Building-to-vehicle-to-building approach for the NZEB target at a micro-grid level: a comprehensive sensitivity and parametric post-optimality analysis

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Abstract. This paper focuses on a novel energy management approach for cluster of buildings connected in micro-grids by taking advantages from plug-in electric vehicles considered as vector devices for renewable energy exchanges, besides additional high-power appliances and house electricity sources. Such approach allows accelerating the development of nearly zero energy buildings and promoting the deployment of renewable energy sources at a micro grid level. To this aim, a dynamic simulation model, implemented in MatLab was developed for the building energy demands and loads assessment. To show the potentiality of the considered concept and approach, a case study based on a micro-grid consisting of a house and an office building connected by an electric vehicle is presented. The optimization of three different layouts, where electricity is alternatively produced by tilted roof or vertical façade photovoltaic panels is conducted by means of a parametric analysis performed by varying the vehicles energy use, battery capacities and solar field size. Preliminary results show that, by considering economic criteria, by exploiting the renewable energy production on and off-site, the buildings final demands decrease to values lower than those commonly considered for NZEBs.

1. Introduction
In order to reduce the energy and environmental impact of the building sector, the use and implementation of energy efficiency strategies, especially based on Renewable Energy Sources (RES), are more and more encouraged [1]. The building integration of energy-efficient and renewable energy technologies is exploited within the Net Zero Energy Buildings (NZEB) framework [2]. In addition, recent international directives require reduced pollutant emissions of cities, mainly caused by the private transport sector, responsible for the largest part of energy consumptions. To deal with these energy and environmental issues, the use of Electric Vehicles (EVs) is becoming a very promising option, especially if they are powered with RES technologies. Among them, solar energy systems are considered as the most attractive and Photovoltaic (PV) panels are expected to cover a huge part of the energy demands of buildings, whereas EVs will significantly contribute to their energy balance [3].

In this framework, this paper aims to analyse the energy and economic performance of a novel concept, namely Building to Vehicle to Building (V2B2), which extends the Vehicle to Home (V2H) and NZEB concepts to a novel zero energy paradigm where buildings are not considered as autonomous entities and are linked to EVs [4]. The key aspect of this new paradigm is the possibility to transfer electricity within the micro-grid, optimizing the utilization of power generation at a system level. To analyse the energy and economic performance of such scheme, a suitable calculation tool (implemented in MatLab) was developed with the aim to conduct parametric analyses for the system optimization. Three different layouts of a micro-grid including two buildings (a house and an office) are analysed by considering different energy storage and PV sizes, driving distances, etc. By evaluating energy and economic...
indexes, the electricity from the grid is minimized and the self-consumption of renewable electricity is maximized, toward the overall NZEB goal at a micro-grid level.

2. System description

In the framework of the V2B² concept, with the purpose to contribute to the achievement of the nearly zero energy target at a micro-grid level, the EV simultaneously acts as energy user, storage and vector. To this aim, the EV stores renewable electricity and transfer it from one building to another. The overall system efficiency depends on the installed RES and on EV motion and final building demands. The investigated micro-grid layout, shown Figure 1 and analysed in this paper, consists of:

- two building users, i.e. a single-family house (namely House) and an office space (namely Office);
- Building Integrated PhotoVoltaic (BIPV) panels, installed either on the tilted roof of the House building or on the South façade of the Office building;
- one EV, moving back and forth between the House and the Office. Its electrical battery, namely EVB, is charged or discharged as a function of the considered daily path and of the micro-grid needs;
- an electricity storage device, namely House System Battery (HSB) and located at the House building.

In order to study the role of electric vehicles as alternative electricity vector among buildings integrating RES, a suitable case study analysis is carried out. Such study refers to three different RES based micro-grid layouts (hereinafter referred to as Case 1, Case 2 and Case 3) compared to a reference traditional one where PV panels (referred to as Case 0) are not installed, as sketched in Figure 1.

Figure 1. Proposed V2B² micro-grid system layout (Case 1-3) and reference one (Case 0).

