

Evaluation of Urban CO₂ Reduction Potential from Demand Response-Ready Residential Heat Pump Water Heaters

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Abstract. This study quantifies the CO₂ reduction potential of demand response (DR) operation of residential heat pump water heaters (HPWHs) in Utsunomiya City, Japan. An evaluation framework was developed by integrating spatiotemporal electricity demand and photovoltaic (PV) generation, both estimated from approximately 410,000 smart meters, along with dynamic grid carbon intensity. Scenario analyses assessed the combined impact of HPWH penetration, DR readiness, and PV adoption. Results show that enabling DR in existing HPWHs can reduce citywide CO₂ emissions from HPWHs by up to 34%, primarily by shifting operation to daytime with lower grid carbon intensity. When PV deployment was doubled or tripled, surplus PV utilization by HPWHs increased substantially, enhancing the CO₂ reduction effect of DR even at current penetration levels. However, the effectiveness of DR varies across the city, as surplus electricity remains scarce in dense areas with high demand. In the most ambitious scenario, where 80% of households adopt HPWHs and citywide PV generation triples, total CO₂ emissions from all residential water heating systems across the city could be reduced by up to 49%. Developing locally optimized strategies that integrate PV, HPWHs, and DR is essential for realizing effective urban decarbonization through DR operation of residential water heaters.

1 Background

In Japan, thermal power generation remains a significant contributor to electricity production, while among renewable sources, solar power has the highest penetration. Consequently, the carbon intensity (CI) of grid electricity tends to be lower during daytime hours, making it effective for decarbonizing buildings and cities to prioritize electricity use during this period. Furthermore, in areas with high penetration of residential photovoltaic (PV) systems, shifting demand to daytime hours can increase self-consumption of PV generation and alleviate grid congestion caused by reverse power flow, thereby improving voltage stability in the power network [1].

In this context, the "DRready" concept is gaining traction in Japan. DRready refers to a technology that enables remote control of household energy generation and storage devices via communication networks, allowing them to participate in demand response (DR). Among the promising control targets for DR-ready systems are residential heat pump water heaters (HPWHs). In Japan, the adoption of HPWHs has been increasing, with a penetration rate of 16.8% nationwide

as of 2021 [2]. These systems consist of a heat pump unit connected to a hot water storage tank, typically utilizing ambient air as a heat source and CO₂ as the refrigerant (R744), resulting in a relatively high coefficient of performance (COP), typically in the range of 3–4. Unlike conventional gas water heaters (GWHs), which rely on fossil fuel combustion, HPWHs heat water using electricity, thereby significantly reducing CO₂ emissions when combined with low-carbon or renewable electricity sources. However, many residential HPWHs are designed for nighttime heating by default. Coordinating a large number of these units for efficient DR control can enable greater use of low-carbon grid electricity during daytime hours and promote self-consumption of PV generation, thereby contributing to urban decarbonization.

Oki et al. proposed and validated a predictive control strategy for HPWHs in a net-zero energy house, adjusting operations based on solar radiation forecasts [3]. The system starts water heating when PV generation exceeds 2 kW and, on cloudy days, schedules heating during periods of low household demand. This approach demonstrated significant potential for reducing grid electricity purchases and enhancing PV self-

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consumption. Another study [4] tested approximately 150 HPWH units equipped with CTA-2045—a U.S. communication standard for grid-connected appliances—demonstrating the effectiveness of DR-based load shifting. The results showed that, compared to uniform control across all units, group-based control tailored to usage patterns and individualized smart control, utilizing two-way communication and feedback to adjust commands, can further increase load-shifting potential.

Previous studies have mainly focused on individual households or small groups, and no research has quantified the CO₂ reduction potential of DR with HPWHs at an urban scale. In Japan, where renewable energy penetration is still in progress, the effectiveness of DR varies significantly depending on local energy demand profiles and PV penetration levels. Therefore, evaluating the impact of DR at the city level under future scenarios is essential for developing strategies to promote HPWH and PV deployment.

