Impact of electrical vehicle (EV) penetration on the cost-optimal building integrated photovoltaics (BIPV) at a small residential district in Sweden

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Abstract. Buildings are transforming into prosumers because of the intensive growth in photovoltaics (PV), electric vehicles (EV) and home batteries. To adapt such transformation trend, this paper optimizes the cost-optimal capacity and positions of building integrated photovoltaics (BIPV) in a small residential district in Sweden, by considering thermal-electricity loads, power sharing among neighbour buildings, and electrical storage. This study focuses on two optimization scenarios with two different objectives: (1) maximizing net present value (NPV) of the BIPV system, and (2) achieving 27% renewable energy sources (RES) (as set by EU Framework for climate and energy). The optimization is performed with varying penetration of EV demand. The results show that: in scenario (1) the increase in EVs enables larger BIPV capacity with slightly improved self-consumption and thus with a little more profit. In scenario (2) however the levelized cost of electricity (LCOE) of the self-consumed electricity sensibly increases with growing presence of EVs, leading to the decreased profit. In conclusion, three main factors were found that are negatively affecting the performance of BIPV in relation to the EVs in the Swedish residential sector: A low electricity price in summer, a prevalence of the EV load at night, and the absence of PV over-production in winter.

1. Introduction

Buildings are becoming pro-sumers as they not only produce energy from distributed recourses, such as photovoltaics, but partly consume the generated energy. The consumption comprises heating, ventilation, air conditioning (HVAC) systems, electric vehicles (EV) etc. Such transformation of the buildings’ role offers great potential for consumers and building owners to economically improve their energy practices. The prosumers are steadily increasing in number, building integrated photovoltaics (BIPV) installations are increasing in capacity in recent years, this reveals a need for the integration of a smart grid infrastructure [1]. To develop strategies for the future, policymakers and planners need knowledge of how many and where BIPV systems could be integrated effectively and efficiently into local energy infrastructure and markets. Up to date, researchers have applied techno-economic optimization of BIPV at building level, by considering the synergies with batteries and thermal envelope [2], load control [3], electricity pricing [4] and façade geometry [5]. However, these studies didn’t consider the synergies of neighbouring buildings and the influence from local EV penetration. On district or above level, numerous researches focus on the general optimization of BIPV showing the impact of solar resources [6], EV and heat pump [7]. But these studies didn’t include an optimization about BIPV’s capacity and location over each building.

A research gap thus lies in the absence of detailed techno-economic optimization of BIPV in relation to different EV penetrations at district level, by involving neighbouring buildings. Research questions are therefore raised up, for instance: how the optimal configuration of BIPV’s net present...
value (NPV) changes as the EV penetration increases? how do the different key performance indicators (KPI) are affected? In addition, according to 2030 Framework for climate and energy [8], the European commission bids to achieve a 27% share of renewable energy source (RES) by 2030. If a coverage of 27% of the available load in the district is needed with the most cost-effective BIPV and battery system, what will be the cost-optimal solution under different EV penetration? A global optimization of BIPV in each scenario is urged.

This study aims to optimize capacity and positions of BIPV in a small residential district, by considering thermal/electricity loads, power sharing among neighbouring buildings and electrical storage. Objectives: (1) maximize the profitability of the system during its lifetime and (2) achieve the 27% RES target. The structure can be depicted as follows: section 2 clarifies the simulation methodology; in section 3 the boundary conditions and input parameters of the simulation case project are summarized; a series of optimization are then performed in section 4 at different EV penetration levels in two scenarios; section 5 finally presents the brief conclusions.

The simulation results will be useful in finding effective strategies of BIPV deployment in different EV penetration scenarios in a Swedish residential district. In the future, the same method could be replicated on different building clusters to confront those KPIs with the residential ones.

2. Simulation methodology

2.1. BIPV system modelling

The BIPV systems are modelled in a simple way to ensure computing speed and reducing the effort for collecting model inputs in the early design stage. The power profile of the PV system depended on the irradiation falling on the module and on the operating cell temperature [9], while aspects such as soiling or AC-DC losses were assumed as part of a static performance ratio coefficient of 0.8. The performance ratio is a location independent measure of the quality of a PV system, it is stated as a percentage and describes the ratio between the actual and theoretical power output of the system.

2.2. Optimization algorithm and fitness functions

In this study the optimization algorithm is an improvement of the one described in [10]. It is characterised by an additional (incremental) behaviour: the optimization algorithm starts with an empty system (no PV is present) and adds PV areas, moves it from one façade to another or adds electric storage for as long as the value of a specific fitness function increases. The fitness functions used in this paper were either NPV function, or \((LCOE_{self})^{-1}\). The latter represents \((LCOE)\) over the electricity self-consumed during the lifetime of the system (provided that 27% self-sufficiency is reached).