The proposed system layouts, namely Case 1, Case 2, and Case 3, and the reference one, Case 0, differ from each other as a function of the i) EVB charging and discharging processes, ii) the location of RES. Briefly, by varying the PV panels site and the batteries features, the obtained layouts (see Figure 1) are:

- **Case 0** (reference case): it is the reference layout simulating the unidirectional Vehicle to Building (V2B) system operation. Specifically, the plug-in EV acts as a power load, and the EVB is charged by the Grid through a home charger. The Grid also supplies electricity to the House and Office for their needs. No RES and stationary batteries (HSB) are considered;
- **Case 1, Case 2 and Case 3** (proposed cases): represent a novel concept of bidirectional V2B² system operation. The plug-in EV is linked with the Grid but it also acts as a power load for the building where the RES is available on-site (the House for Case 1 and Case 2, and the Office for Case 3) and as a source for the other building. PV panels are installed on the tilted roof of the House in Case 1 and Case 2 and on the South façade of the Office in Case 3. In Case 1 and Case 2, the HS, is installed in the House, and it is also used to feed the EVB with available stored energy. The EV transfers stored PV electricity to the building without RES systems, which benefits from off-site renewable production. In Case 1, during the night, if the HSB State Of Charge (SOC) is higher than the EVB one, electricity from HSB is supplied to the EVB (charged by the Grid if necessary). To prevent the need of energy transfer from the HSB to the EVB and, thus, the associated losses, the proposed Case 2 is based on swappable batteries (i.e. two identical batteries are modelled for the House and the EV, and the one with the highest SOC is placed on the EV at the early morning). Finally, for all cases, additional auxiliary electricity for House and Office loads is balanced by the Grid. Electricity stored within the batteries can be supplied to the considered users down to their minimum SOC levels (due
3. Modelling
The simulation model, suitably developed for dynamically simulating V2B² system layouts, and implemented in MatLab, is detailed [4]. Hereinafter, for the sake of brevity, only the main components linked to the V2B² system behaviour are described.

3.1. Building and PV models
The House and Office users’ electrical demands are dynamically calculated by means of an in-house building simulation tool [5, 6], which also allows for the simulation of the electrical behaviour of PV panels integrated in the exterior surface of the buildings [7]. The tool has been modified with the aim to calculate the electrical loads and generation of multiple buildings and building integrated photovoltaic (BIPV) systems [4]. Note that the model is based on a resistive-capacitive (RC) thermal network.

3.2. Electric vehicle and energy storage models
The bidirectional EVB operations, charging and discharging modes of the EVB are modelled by implementing their characteristic curves. The behavior of the Li-ion battery cells is modelled with respect to the terminal voltage, discharge/charge current and state of charge [8]. The power demand of the EVB charger is modelled considering a constant current [9]; in discharging mode for vehicle motion, its power consumption depends on the driving speed. The HSB is modelled by means of an equivalent circuit by a scaled model associating the internal charge curve with the operating power [10].

3.3. Energy and economic model
In order to assess the energy and economic performance of the proposed V2B² layouts, and to compare their performance to the one of the reference Case 0, the Energy Saving (ES) and the Simple Pay Back (SPB) indexes are the two selected cost functions to be maximized and minimized, respectively [4].

4. Case study analysis
The Proposed V2B² System (PS) layouts based on RES (Case 1, Case 2 and Case 3) sketched in Figure 1), are compared to a typical Vehicle to Grid (V2G), considered as Reference System (RS) without RES (Case0 in Figure 1). All simulated cases consist of 2 buildings, the House (128 m²) and the Office (90 m²), and an EV. The electrical power generated from PV panels are distributed between the micro-grid, as well as stored within the HSB and EVB. Aim of the case study analysis is to find out the optimal system design which optimize either the energy or the economic performance of the V2B² layouts. Thus, a parametric analysis is conducted by varying the values of such design system parameters:

- $PVSF = \text{PV surface area (m}^2\text{)},$ varied from 28 to 140 m² with a step of 14 m²;
- $EVDD = \text{EV driving route (km)},$ varied as: 26, 52 and 104 km/day (the driving distance covered per trip is equal to 13, 26 and 52 km);
- $EVB_{CP} = \text{EVB capacity (kWh)},$ varied as: 40, 50, 60, 75, 85, 90, and 100 kWh (featuring commercial battery packs, e.g. Tesla Model 3 and Model S [11]). Note that for Case 0, where no PV are available, a battery of 30 kWh is considered;
- $HSB_{CP} = \text{HSB capacity (kWh)},$ varied from 11 to 18.5 kWh with a step of 2.5 kWh.