The objective of this study is to quantify the CO₂ reduction potential of DR operation of HPWHs at an urban scale. To this end, we developed an evaluation framework that integrates spatio-temporal electricity demand, PV generation estimated from approximately 410,000 smart meters, and the temporal variation of grid CI. Using this framework, we conducted scenario analyses across varying levels of HPWH penetration, DR readiness, and PV adoption.

2 Materials and methods

2.1 Target city

This research focuses on Utsunomiya City in Tochigi Prefecture, Japan. Population and household statistics in Utsunomiya City are shown in Table 1. The data were obtained from statistical reports published by Utsunomiya City [5,6]. The city aims to achieve net-zero CO₂ emissions from residential and commercial electricity use by 2030 as a designated leading decarbonization area. As of fiscal year 2022, the city's solar power generation capacity was 352,479 kW, accounting for 98% of the total renewable energy introduced [7]. With 6.3% of households nationwide using solar power systems [2], Utsunomiya City is considered an advanced region for residential PV adoption in Japan.

Table 1. Population and household data in Utsunomiya City

Population (Dec.2024)	514,595
Young population (aged 0-14) (Dec.2024)	61,215 (11.9%)
Working-age population (aged 15-64) (Dec.2024)	317,470 (61.7%)
Elderly population (aged 65 and over) (Dec.2024)	135,910 (26.4%)
Households in detached houses (2020)	136,172
Households in row houses (2020)	1,375
Households in apartment buildings (2020)	90,922

2.2 Smart meter data

This study analyzed approximately 410,000 smart meters installed in Utsunomiya City's low-voltage power system to estimate the city-scale CO₂ reduction potential of DR implementation for HPWHs. The data, collected by TEPCO Power Grid, Inc. from April 2022 to March 2023, include 30-minute interval records for each 1-km mesh: electricity purchased by pure consumers and prosumers (households with PV systems exporting surplus power), and electricity exported by prosumers. For privacy protection, the dataset reports aggregated values for each mesh.

Fig. 1 shows the Utsunomiya City map and the number of pure-consumer and prosumer meters per 1-km mesh. Around Utsunomiya Station, commercial districts have a high density of smart meters, with about 4,500–9,000 low-voltage meters per 1-km mesh. Surrounding residential areas have 1,000–7,000 meters per mesh. The prosumer ratio near the station is below 10%, while other residential areas generally range from 10% to 30%.

To assess surplus solar power absorption via DR for HPWHs and the associated CO₂ reduction, PV generation in each mesh was estimated from recorded net demand and reverse flow data. We used a previously developed framework [8] that combines this dataset with solar radiation data from Himawari-8/9 satellites [9], with an estimation error confirmed to be within a few percent.

Fig. 2 shows the estimated annual electricity demand and PV generation, calculated by aggregating 30-minute mesh-based estimates. Electricity demand is highest in commercial areas near Utsunomiya Station and relatively high in surrounding residential areas. PV generation is high not only in areas with many prosumers but also in some suburban meshes with large-capacity PV systems.

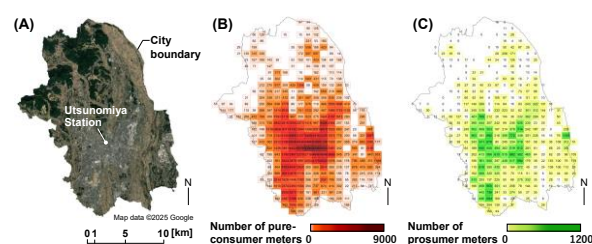


Fig. 1. (A) Utsunomiya City map, (B) Pure-consumer meters per 1-km mesh, (C) Prosumer meters per 1-km mesh. Adapted from [8].