The formula of NPV calculation is expressed as in (1):

\[
NPV = \sum_{t=0}^{N} \left( \frac{c_{P_{t}} + s_{P_{t}} - \omega_{PV} C_{t}}{(1+i)^{t}} \right) - \omega_{PV} \cdot C_{PV,0} - \omega_{ES} \cdot C_{ES,0} - C_{sub}
\]

where \(N\) is the time horizon, \(t\) is the year of operation and \(c\) is the annual cumulative energy produced and instantaneously consumed. \(P_c\) and \(P_s\) are the cost of electricity and the revenues from the grid (i.e. 0.2 and 0 €/kWh respectively), \(s\) is the annual cumulative energy produced and sent to the grid. \(i\) is the discount rate, \(\omega_{PV}\) is the capacity of the PV system and \(C_i\) is the cost for maintenance [€/kWp]. Outside of the sum, there is the initial cost for the components: \(\omega_{ES}\) is the capacity [kWh] of the electric storage, \(C_{PV,0}\) and \(C_{ES,0}\) are respectively the unitary whole system costs for PV and storage. \(C_{sub}\) represents the cost of substitution for inverters and electric storage, this element always equals 0 except for the years when inverters and storages breaks.

The second fitness function is expressed as in (2):

\[
(LCOE_{self})^{-1} = \frac{\sum_{t=0}^{N} s_{t}}{\omega_{PV} C_{PV,0} + \omega_{ES} C_{ES,0}}
\]

This fitness function is heavily penalized in cases where the 27% self-sufficiency isn’t reached.
2.3. Thermal and electrical loads of buildings
TRNSYS is used to simulate the building and energy systems, which then outputs thermal and electrical loads. The whole residential district is built in one model, and the centralized heating, hot water and ventilation systems are also integrated. The heating and hot water for the district are supplied by a single centralised heat pump, the exhaust air serves as heat source. All exhaust air in each building, including kitchen & bathroom, is ducted to a heat recovery heat exchanger unit, powered by a fan, which is in turn located in the attic of each building.

2.4. EV load generator
The EV load is generated by using the Grahn-Munkhammar model [11]. It simulates the EV home-charging based on standard settings of 0.2 kWh/km electricity use and 24 kWh battery capacity available for trips, and a total distance driven per year of about 12200 km as a Swedish average scenario.

3. Project description and input parameters
3.1. Project description
A case study is conducted in Ludvika demo site, located in Sunnansjö, Dalarna, Sweden. This demo site is a multifamily dwelling unit made of three buildings built in 1970/73. The complex (three buildings) includes 48 apartments over 2 floors and a basement. These buildings will undergo a series of renovation plans including installation of BIPV, energy storage, micro grid, and heat pump systems.

3.2. Input parameters
The tool required, to perform the optimization and thus find the optimal capacity and positions of the PV modules, the whole area where the PV can possibly be installed. The tool will retrieve the hourly irradiation over the whole surface using the open source software RADIANCE and use this radiation data as a basis for the simulation. Every point represented a solar collector with a given area and is associated with an hourly irradiation. It is assumed that the maximum penetration possible for the electric vehicle would be of 1 EV per family for a total of 48 EVs. Different optimization have been performed: without EVs, with 24 EVs and with 48 EVs. The price of the electricity for the consumer is assumed to be 0.12 €/kWh in Summer and 0.2 in Winter. This situation is challenging in terms of BIPV profitability as the largest possible earnings are in periods when the radiation is unavailable. It seems the months where most earnings are possible for a BIPV system are only March and October. The electricity that is not contemporaneously self-consumed is assumed to be sent to the grid for 0.05 €/kWh. Nevertheless It is assumed that the price paid by the energy provider for the excess PV electricity is going to decrease alongside the lifetime of the system (of an amount comprised between -1% and -3% linear per year). Aside from these inputs, Table 1 and Table 2 report the set of techno-economic parameters required for the optimization of BIPV and other components.

| Table 1. Input parameters of BIPV system. |
|------------------------------------------|
| **Input name**                           | **value** |
| Module efficiency                        | 0.18      |
| Mesh edge [m]                            | 1         |
| Performance ratio of the system at STC   | 0.8       |
| Price of electricity for the provider [€]| 0.05      |
| Time horizon in years                    | 30        |
| Cost of the finished PV system [€/kwp]   | 1360      |
| Cost of the storage system [€/kwh]       | 670*      |

* Used Tesla powerwall: 1 Powerwall = 13.5 kWh usable power and costs 7.030.00 € (including taxes) + installation costs assumed 2000 € => 9.030.00 € which is ca. 670 €/kWh
Table 2. Techno-economic input parameters.

| Input name                              | min  | max value |
|-----------------------------------------|------|-----------|
| Annual maintenance costs €/kwp year     | 0    | 15        |
| Linear annual growth of the electric load | 0    | 0         |
| Linear annual efficiency losses         | 0.5  | 1         |
| Annual discount rate                    | 1    | 1.5       |
| Linear annual growth of price for consumer | -2  | 2         |
| Linear annual growth of price for provider | -3  | -1        |

Figure 1 represents the variation of electric demand due to the EVs on an annual basis and in the average day. The charging load is not much affected by the season (chart “a”), in annual cumulative terms each EV absorbs little over 1mWh so that each 24 EVs requires an amount of energy almost equal to 30% of the baseload. The hourly average load (chart “b”) shows that the EVs are adding their demand mostly at night, and the additional load thins out during the daytime (especially during the late morning). In general, the annual behavior of the EV demand can be considered advantageous for the PV installation because it acts proportionally more during the summer months when the demand is minor. Nevertheless, the low price of electricity during summer and the prevalence of the load at night risk to render the PV less useful unless electric storage is installed. On the other hand, an electric storage is extremely unlikely to be profitable as there is probably no over-production of PV electricity during the winter months (thus forcing the storage to have idle time and therefore reducing its profitability).