For the Li-ion EVB battery a nominal charge power AC of 7.5 kW (from Grid) and an overall efficiency factor of 0.94 are considered; likewise for discharging mode [9]. Conversely, when the EVB is discharged for vehicle motion needs, the power consumption depends on the driving speed (50 km/h) [8]. The maximum SOC of the EVB and HSB correspond to 95% of their nominal capacity. For the HSB Li-ion battery, a 5.0 kW home/office charger is considered. The EV is only used for home-work commuting, between the House and the Office (the random use of the vehicle for personal mobility is neglected). The EV leaves the House at 8:00 a.m. and the Office at 17:00 p.m., remaining connected to their BMS according to the daily driven time. The House features a two-floor single family residential building with its longitudinal axis East–West oriented and a pitched roof (30° slope, Figure 1), where BIPV panels are installed (Case 1 and Case 2 scenarios). The House is occupied by a typical family with...
5 members spending daytime hours outside. A family member leaves the House to reach his workplace at the Office by the EV which remains parked and plugged to the BMS of the Office until the end of the business day. The Office is a single intermediate floor space of a multi-floor building occupied during daytime hours by 6 people. Such space is modelled as a South facing perimeter thermal zone (with adiabatic internal walls) with the exterior façade consisting of an opaque/glazing/opaque wall where BIPV panels (90° slope, Figure 1) are installed on the opaque surface (in Case 3 scenario). The BIPV field consists of mono-crystalline silicon panels with an efficiency of 0.195 and a peak power of 200 W. Table 1 shows the main House and Office operating assumptions; additional data are reported in [4]. Yearly simulations are carried out through DETECT 2.3, with a 7.5 minutes time step (8 time steps per hour), by elaborating the Meteonorm data file of Naples (Italy). Heating and cooling demands are assessed from November 15th to March 31st and from June 1st to September 30th, respectively (heating and cooling set-points are 20 and 26°C). Finally, for the calculation of energy and economic indexes, the specific capital cost of the HSB / EVB is 260 €/kWh, and of PV panels is 1000 €/kW; whereas the cost of electricity is equal to 0.20 €/kWh for the House and 0.18 €/kWh for the Office.

Table 1. Building operating assumptions

|                         | House   | Office          |
|-------------------------|---------|-----------------|
| Occupancy and appliances schedule [hours] | 18-8    | 9-18            |
| Thermal load [W/m²] due to appliances ([hours]) | 10      | 9 (from 9 to 13) and 15 (from 14 to 18) |
| HVAC system schedule [hours] | 7-8, 18-22 and (8-10, 17-20 weekend) | 9-12, 13-18 |

5. Results
For the latitude of Naples (40.85°), the amount of incident global solar radiation over the whole year substantially changes due to the PV slopes. The yearly total electricity needs of the House (E_{Grid→House}) and the Office (E_{Grid→Office}) are equal to 6.97 and 6.93 MWh/y, respectively. Such values correspond to 54.4 kWhel/m² (House) and 77.0 kWhel/m² (Office), being far from the typical values of NZEBs. The EV has a peak demand of 6.7 kWel (at the average speed of 50 km/h) and yearly energy consumptions of 0.87 MWh/y (EV_{DD} = 13 km/trip), 1.75 MWh/y (EV_{DD} = 26 km/trip), and 3.50 MWh/y (EV_{DD} = 52 km/trip). Thus, a significant amount of the overall electricity needs might be covered by RES generation from the solar fields by optimizing the energy storage capacity. To understand the system operation of the proposed V2B scenarios, it is useful to analyse the time histories of the key electricity flows. As an example, Figure 2 shows the electricity produced by the BIPV field (P_{PV} at PVS = 84 m²), the electricity demand of both the House and Office buildings (P_{Office&House}), as well as the House and Office demands covered from RES (E_{RES→House} and E_{RES→Office}) and from the Grid (E_{Grid→House} and E_{Grid→Office}). The figure refers to Case 1 (BIPV on the roof of the House), whereas the selected days July 27th to 30th are relative to two cloudy (27 and 28 of July) and two sunny (29 and 30 of July) days. Data are obtained for EV_{DD} = 104 km/day, EVB_{CP} = 75 kWh, HSB_{CP} = 27 kWh (only for Case 1). Figure 2 clearly shows that the solar field can almost balance all the House electricity load (occurring in the early morning and in the evening), whereas only a small fraction is balanced by the Grid. Although PV panels are on the House, the Office load is partially balanced by renewable electricity transported from the House by the EV (especially on Monday, last day, after the weekend when the EV is continuously charged). For the sake of completeness, Figure 3 shows the dynamic profiles of PV generation supplied to the HSB, EVB, and Grid, together with the SOC level of the EVB and HSB for the same summer days of Figure 2. Here, at the beginning of the first day, the PV electricity production surplus (P_{PV} > P_{House}) is stored within the HSB installed at the House, with a consequent increase of the SOC level. When this reaches the maximum level (0.95%), the production of PV is fed into the Grid for a significant amount. The SOC_{HSB} decreases in the late evening, being discharged to balance the House load (Figure 2) During the second day (Saturday), the PV surplus is mostly stored in the EVB (when the maximum SOC_{HSB} is reached); further amount of PV electricity is supplied to the Grid; the same behaviour is noted on the third day. Finally, on the last day, Monday, the PV surplus is stored in the HSB, whereas the EVB significantly reduces its SOC level when supplying
electricity to the EV motion and to the Office load (not shown).