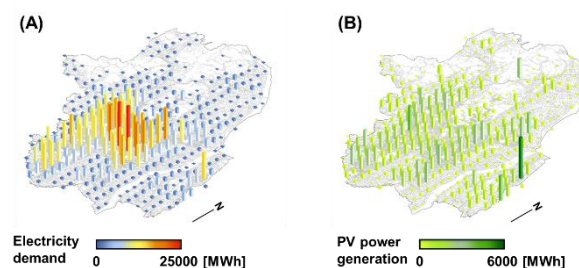


Fig. 2. Estimates for each 1-km mesh: (A) Annual electricity demand, (B) Annual PV power generation. Adapted from [8].

2.3 Heat pump water heater model

Fig. 3 illustrates the concept of DR operation for HPWHs. In Japan, HPWHs commonly operate with a default schedule that heats water during nighttime hours; therefore, the water heating period for non-DR HPWHs was set to 01:00–05:00. For DR-enabled HPWHs, the heating period was shifted to 10:00–14:00, which corresponds to the time window with the lowest average CO₂ emission factor of grid electricity. This was determined based on the annual average of hourly CO₂ emission factors calculated from TEPCO’s power generation data for fiscal year 2022.

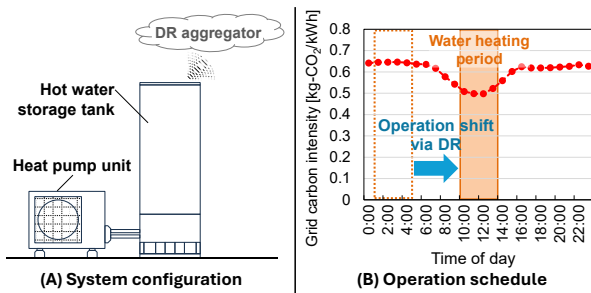


Fig. 3. System configuration and operation schedule of a demand response-ready heat pump water heater.

The system COP of HPWHs—defined as the ratio of the total thermal energy for water heating and storage to the overall electricity consumption, including auxiliary components—has been shown in previous research to be approximately represented as a linear function of outdoor air temperature [10]. In this study, SCOP was calculated using the following linear function:

$$SCOP_{d,t} = 0.04 t_{air,d,t} + 3.00 \quad (1)$$

Here, $t_{air,d,t}$ represents the outdoor air temperature in Utsunomiya City for each 30-minute interval, obtained from the Japan Weather Association [11].

In addition to HPWHs, two other major water heating technologies commonly used in Japan—GWHs and electric water heaters (EWHs)—were also considered when estimating city-scale CO₂ emissions from residential water heating. GWHs are typically instantaneous units fueled by city gas, while EWHs are storage-type heaters that use electric resistance heating during off-peak nighttime hours. Unlike HPWHs, EWHs rely solely on resistive heating, resulting in an effective COP below 1 (set to 0.95 in this study). Based on national statistics on household water heating systems in Japan [2], it was assumed that among the smart meters not associated with HPWHs, GWHs and EWHs were distributed at a ratio of 10:1, respectively.

2.4 Calculation of carbon emissions

To estimate CO₂ emissions under varying penetration rates of DR-ready HPWHs, a calculation framework was established based on three main components: PV surplus estimation, HPWH electricity demand

estimation, and allocation of PV and grid electricity consumption.

The annual domestic hot water demand was assumed to be 17.5 GJ per household [12] (calculated as 47.9 MJ per day by evenly distributing the annual demand without considering seasonal variations), irrespective of the water heating technology. For simplicity, the number of HPWH units in each 1-km mesh was determined by applying the penetration rate to the number of smart meters.

The surplus PV electricity for each 30-minute interval in mesh m at time t on day d was calculated as:

$$s_{d,t}^{(m)} = \max\{0, g_{d,t}^{(m)} - c_{d,t}^{(m)}\} \quad (2)$$

where $g_{d,t}^{(m)}$ and $c_{d,t}^{(m)}$ denote the estimated PV generation and electricity demand [kWh], respectively. These values were derived from smart meter measurements combined with solar irradiance data obtained from Himawari-8/9 meteorological satellites.

