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An Intelligent Infrastructure for Enabling Demand-Response Ready Buildings

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ABSTRACT

In this paper, we present a novel approach developed through the TABEDE project to scale demand response across all building types. To this end, we propose an intelligent infrastructure that enables buildings to follow various demand-response schemes, that optimises the electricity consumption and generation of the buildings to reduce energy cost and promote RES penetration, and that is capable of connecting and controlling appliances seamlessly and in an interoperable manner. The approach is evaluated via a simulated district based on one of the project pilot sites in Cardiff, UK. The results show potential improvements to varying extents in solar PV self-consumption, energy cost reduction, and adhering to grid constraints.

Keywords: demand response, energy prediction, energy optimisation, district simulation, smart grid

1. INTRODUCTION

Among the benefits of smart grids is that they empower energy consumers and allow them to become more active participants in energy markets by selling electricity and flexibility. However, to benefit from this paradigm, customers need to be ready to adopt flexible consumption patterns and to support the demands from the system. Within the framework of the TABEDE [1] project, one of our main objectives is to develop an intelligent infrastructure that enables customers to provide the flexibility and participate in demand-response (DR) schemes. In this paper, we present the proposed infrastructure that aims at optimising energy consumption and injection by exploiting the flexibility provided by the customers to reduce energy bills, promote RES penetration, and support DR signals from demand-response operators. This approach was developed through the TABEDE project, a European Commission-funded Horizon 2020 R&D project to scale demand response across all building types.

Device flexibility is defined as the deviation of consumption or generation of a device that is allowed to be carried out. The flexibility provided by the devices is exploited to participate in different DR schemes. A customer subscribing to a DR program receives a set of DR requests customised based on their consumption and generation. DR programs can be categorised into price-based and incentive-based. Price-based programs provide customers with time-varying energy tariffs. Incentive-based programs offer direct payments to customers to change their consumption patterns upon request.

Optimised behaviour of individual buildings, however, may not present a positive collective behaviour as observed by the grid. For instance, if all the buildings shift their consumption to an off-peak period to benefit a cheaper energy price, the grid will be overwhelmed by the new peak of demands. To study also the collective behaviour, we propose a simulation environment as a part of our solution to assess the impact of the infrastructure at the district level and to propose alternative consumption and generation patterns to alleviate the issue affecting the grid.

2. TABEDE APPROACH

TABEDE infrastructure is built on top of five main components: Demand Response Automated Server

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[1] https://www.tabede.eu/

(DRAS), Real-time Energy and Environmental Forecasting and Simulation (REEFS), Agent-Based Optimiser (ABO), Building Management System Extender (BMS-E) and Smart Operations (SO). DRAS represents the demand-response operator and sends price-based and incentive-based DR signals. REEFS provides weather and energy forecasts. ABO handles building-level energy optimisation. BMS-E serves as a smart gateway and is installed in the buildings. It gathers data from different sensors and measurement devices, transforms and stores the data in an unified format, relays the exchanges of data and messages among TABEDE components, and controls the appliances in the building as instructed by ABO. SO analyses the suggested consumption and generation with respect to grid constraints and generates alternatives if the constraints are violated.

From an operating perspective, in a nutshell, TABEDE approach proceeds as follows: (1) the system forecasts weather and energy consumption and generation for the next 24 hours, (2) based on user preferences and inputs from a demand-response operator, it optimises the consumption and generation for the next 24 hours, and (3) it controls the appliances according to the optimised profiles in an automated way. The system repeats these steps every 15 minutes, in order to assure responsiveness to user preferences, demand-response signals and environmental changes.MQTT protocol is used for handling the interactions between the components. The message flow for one iteration is as follows: (1) REEFS and ABO collect real-time data from the buildings through BMS-Es, (2) DRAS sends the DR signals to ABO, (3) REEFS sends the forecasts to ABO, (4) ABO does the optimisation and sends the optimised device profiles and schedules for device control to the corresponding BMS-Es and (5) BMS-Es send control signals to the appliances according to the schedules from ABO.

To study the impact of TABEDE at the district/community level, we also have developed as a part of the infrastructure a simulation environment providing the ability to simulate and test a high diversity of situations, for instance, weather conditions, day of the year, consumption patterns, types and number of buildings, and grid topology. The results obtained from applying TABEDE in this simulated context represent not only the behaviour of individual buildings, but also the collective behaviour of the community.

