II.

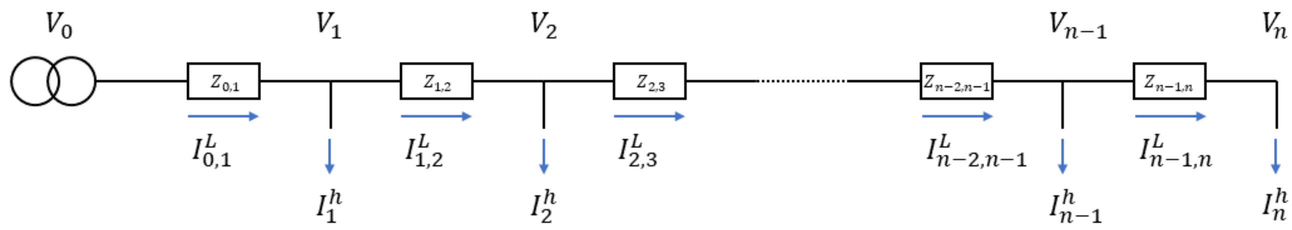


Fig. 4: Generic network architecture, where V is the node voltage, I^L and Z are the current flowing from one node to the next and the line impedance, respectively, and I^h is the current flowing into the houses.

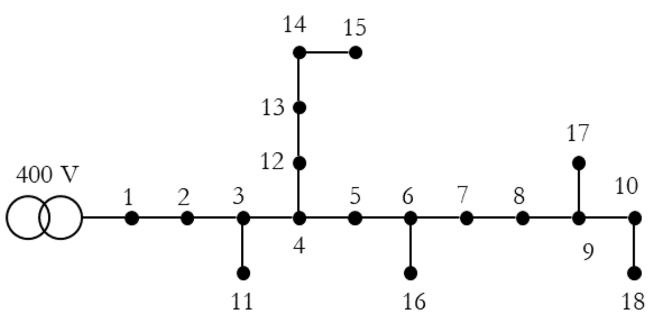


Fig. 5: One-line diagram of the CIGRE test network [19]

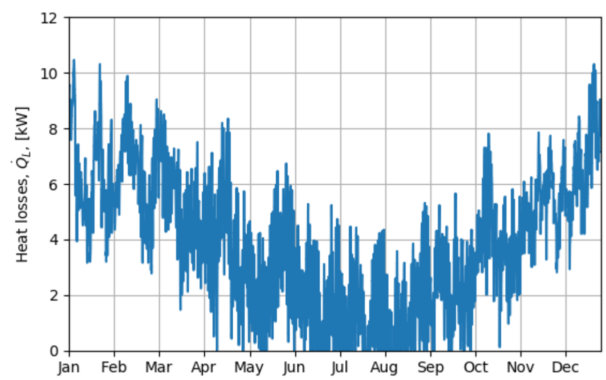


Fig. 7: Thermal losses considered throughout the year.

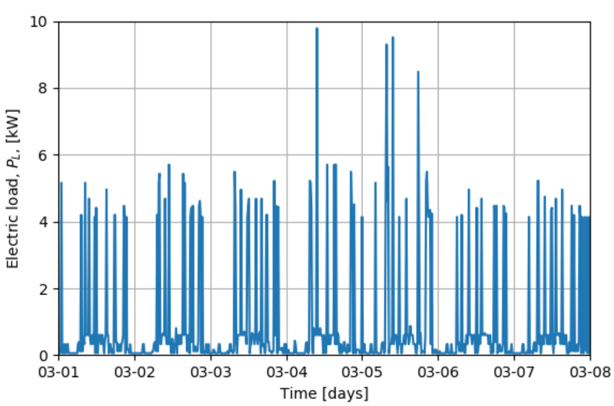


Fig. 6: Representative week of electric load.

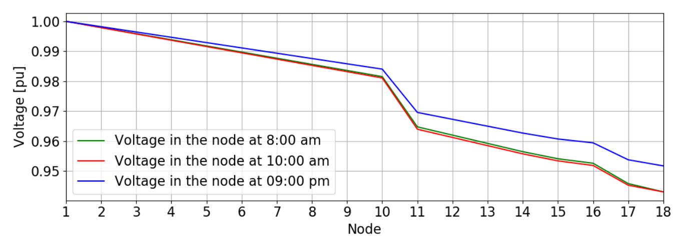
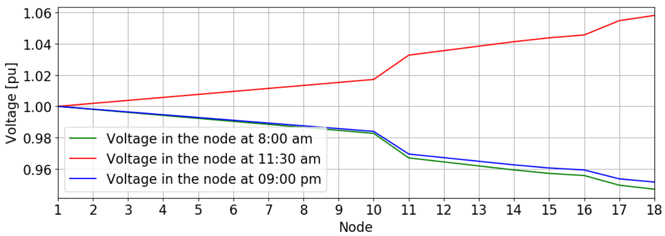


Fig. 8: Minimum voltages in the network for the case 1: load without PV or MCES.