Figure 2. Case 1 - Dynamic profiles of PV generation and House and Office electricity demands for few summer days (July, Friday 27th to Monday 30th). Electricity supplied from Grid and from RES.

Results of the parametric analysis (conducted by varying the values of the parameters PVSF, EV DD, EVB Cp, and HSB Cp) show that the higher the energy storage capacities, the better the energy performance, whereas the opposite occurs for the economic one. Specifically, at the current high cost of the EES (about 260 €/kWh), the lower the storage capacity the lower the SPB. In addition, due to favourable electrical national pricing conditions, the exported electricity is significantly exploited.

According to the results of this analysis, the optimal design parameters are:
- min SPB is obtained for Case 3, \( PVSF = 84 \text{ m}^2, EVDD = 26 \text{ Km/day}, EVB_{Cp} = 30 \text{ kWh}; \)
- max ES is obtained for Case 2, \( PVSF = 84 \text{ m}^2, EVDD = 26 \text{ Km/day}, EVB_{Cp} = HSB_{Cp} = 100 \text{ kWh}. \)

The variation of the SPB, the energy imported from the Grid and the ES as a function of the EVB\(_{Cp}\), \( PVSF \) and \( EVDD \) can be observed in Figure 4, which highlights the slope of the variation of plotted indexes. Figure 4 (left) shows that the SPB, calculated for the optimal economic case, can vary considerably when the EVB increases, and the lower the PV size, the higher the weight of the EVB capacity on the overall performance. Similar considerations can be done for the imported energy and energy saving.

Finally, the proposed V2B\(^2\) schemes allow for the achievement of the NZEB goal at the microgrid level by dispatching electricity through the EV from one building to another. In this regard, it is worth noting that by taking into account the economic criterion (and without considering the additional benefit achievable with the purchase of electricity feed into the Grid), the final yearly total electricity needs of the House (\( E_{\text{Grid} \rightarrow \text{House}} \)) and the Office (\( E_{\text{Grid} \rightarrow \text{Office}} \)) are equal to 4.87 and 1.13 MWh/y,
corresponding to 38.0 kWe/m² and 12.0 kWe/m². Such values, lower than the typical ones recommended for NZEBs, are obtained by the exploitation of on-site and off-site RES. Finally, the reduction of the electricity imported from the Grid is equal to 45% for the House and to 77% for the Office.

Figure 4. V2B² scheme: (left) SPB period [years] for Case 3 and EVDD = 104 km/day, (right) electricity from Grid and (middle) ES [MWh/year] for Case 2, EVDD = 26 km/day, and HSBcp = EVBcp.

6. Conclusion
This paper analyses the energy and economic performance of a novel energy management scheme for grid-connected buildings and electric vehicles, namely Building to Vehicle to Building (V2B²). By means of simulations performed with an in-house developed tool, the achievement of the NZEB target of a micro-grid consisting of 2 buildings (a house and an office) and an electric vehicle is analysed. Simulation results relative to the proposed case study show that the use of electric vehicle as energy vector can effectively benefit the whole system (with lower fossil electricity consumption and higher renewable self-consumption). For the investigated system layout which minimizes the simple pay-back period, the final yearly total electricity needs of the residential building passes from 54.4 to 38.0 kWe/m², by exploiting electricity produced off-site (at the office building with PV panels). Similarly, the office building electricity demand decreases from 77.0 to 12.0 kWe/m², achieving the NZEB target.

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