3. FORECASTING AND SIMULATION COMPONENT

REEFS provides a real-time prediction of weather and electricity demand and generation for buildings and neighbourhoods. It uses historical weather condition, historical energy profiles and building physical information to calculate day-ahead weather, electricity demand and generation profiles from device to district level by implementing a whole building simulation program and data-driven models.

In the simulation environment, EnergyPlus (EP) is used as a simulation engine, which is a whole building energy simulation tool to adequately consider the dynamic aspects of building thermal response to weather [1]. The key elements and steps taken to construct the simulation environment are thermal and electrical model development. For running the simulation, EP requires two inputs, namely building energy models in IDF[2] format and weather data as EPW[3] of the site location. In order to reduce the simulation time, each unit is modelled as a separate IDF that contains data regarding building physics information and construction materials, taking into account the site's characteristics. Information regarding the occupancy number and behaviours are also included in the energy models.

4. OPTIMISATION COMPONENT

The role of the optimisation component, ABO, is to provide optimised energy consumption, generation, and storage of the building, taking into account the demand response schemes. In TABEDE, a wide range of devices is considered; each device possesses its own dynamic constraints and objectives. Performing an optimisation in such a context over a time horizon entails dealing with a large number of variables, making it computationally impractical to solve in a centralised manner [2].

Advances in decomposition methods such as Alternating Direction Method of Multipliers (ADMM) [3] have been applied to solve the optimisation of energy flow due to their robustness and privacy-preserving features. To solve this optimisation problem in a distributed fashion, thereby ensuring efficiency, scalability, and privacy, we propose a multi-agent optimisation approach based ADMM. For each type of devices, we model its objective function and constraints incorporating user constraints and demand-response incentives, when applicable.

[2] Input Data File (IDF)

[3] EnergyPlus Weather format (EPW)

In our optimisation approach (refer to [4] for a complete description), each device is modelled as an agent. Virtual agents, called net agents, are modelled to represent energy exchange zones between devices, which constrain the energy schedules of their associated devices. As ADMM, our approach iteratively solves the problem until convergence. In each iteration, first, each device computes in parallel its best response to the price and energy requested by nets. Second, each net, upon receiving the offers from all the devices connected to it, checks if the convergence has been reached. If there is no convergence, nets compute new requests for the devices considering the devices' previous offers and send the new request to the devices. Third, nets update the scaled dual variables. The result of the optimisation is the optimal energy flow, i.e., consumption and generation profiles that consider the incentives from demand-responses schemes, while respecting user constraints.

5. SMART OPERATION

Smart Operation [5] is a distribution network operational tool, proprietary software of Engie Impact, used for optimising electric power flows. The tool assesses the optimal operation of an electrical distribution network in the presence of distributed energy resources such as photovoltaic (PV) systems, wind turbines, electric vehicles (EVs), and battery storage systems, ensuring the adherence to grid constraints such as voltage and current limits. The tool is built around a state-of-the-art multi-period AC optimal power flow calculation core [6]. It is built for static and balanced flows on radial grids, allowing the convexification of its internal formulation and hence uniqueness of its mathematical solution. It gives as an output the optimal dispatching strategy of flexible resources: load shifting and shedding, generation curtailment, and EVs and batteries charging/discharging patterns. In TABEDE, SO is used for analysing the optimisation results of ABO to estimate the impact at the community level. It provides the optimal strategies to manage the flexibility offered by the community.

6. EVALUATION

The evaluation of the proposed infrastructure is conducted via the simulation environment, which enables us to assess its impact at the building level and the district level. The simulated district is modelled based on a part of a neighbourhood and its grid in Cardiff, UK, in which one of our pilot sites is located. It includes 66 units distributed across seven archetypes including apartment buildings and terraced houses that allow for a fair representation of energy demand for district-level simulation purposes. The occupancy number and behaviours are estimated based on the house size with considerations of the household type distribution in Cardiff. User behaviours are simulated according to predefined occupancy profiles of UK houses [7].

The neighbourhood's grid is composed of a single MV/LV transformer with three feeders. One single feeder of the network is selected for simulations to which 66 buildings are connected to ensure that computation time remains acceptable. The technical characteristics of the grid including resistance and reactance of the cables, nominal capacities of transformers and lines, and technical restrictions for voltage quality were obtained from its local DSO.