The electricity consumption [kWh] of HPWHs in mesh m at time t on day d was calculated from the hot water load and system COP as:

$$c_{HPWH,d,t}^{(m)} = \frac{q_{d,t}^{(m)}}{SCOP_{d,t} \times 3.6} \quad (3)$$

where $q_{d,t}^{(m)}$ is the hot water load [MJ] and $SCOP_{d,t}$ is the system COP estimated based on the outdoor air temperature at each time step. The hot water load was assumed to be 5.99 MJ per smart meter for each 30-minute interval.

Finally, the allocation of HPWH demand between PV surplus and grid electricity was calculated as:

$$c_{PV,d,t}^{(m)} = \min\{c_{HPWH,d,t}^{(m)}, s_{d,t}^{(m)}\} \quad (4)$$

$$c_{grid,d,t}^{(m)} = \max\{0, c_{HPWH,d,t}^{(m)} - s_{d,t}^{(m)}\} \quad (5)$$

where $c_{PV,d,t}^{(m)}$ represents the HPWHs demand covered by PV surplus in mesh m at time t on day d , and $c_{grid,d,t}^{(m)}$ is the remaining demand supplied by the grid.

As shown in Equation (6), PV self-consumption and grid electricity consumption in each mesh, combined with the CO₂ emission factor for PV and the time-dependent emission factor for grid electricity, were used to estimate hourly CO₂ emissions from HPWHs.

$$e_{HPWH,d,t}^{(m)} = c_{PV,d,t}^{(m)} CI_{PV} + c_{grid,d,t}^{(m)} CI_{grid,d,t} \quad (6)$$

Where CI_{PV} denotes the CI of residential PV electricity (0.038 kg-CO₂/kWh), and $CI_{grid,d,t}$ represents the time-dependent CI of grid electricity for each 30-minute interval. The grid CI was calculated as the weighted average of the lifecycle CI of each generation source, based on TEPCO’s hourly power mix, with emission factors for each generation type detailed in our previous study [8].

Fig. 4 shows an example of grid CI on a clear day. In most regions of Japan, thermal power is the primary

source of electricity generation, resulting in higher CI during nighttime. In contrast, CI decreases during daytime hours when PV generation increases. Therefore, shifting HPWH operation to the daytime can reduce CO₂ emissions, even when surplus PV electricity within a mesh cannot be self-consumed.

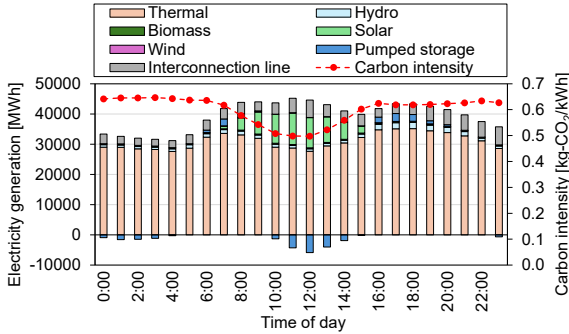


Fig. 4. Hourly power source composition and calculated carbon intensity for grid electricity on December 20, 2022 (sunny day). Adapted from [8].

The electricity consumption of EWHs was calculated assuming a constant heating efficiency η_{EWH} (= 0.95), independent of outdoor temperature, and a scheduled heating period from 23:00 to 07:00 (8 hours). The daily hot water load of 47.9 MJ was evenly distributed across this period, resulting in a 30-minute load of 2.99 MJ. The electricity consumption per 30-minute interval for each unit was then calculated as:

$$c_{EWH} = \frac{2.99}{\eta_{EWH} \times 3.6} \approx 0.87 \text{ kWh/30 min} \quad (7)$$

The total electricity consumption within each 1-km mesh $c_{EWH,d,t}^{(m)}$ was obtained by multiplying the assumed value by the number of EWH units determined from the smart meter dataset. Furthermore, CO₂ emissions from EWHs $e_{EWH,d,t}^{(m)}$ were also calculated using the following equation, considering the CI of grid electricity.

