Impact of demand response on BIPV and district multi-energy systems design in Singapore and Switzerland

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Abstract. This paper demonstrates the impact of demand response (DR) on optimal multi-energy systems (MES) design with building integrated photovoltaics (BIPV) on roofs and façades. Building loads and solar potentials are assessed using bottom-up models; the MES design is determined using a Mixed-Integer Linear Programming model (energy hub). A mixed-use district of 170,000 m² floor area including office, residential, retail, education, etc. is studied under current and future climate conditions in Switzerland and Singapore. Our findings are consistent with previous studies, which indicate that DR generally leads to smaller system capacities due to peak shaving. We further show that in both the Swiss and Singapore context, cost and emissions of the MES can be reduced significantly with DR. Applying DR, the optimal area for BIPV placement increases only marginally for Singapore (~1%), whereas for Switzerland, the area is even reduced by 2-8%, depending on the carbon target. In conclusion, depending on the context, DR can have a noticeable impact on optimal MES and BIPV capacities and should thus be considered in the design of future, energy efficient districts.

1. Introduction
Solar energy is considered as one of the pillars for designing future sustainable districts. Consequently, ways to efficiently integrate it into buildings and cities are subject to numerous research efforts [1]. With our study, we aim to investigate the impact of demand response (DR) on the design of district multi-energy systems and optimal investment decisions of (building integrated) photovoltaic (BIPV).

DR is a controls policy that exploits temporal load flexibility of electric appliances and thermal (heating and cooling) supply systems and their emitters. The rationale behind electric appliances is that certain services do not need to follow a strict schedule (e.g., dishwasher, laundry, etc.), while for cooling and heating, DR relies on the thermal inertia of the building construction that allows for temporary reduction of room conditioning without compromising thermal comfort. The question arises in how significant DR impacts the design of optimal energy systems, including renewables, when aiming for cost and carbon emissions reduction.

An established approach for the optimal design of multi-energy systems (MES) is introduced with the energy hub concept, which uses mathematical optimization to identify ideal system configurations based on an optimal generation, conversion, transmission and storage of multiple energy carriers [2]. The importance of using an MES as modeling basis for making PV investment decisions has been demonstrated in [3], where a purely electrical scenario has led to significantly larger BIPV surface areas than in an MES scenario. For the Swiss context, recent work uses an energy hub to demonstrate that both South and West directions should be utilized for PV, as it temporally diversifies renewable...
electricity generation [4]. Electric and thermal DR has been studied as well with energy hubs and a recent study has demonstrated its benefit in the cooling case [5]. Also, [6] have shown the importance for simultaneously designing and optimizing buildings (demand side) and MES (supply side) by introducing a coupled methodology using energy hubs. With our work, we wish to focus on BIPV specifically and study the impact of DR on systems design under different contexts, namely Singapore and Switzerland, for current and future climate. Furthermore, our study shall provide an outlook on how DR can influence the design of solar architecture and districts.

2. Methodology

To investigate the impact of DR on the optimal design of MES and BIPV, we develop a deterministic linear energy hub model, including constraints for DR, for the selection and sizing of energy technologies. The model informs on under which conditions and on which building surfaces BIPV is viable from an economic and environmental perspective. In the following sections, the case study, the simulation models for estimating building loads and solar potentials (used as inputs to the energy hub), as well as the energy hub itself are explained.

2.1. Case Study

As a case study district, we use a new development near the lake of Lucerne in Switzerland (called “Suurstoffi”). We include multi-story buildings that sum to a total floor area of 170,000 m² and assign a total available area on roofs and facades for BIPV of 42,325 m². The available area for PV is determined by estimating window-to-wall ratios on the buildings from a detailed 3D model and Google Maps. We assign 34% of the buildings as multi-family residential, 35% as office, 15% as university, 5% as schools, 6% as retail, 3% as restaurants, and about 1% as library, gym and laboratory, respectively. The 3D model of the district is shown in Figure 1, including the wider topography. Even though the actual district lies in Switzerland, we use it for our Singapore simulations as well in order to have better interpretable comparisons on the impact of DR.

2.2. Building Energy Demand

Building energy demand simulation is conducted for all buildings in the district using an open-source software, the City Energy Analyst (CEA) [7], which computes hourly building thermal loads using a bottom-up single-zone resistance-capacitance model. Input data includes building geometry, local weather files1, building construction properties, and building electricity use and occupancy profiles [8]. Building construction properties and occupancy densities vary in the context of Switzerland and Singapore; the respective properties are retrieved from the database of CEA and represent cantonal / national norms. Outputs from the demand simulation includes space heating and cooling demand, electricity demand for appliance and lighting, and domestic hot water demand.

We use current meteorological weather data and projections for the year 2050 under climate change (RCP8.5) for Singapore and Risch, Switzerland (“Suurstoffi” location). Most notable differences between Singapore and Switzerland are significantly higher cooling and electric loads in Singapore due to the climate and different occupation densities. Cooling loads naturally increase with RCP8.5 in both Singapore and Switzerland.