The billing structure used corresponds to the one applied to that specific district: Buying peak price of 0.20 €/kWh ([07:00, 00:00[) and off-peak price of 0.13 €/kWh ([00:00, 07:00[) and selling price of 0.04 €/kWh.

6.1 Scenarios

The development of the scenarios was carried out based on (1) the ownership rates of PV & TABEDE solution and (2) the configurations of electrical loads among customers. The district solar generation depends on the number of customers owning a PV module and their power capacity; hence, different PV ownership rates are proposed to assess TABEDE's ability to manage the RES penetration. The capacity of PVs is defined according to common domestic PVs (3-4 kWp) in the UK, house size, and load demands. These ownership rates are also used for TABEDE penetration, as shown in Table 1. The ownership of TABEDE solution is set based on the presence of PVs among customers. For instance, in scenario SC_01, 33 out of 66 houses (50%) are equipped with a PV, and 7 out of 33 houses (10% of 66 houses) have TABEDE installed.

The number and load profiles for individual electrical appliances are key elements for estimating electricity load profiles since gas boilers are used for heating systems in the district. The electrical load profiles are developed according to the ownership rates of common electrical appliances in residential houses in the UK. The types of these appliances (flexible or non-flexible) include wet appliances (washing machine, cloth dryers, and dishwasher), cooking appliances (electric hob, electric oven, kettles, and microwaves), cold appliances (refrigerator and freezer), and miscellaneous appliances (TV, vacuum cleaner, iron, and PC). The frequency and utilisation period are defined basis on the UK Time of Use Survey scenarios [8].

Table 1: Penetration rates of PV and TABEDE in the district

Scenario	Penetration rate [%]	
	PV	TABEDE
SC_01	50	10
SC_02	50	50
SC_03	50	100
SC_04	100	10
SC_05	100	50
SC_06	100	100

To assess TABEDE with the presence of all the appliances, a set of configurations for flexible appliances is used to run the six scenarios, as shown in Table 2. The highest customers' utilisation rate (100%) with 8% increase in ownership rates are set for wet appliances. Extreme days with the higher and lower amount of solar radiation driven from one year of data (2019) are selected. The simulation is carried out for both a summer day (highest solar -19/06/2019) and a winter day (lowest solar 19/12/2019).

Table 2: Electrical loads configurations

	Appliance	Config_01	Config_02
Ownership	Washing machine	92%	100%
	Dryer	58%	65%
	Dishwasher	46%	50%
	Fixed loads		+ 8%
Utilisation	Washing machine	66% weekday, 80% weekend	100%
	Dryer	66% weekday, 80% weekend	100%
	Dishwasher	42%	100%

6.2 *Empirical results*

The community's electricity demand and generation of different scenarios previously described are shown in Figure 1. The total consumption of the buildings (approximately 960 kWh) is fixed by design and remains constant for all the scenarios. The total generation varies across the scenarios: *Winter 50% PV* penetration shows the lowest generation rate of approximately 70 kWh, whereas *Summer 100% PV* corresponds to 1800 kWh, which is the highest. These two scenarios represent two extreme situations that can be encountered along the year. Summer scenarios have enough locally produced energy to cover the needs of the community, while in winter, solar production represents a small percentage of the total consumption. It is noteworthy that the buildings' consumption patterns are fixed to demonstrate the dependency of the TABEDE's effectiveness with respect to the available solar energy. Flexible consumption represents the amount of consumption exploitable by TABEDE (e.g., shifting or shedding). Only the houses with TABEDE installed are considered to provide a certain amount of flexibility. As shown in Figure 1, this amount increases in function of the rate of TABEDE penetration in the community.