$$e_{EWH,d,t}^{(m)} = c_{EWH,d,t}^{(m)} CI_{grid,d,t} \quad (8)$$

For GWHs, annual CO₂ emissions were estimated assuming a hot water demand of 17.5 GJ per household per year, a combustion efficiency η_{Gas} (= 0.85), and an emission factor for city gas of 0.061 t-CO₂/GJ. The annual emissions per meter with a GWH unit were calculated as:

$$e_{Gas} = \frac{17.5}{\eta_{Gas}} \times 0.061 \approx 1.26 \text{ t-CO}_2/\text{year} \quad (9)$$

The total annual CO₂ emissions for GWHs in each mesh were obtained by multiplying this value by the number of meters using GWHs in that mesh.

2.5 Simulation scenarios

To evaluate the CO₂ emission reduction potential through DR operation of HPWHs in Utsunomiya City, a parametric analysis was conducted. The analysis varied

three key parameters: (1) the DR readiness rate of HPWHs, (2) the penetration rate of HPWHs, and (3) the installed capacity of PV systems in the city. The impact of each factor on residential water heating-related CO₂ emissions was quantitatively assessed.

3 Results and discussions

3.1 Impact of enabling DR readiness in existing HPWH installation

Fig. 5 illustrates the CO₂ emissions from HPWHs across each mesh for different DR adoption rates. The analysis assumes that the HPWH penetration rate in all meshes is equal to the national average of 16.8%, and evaluates the resulting CO₂ reduction potential when these units operate under DR. As a result, CO₂ emissions are most concentrated in areas near train stations where meter density is high, and relatively high emissions are also observed in the surrounding suburban residential areas. As the DR adoption rate increases, CO₂ emissions across meshes exhibit a general decreasing trend.

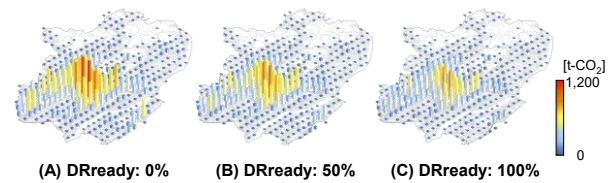


Fig. 5. CO₂ emissions from HPWHs across each mesh under varying DR adoption rates, based on the current HPWH penetration (16.8%) and present PV generation conditions.

Fig. 6 presents the electricity consumption and CO₂ emissions of HPWHs across the entire Utsunomiya City for varying DR adoption rates. The figure shows the electricity consumed from the grid during nighttime without DR, the electricity consumed from the grid during daytime with DR, and the electricity consumed from surplus PV generation within each mesh under DR operation, along with the corresponding CO₂ emissions. The slight reduction in electricity consumption with higher DR adoption rates is attributed to improved COP, resulting from HPWH operation during daytime periods with moderately higher ambient temperatures.

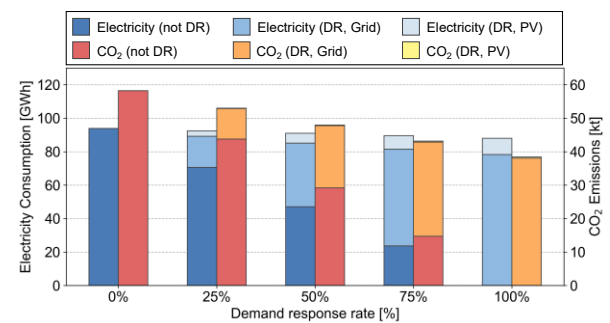


Fig. 6. Electricity consumption and CO₂ emissions of HPWHs across the Utsunomiya City for varying DR adoption rates, based on the current HPWH penetration (16.8%) and present PV generation conditions.

A CO₂ emission reduction of 34% was observed when the DR adoption rate increased from 0% to 100%. However, under the current level of PV deployment, self-consumption of surplus PV electricity remains limited. The observed reductions are primarily due to the shift in electricity demand to periods with higher shares of renewable energy on the grid. These findings highlight the importance of combining DR with other strategies, such as expanding PV installations, to enhance decarbonization efforts.