4. Results and discussion

4.1. Function 1: achieving maximum NPV of BIPV system

BIPV optimization in Function 1 is shown Figure 2. The southern portion of the roof is the first one to be occupied by the PV system because it is the most irradiated. With increasing presence of EVs, it is visible how the PV system grows in size. Despite having more or less a similar irradiation, the east and west portions of the roof are entirely excluded for the application of PV by the algorithm, the southern facades are used instead. The reason for this noticeable behaviour lies probably in the difference of price for the electricity: having a better performance in winter months, when the sun angles are closer to the horizontal, the façade integration results to be more profitable, thus prioritized by the algorithm.

Table 3 shows various KPIs at the three levels of EV presence. The “expected self-consumed LCOE” refers to the levelized cost of the electricity for the fraction of it that is self-consumed, it is therefore obtained as the total costs of installation and maintenance divided by only the electricity self-consumed. In other words it is the inverse of Equation 2. Despite a noticeable growth in the installed capacity, the larger growth of the demand forces the share of PV electricity to go down. There is a slight increase in self-consumption (not surprising considering that the whole system shifts towards larger load and larger capacity), thus a small reduction in the LCOE of the self-consumed electricity.
Figure 2. BIPV visualization in scenario 1 (a) no EV case; (b) 24 EV case; (3) 48 EV cases.

Table 3. Various KPIs at the three levels of EV presence in scenario 1.

|                     | 0 EV (a) | 24 EV (b) | 48 EV (c) |
|---------------------|----------|-----------|-----------|
| Installed capacity  | 44.640   | 48.780    | 53.280    |
| Expected self-consumed-LCOE [€/kwh] | 0.095     | 0.094     | 0.094     |
| Self-consumption [%] | 85.9      | 87.6      | 89.0      |
| Self-production [%] | 16.9      | 14.6      | 13.1      |
| Annual cumulative demand [mwh] | 205.408   | 264.446   | 322.320   |

4.2. Scenario 2: achieving 27% of RES sharing in electrical load

In this case, the PV system can be unprofitable. The algorithm is forced to install a specific amount because it is mandatory to cover 27% of the demand even if generating financial losses. Even in this case the unshaded part of the façade is preferred to the east-west oriented roof, but the need for larger capacities eventually forces the algorithm to use these areas as well. Table 4 similarly shows the variation of some KPIs with varying EV penetration. Figure 3 illustrates the optimization results.

Figure 3. BIPV visualization in scenario 2 (a) no EV case; (b) 24 EV case; (3) 48 EV cases.

Table 4. Various KPIs at the three levels of EV presence in scenario 2.

|                     | 0 EV     | 24 EV    | 48 EV    |
|---------------------|----------|----------|----------|
| Installed capacity  | 131.04   | 200.16   | 270      |
| Installed storage capacity[kwh] | 0        | 0        | 6        |
| Expected self-consumed-LCOE [€/kwh] | 0.168     | 0.199    | 0.223    |
| Self-consumption [%] | 51.6      | 44.4     | 40.7     |
| Self-production [%] | 27.1      | 27.1     | 27.0     |

It is noticeable that with increasing number of EV it becomes more challenging for the PV to cover the 27% of the load. In fact, the installed capacity is, in perceptual points, much larger than the actual growth of the load. This is due to a growing ineffectiveness of the PV system with increasing penetration of EVs. The growth of the dimension of the PV system only marginally increases the coverage of the load, while the share of electricity sent to the grid increases. This situation sensibly increases the LCOE of the self-consumed electricity with growing presence of EVs.
5. Conclusion
There are three factors that are negatively affecting the performance of BIPV in relation to the EVs:

• a low price of the electricity in the season when BIPV energy is available: discourages the purchase of storage to collect excess production in summer.
• a prevalence of the EV load at night: the increase of load due to EV does not promote a higher contemporary self-consumption for BIPV electricity, it requires an electric storage to be functional.
• the absence of BIPV over-production in winter which renders the electric storage unprofitable: aside the low price of electricity in summer, the lack of over-production in winter forces the electric storage to have long idle moments in the winter months.

The particularly negative interaction between BIPV and EVs in the residential area of the country of Sweden suggests to replicate the optimization process in other clusters, instead of only residence. The relation between BIPV and EVs could be more synergetic in offices and commercial activities due to the better contemporaneity of production and demand.

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