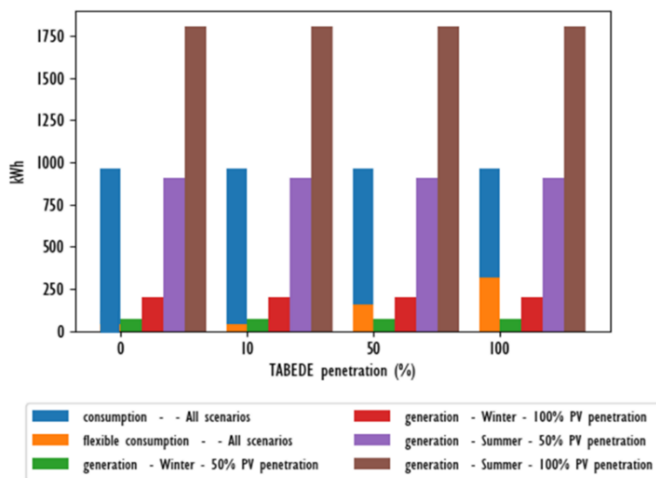

Figure 1: 24h total demand and generation for different scenarios

The net-consumption costs (i.e., the consumption cost of the community minus its injection revenues) of different scenarios in the function of TABEDE penetration rate is shown in Figure 2. These costs are calculated using the optimised consumption and generation profiles of the 66 houses suggested by ABO. The energy cost reduction increases as more houses are equipped with TABEDE. More specifically, from *Winter 50% PV* to *Summer 100% PV*, this reduction goes from 6% to 34%, respectively. It is noteworthy that during the low production of PV as in the case of *Winter 50% PV*, the cost reduction results mainly from optimising the flexible consumption to benefit the off-peak price.

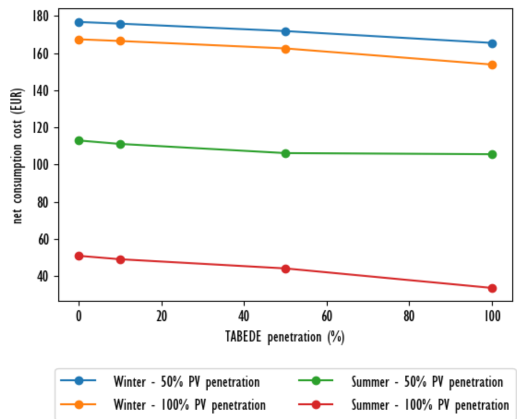

Figure 2: Optimised net-consumption cost across different scenarios

A decomposition of the optimised cost and revenues of *Winter 50% PV* and *Summer 100% PV* is shown in Figure 3, which corresponds to the worst and the best-case scenarios, respectively. It can be seen that during winter the consumption cost is higher due to lower production of PV, which results in a smaller amount of saving from self-sufficiency (i.e., local consumption of PV). Furthermore, when increasing TABEDE penetration rate, the net-consumption cost is reduced in both summer and winter scenarios. For the former, TABEDE maximises PV consumption, and thus increases savings from self-consumption. For the latter, since solar energy is minimal, this cost reduction results from the increase of energy consumed during the off-peak periods, and thus less in the peak periods, as suggested by TABEDE.

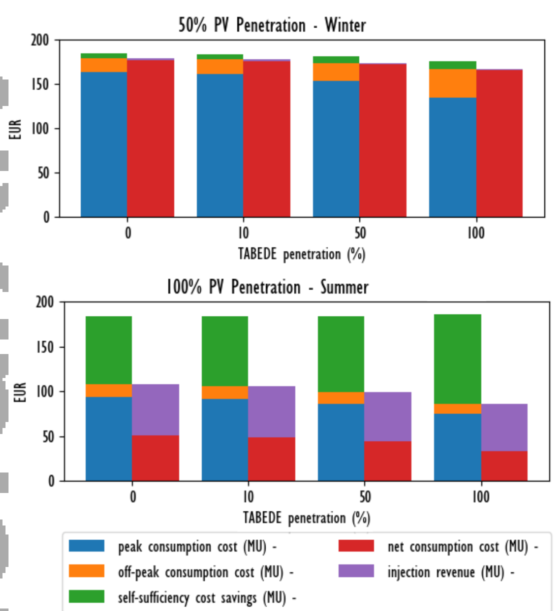

Figure 3: Optimised costs of Winter 50% PV and Summer 100% PV

The next part of the analysis considers the impact of TABEDE on the electricity network interconnecting the buildings when grid constraints are introduced. For this demonstrative example, we select injection limit as the grid constraint. For this analysis, we focus on the case of 50% TABEDE penetration for *Summer 100% PV* scenario, which consists of significant PV injection.