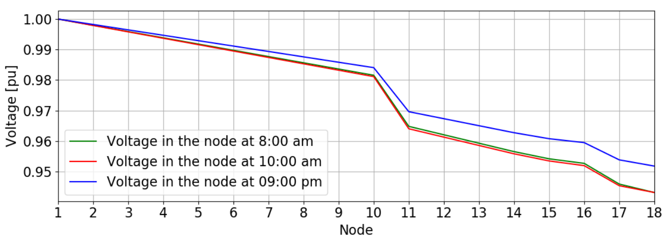
The PV power depends on the seasons. Thus, a day from winter and a day from summer were selected to evaluate seasonality. As shown in Fig. 9a, during summer, the systems inject power into the grid when there is surplus PV power. Injecting power into the grid causes a voltage increase in the nodes and reverse currents if the production exceeds the load. During the evening peaks, the PV system no longer produces enough power, and the voltage behavior is similar to case 1. In winter, on the other hand, the voltage behavior is similar to case 1, as the PV production is low (see Fig. 9b).

C. *Case 3: Buildings with the full MCES*

Our final case considers a multi-carrier energy system on each building, as shown in Fig. 1. Table II presents the sizes of each component. During summer, the buildings do not demand heat, so only the PV and the BESS affect the energy exchange between the grid and the buildings, as shown in Fig. 10a. For the winter, we considered three possible operation conditions: heat provided only by the HP (Fig. 10b), heat provided by the HP and a solar collector (Fig. 10c), and heat provided by a HP, a solar collector and a thermal energy storage system (Fig. 10c). The results suggest that using only heat pumps to supply the thermal load per node in a non-coordinated fashion can cause voltage drops outside the voltage limit indicated in



(a) Voltage in the network for the case 2 during summer.



(b) Voltage in the network for the case 2 during winter.

Fig. 9: Minimum and maximum voltages in the network for case 2: load with PV but without MCES.

EN50160. This way, adding the solar collector and the TESS reduces the activation frequency of the HP, keeping the voltage within an acceptable range.

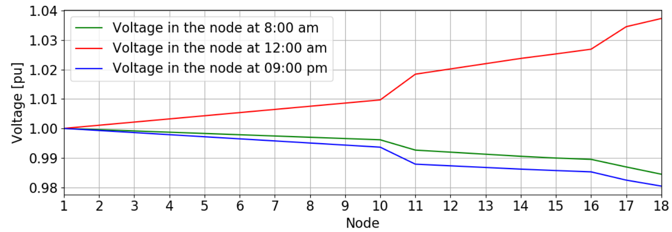
V. Discussion

As the case study presented is in The Netherlands, we used the European Standard EN50160 as a reference for power quality on the network. It specifies that for low voltage networks, the voltage magnitude should be between 0.9-1.1 pu during 95 % of the week (i.e., 8.4 h per week) and between 0.85-1.1 pu at any moment [20]. Table III shows the maximum and minimum voltage obtained for each case to evaluate compliance with this technical standard.

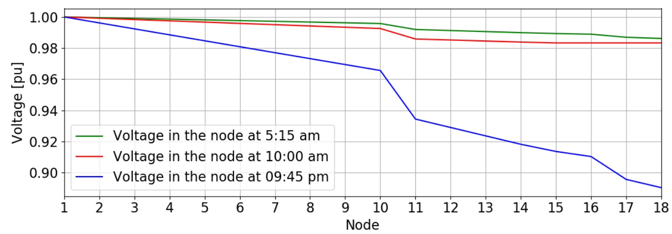
TABLE III: Summary of the results per case

Case	Season	Maximum voltage (pu)	Minimum voltage (pu)	EN50160 compliance
1	-	1	0.943	Satisfied
2	Summer	1.058	0.943	Satisfied
2	Winter	1	0.943	Satisfied
3	Summer	1.037	0.980	Satisfied
3	Winter: HP	1	0.890	Not satisfied
3	Winter: HP, SC	1	0.912	Near limit
3	Winter: HP, SC, TESS	1	0.952	Satisfied

