DC BUILDING NETWORK AND STORAGE FOR BIPV INTEGRATION

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ABSTRACT

Electricity loads in buildings are increasingly supplied by distributed renewable generation sources such as photovoltaic (PV) modules or fuel cells. Often these systems are combined with an electricity storage to raise the level of self-consumption in buildings and to reduce the load on the electric grid. PV production and battery storage are both inherently based on direct current (DC) power. At the same time, an increasing number of energy-efficient devices that are part of the building service systems – such as LED's, electronic equipment, or variable speed motors for efficient operation of ventilation units and heat pumps – use DC internally. Consequently, direct coupling of PV generation with electricity storage and DC loads in a local DC network has the potential to avoid power conversion losses arising in conventional alternating current (AC) based systems. In addition to the more efficient use of local generation and storage, an independent building micro-grid can provide system reliability in case of power outage.

In this work, we perform a first evaluation of potential efficiency gains of low-voltage DC versus AC distribution in residential buildings with PV generation and battery storage. We take into account high-resolution electric load and PV generation profiles for a net-zero energy building. We find that relative to a conventional AC system, a DC network improves energy efficiency by approximately 2% without storage and 4% with storage. Moreover, we analyse the sensitivity of the results to variations in PV system size and battery characteristics. We show that the benefit of the DC system becomes more significant with increasing local generation and storage and that energy efficiency improvement and building self-sufficiency are correlated. The theoretical analysis provides guidance for a lab-scale hardware implementation of a small AC/DC hybrid system, which is currently in preparation.

Keywords: Building integrated photovoltaics (BIPV), DC network, energy efficiency, electricity storage, self-consumption, net-zero energy building

INTRODUCTION

In recent years, the installed capacity of building integrated photovoltaics (BIPV) has strongly increased. At the same time, the structure of energy demand in buildings is changing rapidly. This includes a rising share of efficient HVAC technologies and consumer electronics, which use direct current (DC) internally. In fact, all semiconductor electronics for computers, LED, LCD, stereo systems, etc. are DC-based. In addition, the most efficient compressors and fans in heat pumps and ventilation units are using brushless DC motors (BLDC). These motors can operate at variable speed, which increases the efficiency of space heating, cooling, and ventilation by 20-50% compared to simple on/off control [1-5]. An analysis of 32 electricity end-uses shows that energy savings of about 33% are possible by switching the entire load of an average residential building in the U.S. to the most efficient DC-internal technologies [1,2]. While such savings might occur independent of a change to DC power networks, it demonstrates the potential of these technologies to improve building energy efficiency.

Alternating current (AC) allows efficiently transforming voltage for distribution over distance and near the load. However, it seems less attractive for emerging small-scale systems with distributed renewable DC generation, stationary or electric vehicle batteries, and a large fraction

of DC-internal appliances. In this case, a DC bus connection of photovoltaics, battery storage and loads has clear advantages in terms of efficiency, reliability, and cost [6,7]. DC power systems have been successfully implemented in data centers and telecom facilities relying on uninterruptible power supplies with efficiency improvements ranging from 5% to 30% [8,9].

In this research, we estimate potential electricity savings of using low-voltage DC versus AC distribution in a residential building combined with PV generation and battery storage. Only a few studies have analyzed the efficiency gains of DC networks for the integration of local DC power sources, loads, and storage [1,2,6,9]. The reported savings range from 1% to 14%, depending on the assumptions about converter efficiencies, load type and timing, distribution voltage, system size, and the availability of an electricity storage. In this work, we develop a numerical, steady-state model of different AC and DC network topologies with power system conversion efficiencies based on literature data. We take into account a high-resolution electric load and PV generation profile of a single family home located in central Europe. We model the building with a net-zero energy balance between annual electric demand and PV production. We introduce several energy evaluation metrics for the comparison of different systems. The modelling framework is fully parametric and we analyse the sensitivity of the results to variations in component sizes and efficiency.

METHODS

Modelling framework

We analyse four different system topologies for the integration of building electric loads, PV generation and the electric grid: We distinguish between AC and DC distribution, with or without battery storage. Each system is grid-connected to balance electric load and PV production. The components and possible power flows are illustrated in Fig. 1. The model is implemented in Matlab.
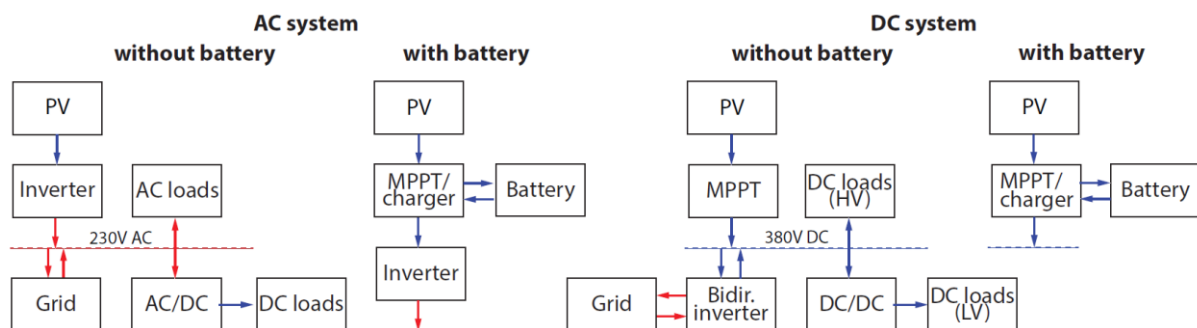