3.2 Scenario Analysis under Expanded PV Deployment

This section analyses scenarios in which the current level of PV deployment is doubled or tripled. For each scenario, the projected PV generation for each 1-km mesh, estimated every 30 minutes based on smart meter data, was multiplied by a factor of two or three to simulate increased PV output.

Fig. 7 presents the annual surplus PV electricity for each mesh under the respective scenarios. Under the current conditions, surplus PV electricity is generated only in limited areas, primarily concentrated in agricultural zones with large-scale PV installations located in suburban regions distant from the city center. However, when PV generation is doubled or tripled, surplus electricity is also observed in a broader range of areas, including residential zones in suburban areas.

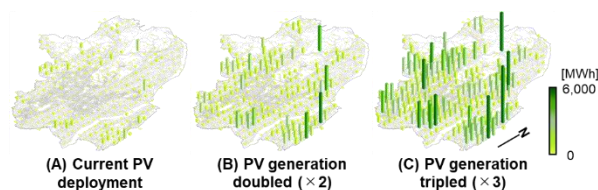


Fig. 7. Annual surplus PV electricity for each mesh under the respective scenarios.

Fig. 8 shows the CO₂ emissions from HPWHs (with a penetration rate of 16.8%) across Utsunomiya City for each combination of PV deployment level and DR adoption rate. In addition, the figure presents the surplus PV power utilization, defined as the share of electricity consumed by DR-operated HPWHs that was covered by surplus PV—that is, the ratio of surplus PV electricity to the total electricity consumption of these units, including both surplus PV and grid electricity.

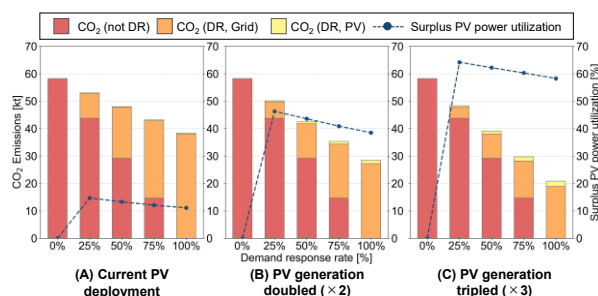


Fig. 8. CO₂ emissions from HPWHs (with a penetration rate of 16.8%) across Utsunomiya City for each combination of PV deployment level and DR adoption rate

The analysis reveals that increasing PV deployment significantly enhances surplus power utilization and substantially reduces CO₂ emissions. However, across all PV deployment scenarios, surplus PV power utilization tends to decrease as the DR adoption rate increases. This is because areas with high electricity demand—typically urban centers—generate limited surplus PV, resulting in a mismatch between the shifted electricity demand and PV supply under DR operation. These findings suggest that instead of applying uniform DR control across the entire city, it is more effective to prioritize DR operations in suburban areas where surplus PV electricity is more likely to be available.

3.3 City-scale CO₂ mitigation via HPWH, DR, and PV integration

Finally, this section evaluates the impact of widespread HPWH adoption on city-wide CO₂ emissions from residential water heating systems in Utsunomiya, including EWHs and GWHs. Fig. 9 shows how PV deployment levels, HPWH penetration rates, and DR adoption rates influence total CO₂ emissions associated with domestic water heating across the city. Under the baseline scenario, which assumes the current HPWH penetration rate of 16.8% and no DR implementation, annual emissions amount to approximately 530 kt, with the majority attributed to GWHs and EWHs.