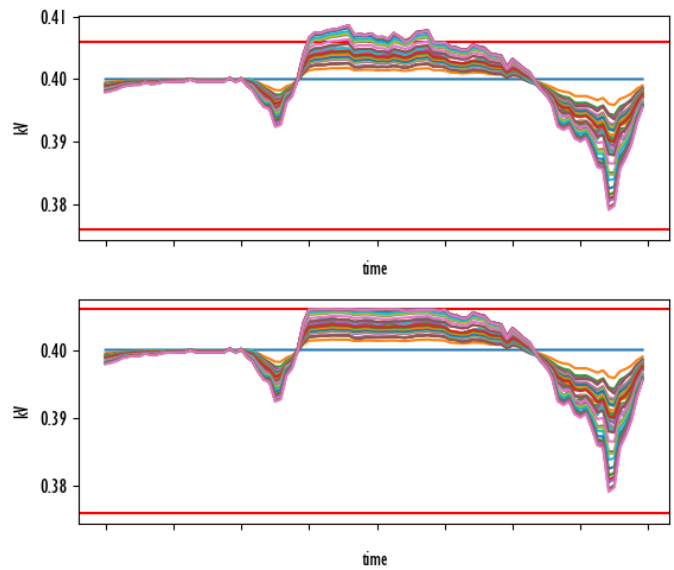

Figure 4: voltage profile for all nodes - summer 100% PV penetration - 50% TABEDE penetration

The first step of the analysis was performed by conducting a power flow computation on the electrical grid connecting the buildings. This was done by SO based on the consumption and generation profiles of each of the buildings optimised by ABO. We specifically look at the voltage increase on the nodes as it is commonly known as one of the main problems faced by electricity distribution grids due to local generation. The upper graph of Figure 4 shows the 24h voltage variation profiles of all the nodes in the network. The rated voltage is represented by the blue line, whereas the maximum and minimum allowed values are the red lines. We observe how some nodes reach a voltage value above the maximum limit. This is the outcome of simultaneous intense solar injections to the grid, especially during midday. The lower graph of Figure 4 depicts the alternative generation profiles optimised by SO to curtail the amount of solar energy in order not to breach the maximum limit.

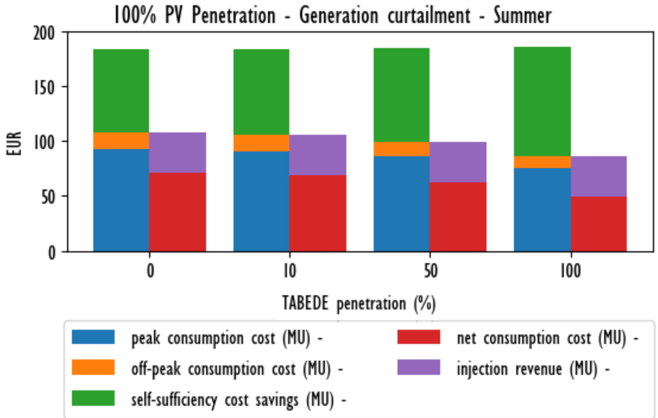

Figure 5: Costs when generation curtailment is activated to respect grid constraints

Figure 5 illustrates the *Summer 100% PV* scenario's cost decomposition when generation curtailment is considered. When compared with a situation without curtailment (lower graph of Figure 3) it can be seen that one of the consequences of considering grid restrictions is an absolute reduction of the injection revenue. Indeed, buildings now cannot sell their electricity back to the grid because of grid quality restrictions. However, even if this curtailment happens in all the four situations, i.e. with and without TABEDE, we still observe a relative reduction of around 30% (from around 71€ to 50€) on the net consumption cost when the penetration rate of the system is increased (from 0% to 100%). These last observations show the importance of considering the limitations imposed by the grid when assessing the impacts of the system. In such a scenario with operational constraints, TABEDE still proves to be useful, though with reduced gains due to the grid's constraints.

7. CONCLUSION

It has been shown that the proposed approach is able to reduce energy bills up to over 30% of the community in the best-case scenario by prioritising local consumption of the PV and exploiting the flexibility of consumption to benefit the off-peak price. When considering grid constraints in the analysis, even if the absolute benefits to the system might be reduced, the potential relative gain due to TABEDE still showed promising results. Assuring quality is a fundamental element of any grid's operation, and the systemic analysis performed in the current implementation might help, in a next step, to quantify the correct incentives to offer to customers for their willingness to actively participate in maintaining grid standards.

Due to the page limit, the infrastructure and the components are presented in a concise manner, and the evaluations included represent only the demonstrative cases. However, other specific cases are also to be considered such as the evaluation of the impact of SO's alternative consumption and generation patterns when applied to the buildings.

ACKNOWLEDGEMENT

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