Fig. 1. System setups for AC and DC building network. The configurations with battery are only shown for the part before the main AC and DC bus.

As distribution voltage, we assume 230 VAC or 380 VDC. A 380V standard for DC distribution in data centers and residential buildings is in preparation by the EMerge Alliance [10]. Note that even though distribution losses are not accounted for in this paper, power cable losses are lower when operating with the proposed DC voltage compared with 230 VAC distribution [7]. Alternatively, the cable diameter can be reduced and copper saved, achieving the same efficiency as the AC grid. If the system is modeled with battery storage, four different operation modes are distinguished: a) excess PV production, battery not fully charged, supply of excess to the battery; b) excess PV, battery fully charged, supply excess to grid; c) insufficient PV, battery not discharged, partial or full battery supply; d) insufficient PV, battery discharged, grid backup. The state-of-charge (SOC) of the battery is estimated by integrating the current, and is limited between 10% and 90%. The assumed peak power conversion efficiencies for system components are summarized in Table 1 [1,2,11].

Table 1. Power conversion efficiencies in % (Sources: [1,2,11])

AC system				DC system			
w/o battery		**w/ battery**		**w/o battery**		**w/ battery**	
Inverter (incl MPPT)	95	MPPT/charge control	98	MPPT	98	MPPT/charge control	98
AC/DC appliance	f(P)	Inverter	97	DC house -> AC grid	97	DC house -> AC grid	97
		Battery (round-trip)	90	AC grid -> DC house	93	AC grid -> DC house	93
		AC/DC appliance	f(P)	DC/DC	95	Battery (round-trip)	90
						DC/DC	95

Load profile and PV generation

The building electric load profile is based on a high-resolution stochastic model for domestic electricity consumption developed by Fraunhofer ISE [12]. It has a time resolution of 10 seconds and provides a detailed breakdown by appliance type. The electric load profile used is representative for a single-family home. Ambient temperature and solar irradiation are based on reference weather data file for Southern Germany. It is assumed that the house has an annual heating demand of 50 kWh/m^2, and is equipped with a heat pump for space heating and domestic hot water generation with an annual performance factor of 3.5. The PV modules are oriented south and have an inclination angle of 33°. Fig. 2a shows the assumed annual load and PV generation profile. Fig. 2b shows the electric load by appliance and the power flow between house, grid and battery for one day in summer.
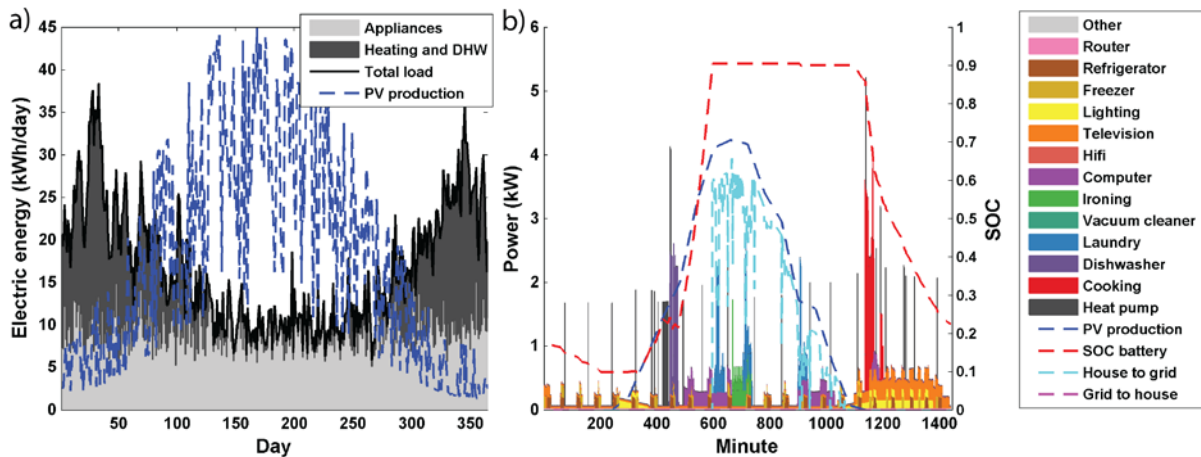