1 https://meteonorm.com/
2.3. Solar Potentials
To model solar potentials, we follow the same methodology as in [3], which used the same case study geometry too (i.e., Suurstoffi), but with a focus on one individual building only. Since the present study is on a district scale, we simplify a number of settings as compared to [3]: we use lower resolution meshes resulting in fewer sensor points per building, we ignore trees and vegetation, and we ignore specular reflections from water bodies and glazed surfaces (however, diffuse reflection is still considered). The topography is included, since high mountains lie to the South of the district that especially have an influence on solar potentials for the Swiss scenarios (Figure 1, right). In total, we simulate hourly annual solar potential profiles for 772 different sensor points distributed over all buildings on roofs and facades. This means that the energy hub will have 772 possible surface areas for installing BIPV. As an example, Figure 1 (left) shows annual solar potentials on the considered buildings for Risch, Switzerland, for the current climate.

2.4. Energy Hub
The energy hub in this study is a deterministic Mixed-Integer Linear Programming model using CPLEX as solver. The model informs on optimal technology selection and sizing while minimizing total levelized operational and investment cost under varying carbon reduction targets. Carbon minimization is implemented as ε-constraints with 5 cuts and includes operational and embodied emissions of energy technologies – embodied emissions of the building constructions are ignored since they are constant.

Available technologies in the model are air source heat pump (ASHP), electric chiller, cooling tower for the waste heat of the chiller, battery storage, photovoltaic (PV, the same PV technology is assumed for both roof and façade for simplification), natural gas boiler, biomass boiler, heat exchangers to connect each building to the district cooling and heating network, thermal energy storages for heat (TES\textsubscript{heat}) and cold (TES\textsubscript{cold}), and natural gas combined heat-and-power (CHP). 772 individual PV surfaces can be selected, and the maximal installed PV area is bound by the geometry case study and window-to-wall ratios of the buildings. Maximal biomass boiler operation is limited by an annual availability parameter for biomass (zero assumed for Singapore). For better comparisons on the impact of DR, we assume cost, carbon emission, efficiency and other technology parameters as identical between the Singapore and Swiss cases. We use the data from [9], [10].

Demand response is implemented according to [5], [11]: $\forall \, t = \{1, \ldots, H\}$ (t being the time step and $H$ the horizon) and $\forall \, l = \{\text{electricity, heating, cooling}\}$:
\begin{align*}
    y_{l,t}^{+} + y_{l,t}^{-} &\leq 1 \tag{1} \\
    x_{l,t}^{+/-} &\leq M y_{l,t}^{+/-} \tag{2} \\
    \sum_{t \in d} x_{l,t}^{+} = \sum_{t \in d} x_{l,t}^{-} \quad \forall \, d = \{1, \ldots, H/24\} \tag{3}
\end{align*}

with $x_{l,t}^{+/-} \in [0, l_{t} b_{t}]$ being the continuous demand shifting variable for either positive (i.e., “generating” / “less demand”) or negative (i.e., “consuming” / “additional demand”) load shift, bound by a coefficient $b_{t}$ and the actual load at that time step, $l_{t}$. Following [5], for $b_{t}$, we assume 20% for electric shifting and 10% for cooling and heating. However, exact values depend on the specific building and context and should be elaborated case study specifically. $y_{l,t}^{+/-} \in \{0,1\}$ are binary variables to indicate positive or negative shift at time step $t$. $M$ is a sufficiently large number (Big-M method). Eq. (1) limits load shifting to either positive or negative at $t$, Eq. (2) indicates whether load shifting in either direction is active at $t$, and Eq. (3) states that the sum of positive load shifting must equal the sum of negative load shifting over each day.

The energy hub model uses a typical days approach to reduce the time horizon. Here, 12 typical days + 3 peak load days for heating (domestic hot water and space heating is aggregated), cooling and electricity are used. The source code of the energy hub and all input data / parameters are available online for reproducibility.²

² https://github.com/christophwaibel/EnergyHubs/tree/master/CplexEnergyHubs/CISBAT21
3. Results and Discussion

3.1. System Operation with DR

Figure 2 shows hourly operations of energy technologies, as well as the actual loads versus the effective loads using demand response (DR). In the left image, it is noticeable how the first peak at $h = 11$ is shaved due to limited PV energy generation. In the right image, the peak load at $h = 8$ is reduced as well, thus leading to smaller necessary technology capacities. Effectively, DR serves as a “free” storage under the assumption of load flexibility. As mentioned earlier, it should be critically noted that the flexibility coefficients used depend on the actual building and climate context and should be determined case specifically. Especially thermal flexibility might be more limited (or abundant) in certain real scenarios (e.g., low inertia building in the tropics vs. high inertia building in cold climates).

![Figure 2: Electricity (left) and heating (right) loads for a typical winter day in Risch, Switzerland (2050) in a carbon minimization scenario. Dashed curves show actual loads, solid curves the effective loads with demand response (DR)](image)

3.2. Energy Systems and PV Capacities

In most of the Singapore scenarios, the energy hub utilizes more area for PV than in the Swiss cases; in carbon minimization scenarios, the optimum for Risch, Switzerland is at 0.15 m² PV installed per m² floor area (m²/m²), whereas for Singapore it is 2/3 more at 0.25 m²/m². In cost minimization cases, in both Singapore and Switzerland, the optimum is at 0.08 m²/m² installed PV. With DR enabled, the optimal PV area in Singapore is up to 1% higher than without DR. In Risch, Switzerland, the trend is contrary, where DR leads to 2-8% less PV area than without DR. This indicates that for Switzerland, DR increases marginal costs of PV systems, whereas in Singapore it reduces marginal cost. As a consequence, such information may influence the utilization of building surfaces and roofs for alternative services, such as greenery.