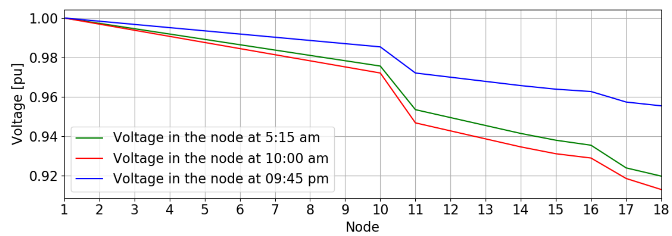
We sized the BESS to complete an entire cycle per day under normal residential loads. They discharged during the peak period (7:00 am to 11:00 pm) and charged during the off-peak hours. Under this operation mode, the load is partially shifted to the off-peak hour. In summer, including batteries reduces near 0.02 pu the voltage increments caused by the injection of the surplus of PV power.



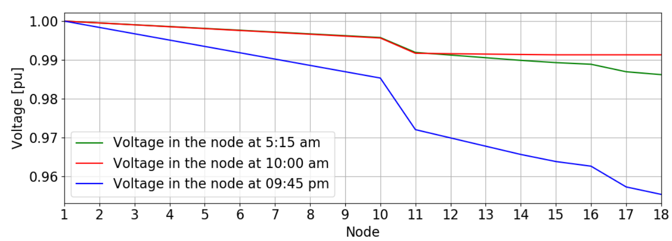
(a) Voltage in the network for case 3 during summer.



(b) Voltage in the network for case 3 during winter with a heat pump as the only heat source.



(c) Voltage in the network for case 3 during winter with a heat pump and a solar collector as heat sources.



(d) Voltage in the network for case 3 during winter with a heat pump, a solar collector, and a TESS as heat sources.

Fig. 10: Minimum and maximum voltages in the network for case 3: load with PV and MCES.

During winter, however, the HP can increase the demand between 45 % and 135 %. In case 3, the heat load during the night in winter is always higher due to lower temperatures, causing the highest voltage drop in the network, going outside the limits when the HP is the only heat source. Adding the solar collectors marginally keeps the voltage above the lower limit. The PV cannot supply this load increase, and due to the maximum capacity of the BESS inverters, the batteries cannot shift the load to the off-peak period completely. Instead, they can only partially shave the HP power peaks. Still, the BESS can distribute its charge at night to minimize the charging stress in the battery and the power required for the charge. When we included the TESS, it was possible to avoid wasting the thermal energy produced by the SC when the indoor temperature was above the lower limit. This way, the thermal demand was supplied more uniformly throughout the day, requiring the HP less frequently, reducing the congestion by decreasing the power demand and increasing the minimum voltage to 0.952 pu.

A system with the architecture as the one we used can also provide ancillary services to the grid. Demand response and direct load control can be implemented to avoid voltage issues. However, this cannot be guaranteed without aggregating individual households and complex energy management strategies. Additionally, it might be worth increasing the size of the BESS to support the grid through voltage compensation. Nevertheless, the IEEE Standard 1547 does not allow any inverter interconnected with the grid to adjust its voltage using reactive power compensation [21]. Instead, it designates the DSO to ensure voltage stability while limiting the possibility of inverters providing reactive power compensation.

VI. Conclusions

In this paper, we simulated the 18-node CIGRE test network to evaluate how replacing gas-based boilers with different combinations of a heat pump, a solar collector, and thermal energy storage affects a low-voltage network. As documented, adding only PV increases the voltage in summer since, during solar peak hours, the PV power can surpass the demand and inject excess into the grid. On the other hand, replacing gas-based boilers for heat pumps as sole heat sources in most buildings can cause the voltage to drop outside the limit allowed by the technical standard EN50160. When we added a solar collector to each building, the heat pump was used less frequently, improving the lowest voltage in the network but still keeping it near the limit of the standard. The scenario with thermal storage showed the best performance, showing the smallest voltage ranges among all cases. Therefore, thermal energy storage can provide flexibility to the electrical network. Further work is recommended in aggregating the individual MCES systems to enhance the flexibility of the network and how coupling BESS with HP could affect the battery's aging. Moreover, including EV chargers or evaluating the spatial constraints to implement TESS can also be considered, as well as the effects on the cables and protection devices of the distribution network.

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