Fig. 2. a) Annual daily load and PV generation. b) Load profile by appliance, PV generation, and battery SOC for one day in summer

Efficiency improvements of DC appliances and power systems

In a conventional building AC network, DC-internal technologies are powered using internal or external rectifiers (e.g. used for laptops, LED, or variable speed DC motors). Direct-DC power systems offer energy savings by avoiding AC/DC conversion losses. Fig. 3 shows the efficiency of certified AC/DC power supplies for 230V input voltage. Based on this data and contact to industry experts we estimate the potential energy savings of using direct DC-coupling. For LED lighting, computers, and other electronic devices we estimate 15-25% efficiency gains, depending on the power level. Furthermore, we estimate 2-5% efficiency improvement for heat pumps, ventilation units, and other devices using variable speed BLDC motors.
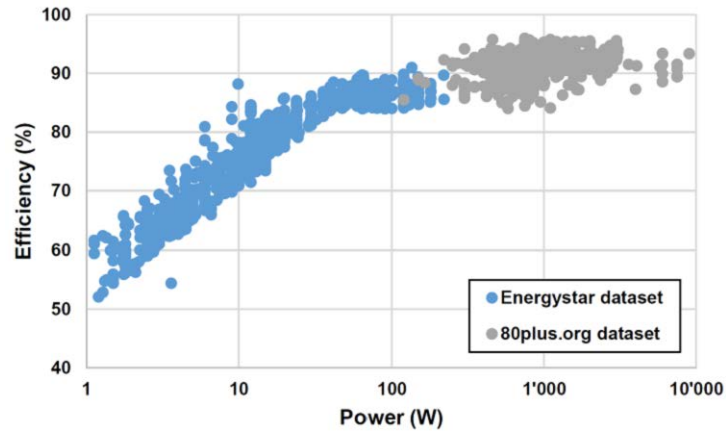
Fig. 3. Efficiency AC/DC power supplies as a function of rated power (Sources: [2,13,14])

Energy evaluation metrics

For the evaluation of different systems, we use four metrics:

- Energy balance: difference between electric energy to and from the grid for a specific house configuration per year

- Efficiency gain of DC over AC system: difference in the energy balance between the AC and DC system relative to the total electric load

- Self-sufficiency: share of the annual electric load covered by PV generation [15]

- Self-consumption: share of annual PV production used directly in the building [15]

RESULTS

Base case

In the base case, we model the building as being net-zero energy and connected to the electric grid. Accordingly, the PV system is sized to produce the total electric demand of the AC house per year (6131 kWh/y, 7.4 kW$_{peak}$). The battery has a storage capacity of one kWh per kW PV peak power, which is close to the average for grid-connected PV battery systems [15]. Table 2 presents the results for the reference case. For the same installed PV power the energy balance is better for the DC than the AC system, i.e. the DC system uses less energy from and feeds more energy to the grid. This means that the DC system uses the electricity more efficiently. Self-sufficiency and self-consumption increase by approximately 20% for the assumed battery storage size of 7.4 kWh. The efficiency gain of the DC over the AC system is higher with battery storage, as expected, as this configuration incurs additional conversion losses for the AC system.

Table 2. Simulation results in the base case by system

	w/o battery		w/ battery	
	AC	**DC**	**AC**	**DC**
PV to grid (kWh)	4645	4748	3069	3195
Grid to house (kWh)	4645	4606	3177	3053
Energy balance (kWh)	0	143	-107	142
Efficiency gain (%)	-	2.3	-	4.1
PV self consumption (kWh)	1486	1430	2955	2874
Self sufficiency (%)	24.2	25.0	48.2	50.3
Self consumption (%)	23.0	22.2	45.8	44.5