In accordance with the climatic differences, optimal solutions in Singapore have larger cold storages and electric chillers, whereas hot water storages and heat generation technologies are more important in Switzerland. Electric chillers are sized consistently smaller with DR in all scenarios, with up to 8% smaller chiller capacities in Switzerland under cost optimization. Also, in Switzerland, ASHPs have an increase of 5-10 % in capacity with DR in comparison to no DR. Thermal storages can be reduced in all scenarios with DR: about 2% smaller $\text{TES}_{\text{heat}}$ capacities in Switzerland and around 5-16% smaller $\text{TES}_{\text{cold}}$ in SG. When optimizing for carbon emissions in Singapore, DR even leads to system designs without a $\text{TES}_{\text{heat}}$.

Batteries are not selected in any of the scenarios, presumably due to the high embodied carbon emission and cost parameters used. The data has been collected in a recent study [9], which also showed that batteries are not necessary / optimal in some scenarios. In our case study here, the energy hub would only select batteries in carbon minimization cases with significantly lower embodied emissions of the batteries, or in cost minimization with significantly lower cost parameters. It seems that in a diverse district with façade PV at different directions and with DR enabled, batteries are neither cost nor carbon
efficient – at least with the technology parameters from [9]. Naturally, it should be studied how other important features, e.g., mobility coupling, or grid constraints change the optimization outcomes with respect to battery storages.

3.3. Solar Utilization
Solar self-consumption (self-consumed on-site generated PV electricity) is always 100% in all Singapore scenarios, due to the high electricity loads for appliances and cooling. In Switzerland, about 2-9% of on-site generated PV electricity is fed into the grid, and DR leads to higher self-consumption rates. For example, in the 2050 RCP8.5 scenario, without DR, 9% is fed into the grid, whereas with DR it decreases to 6-8% depending on the carbon reduction target.

Solar self-sufficiency (SS) only changes marginally with DR. In Singapore, SS is at around 14% for carbon optimized cases and around 8% under cost minimization; DR has almost no impact on SS. In Switzerland, SS ranges from 22% - 34% depending on climate (future climate has lower SS) and whether it is optimized for carbon emissions (higher SS) or cost. DR slightly increases SS in most scenarios in Switzerland. Apparently, DR does not have a noticeable impact on SS in this case study. If SS was an intended performance indicator, it could be implemented as a constraint or objective function into the energy hub. However, the cost of grid integration of PV should ideally be internalized by, e.g., dynamic feed-in tariffs or intermittency penalties.

Figure 3 shows the economic and environmental viability of BIPV and it should be noted that DR has no general impact on the overall trends here. However, the left figure demonstrates that in Singapore, surfaces with lower irradiation have a higher likelihood for PV being sized by the energy hub than in Switzerland, as the red points lie more towards the left. In the right graph, it is striking that PV is installed at lower solar potentials while there still remain unused surfaces with higher irradiation (e.g., in Singapore at 400 and 600 kWh/m²a, respectively). As already demonstrated in, e.g., studies [3], [4] for the Swiss context, it appears viable to diversify PV installation towards other orientations as well, such as Westwards, albeit lower total irradiation.

3 SS is defined as \( \frac{\sum_t (E_t^{\text{PV}} - E_t^{\text{FeedIn}})}{\sum_t (E_t^{\text{PV}} + E_t^{\text{Grid}} - E_t^{\text{FeedIn}})} \), with \( E \) being the power flow.

3.4. Cost and Emissions
Figure 4 shows cost and carbon emissions of all optimal solutions from the energy hub model. It is striking that in all scenarios, both Switzerland and Singapore, current and future climate, DR can significantly reduce cost and emissions. In the present study, we used constant grid emission factors and peak/off-peak grid electricity prices. However, it should be expected that the economic and environmental benefits of DR under dynamic pricing and grid emissions schemes will be even higher.
4. Conclusion

In this study, we demonstrate the overall benefits of demand response (DR) schemes towards reducing cost and carbon emissions when designing district multi-energy systems (MES) with BIPV, in a Singapore and Swiss context. Energy systems capacities can be reduced as well, as DR leads to peak-shaving / reduction. Regarding PV installation, the implementation of DR marginally increases the optimal area of PV placement for Singapore (1%), while leading to a reduction in the Swiss context (2-8%). Furthermore, solar self-consumption and self-sufficiency would need to be explicitly captured in the model (e.g., dynamic feed-in tariffs), such that there is an incentive to improve these performance indicators. As a final conclusion, this paper confirms that DR is an essential strategy when designing future energy efficient districts with BIPV, as it has a noticeable impact on the economic and environmental evaluation, as well as on systems designs.

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