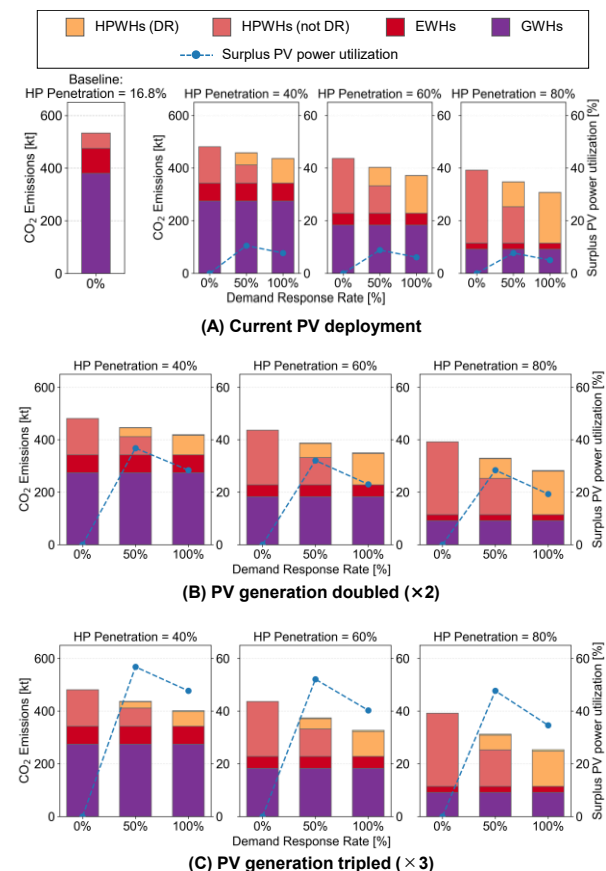


Fig. 9. Total CO₂ emissions from residential water heating in Utsunomiya City under different combinations of PV deployment, HPWH penetration, and DR adoption.

The results indicate that increasing both HPWH penetration and DR adoption significantly reduces overall CO₂ emissions. In a scenario with three times the current PV deployment, an 80% HPWH penetration rate, and 100% DR adoption, annual CO₂ emissions decrease to approximately 270 kt—representing a 49% reduction relative to the baseline. Even when PV deployment is doubled, emissions are limited to around 290 kt, corresponding to a 45% reduction.

Conversely, if PV deployment remains at current levels, the potential for self-consumption of surplus PV electricity is limited, even with aggressive HPWH and DR adoption. As a result, the surplus PV power utilization ratio remained below 10%. These results highlight the importance of advancing PV deployment, HPWH adoption, and DR implementation in parallel, while accounting for their interactions and the distinct demand characteristics across different urban areas.

4 Conclusions

This study quantified the CO₂ reduction potential of DR operation of HPWHs at the urban scale, using an evaluation framework that integrates spatiotemporal electricity demand and PV generation, both estimated from approximately 410,000 smart meters, along with dynamic grid CI. Scenario analyses were conducted across varying levels of HPWH penetration, DR readiness, and PV adoption.

The results showed that enabling DR in existing HPWHs can reduce CO₂ emissions by up to 34%, primarily by shifting operation to periods with higher shares of renewable energy and lower grid carbon intensity. When PV deployment was doubled or tripled, surplus PV utilization by HPWHs increased significantly, and the CO₂ reduction effect of DR was further enhanced, even at the current penetration rate of 16.8%. However, in dense urban areas with high electricity demand and limited rooftop PV potential, surplus PV remains scarce, limiting opportunities for self-consumption. While DR can still reduce emissions by taking advantage of lower daytime grid carbon intensity, its effectiveness is maximized when deployment strategies are aligned with local demand characteristics and surplus PV availability.

In a scenario where 80% of households adopt HPWHs and citywide PV generation triples, total CO₂ emissions from residential water heating could be reduced by up to 49%. While expanding PV deployment, increasing HPWH adoption, and implementing DR are all effective decarbonization strategies, their feasibility and impact vary across urban areas. For example, dense city centers often face space constraints for both PV systems and HPWHs, particularly in multifamily buildings. To advance urban decarbonization effectively, it is essential to develop locally optimized strategies that integrate PV, HPWHs, and DR based on spatial differences in electricity demand and infrastructure.

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