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Sensitivity analysis

We analyse the sensitivity of the results by varying the size and efficiency of system components. In particular, we investigate the influence of battery size, battery efficiency, and installed PV capacity on self-consumption and efficiency improvement. Fig. 4 shows how self-sufficiency and the efficiency gain of the DC over the AC system increase with installed PV and battery capacity. This means that the benefit of the DC system becomes more significant with increasing local generation and storage. Self-consumption is reduced with installed PV power and decreasing battery size, because a lower fraction of local production can be used directly in the building.
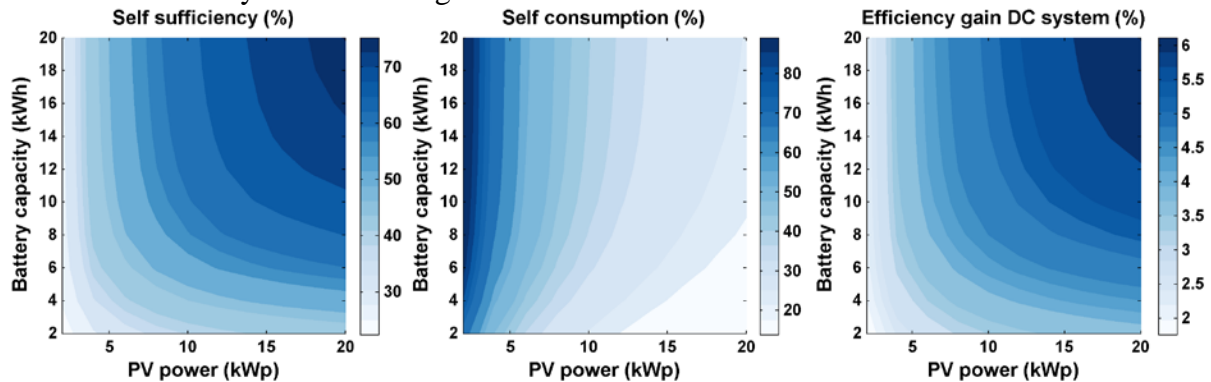

Fig. 4. Self-sufficiency and DC efficiency gain as a function of installed PV power and battery size. The load of the building is constant.

System efficiency with local storage strongly depends on battery performance. In the reference case, we have assumed a round-trip efficiency of 90%, which is realistic for li-ion batteries. However, lead-acid batteries have lower efficiencies about 80% [11]. Fig. 5 shows the dependence of the energy balance of the AC and DC system as a function of battery size and efficiency. In this case, the PV system is sized to meet the annual building electricity demand.
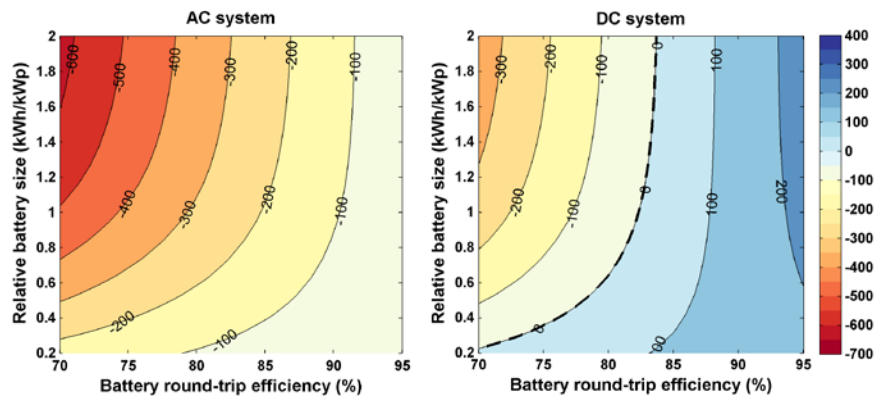

Fig. 5. Difference between energy to and from the grid for the AC and DC system

DISCUSSION

The results presented show that for local PV generation, a DC building network has the potential to improve overall system efficiency. The improvement is particularly high if the PV system is combined with battery storage. The absolute efficiency improvement of 2 to 4% is similar to the results of [7,9], but lower than the values found in [1,2] due to more conservative estimates about potential savings from avoiding AC/DC conversions. The efficiency gains are highest for electronic appliances operating at low power such as consumer electronics or LED lighting. Therefore, it may be most effective to focus on the integration of these devices with PV generation, battery storage, and DC distribution first.

This can be technically also achieved in a hybrid network coupling AC and DC loads simultaneously [16]. Note that electricity savings are greater for commercial than residential buildings because of the higher share of electronic appliances and the better coincidence of PV generation and load.

CONCLUSIONS AND OUTLOOK

In this work, we developed a model for the analysis of DC compared to AC distribution in buildings with PV generation and battery storage. We find that relative to a conventional AC system, a DC network improves system efficiency. Furthermore, we quantified the effect of battery and PV system size on self-consumption and showed that efficiency gains of the DC system correlate with building self-sufficiency.

In the future, we will improve the model by taking into account the variable efficiency of power converters and cable losses. In addition, more advanced battery charging strategies (e.g. peak shaving), demand side management, and additional building DC supplies or loads such as electric vehicles will be considered. Further to the theoretical analysis, a lab-scale hardware implementation of a small AC/DC hybrid system is in preparation to test the feasibility and for validation purposes. The setup is scheduled to be tested in the context of the Adaptive Solar Façade for the ETH House of Natural Resources (http://www.honr.ethz.ch) and the NEST HiLo building at EMPA (www.hilo.arch.ethz.ch).

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