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The potential of rooftop photovoltaics to meet Dutch residential electricity demand under heat transition scenarios

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ABSTRACT

Rooftop photovoltaics (RPVs) are essential for advancing energy transition and achieving climate goals. However, there is limited understanding of their future potential at a granular geographical level and their potential to meet future electricity demand from buildings under different heat transition scenarios. This study presents a comprehensive assessment of the RPV potential at the individual building level in the Netherlands, considering detailed building stock dynamics, renovation strategies, and heat transition scenarios. The results show that RPVs currently generate 3.86 TWh of electricity, with the potential to increase to 19.52 TWh. The total electricity demand of the residential building sector is about 27.26 TWh in 2020, which can increase significantly to 34.19–45.11 TWh by 2050, depending on heat pump penetration and renovation standards. RPVs alone can potentially meet about 43–57% of this electricity demand and save up to 11.32 Mt CO_2-eq in 2050 (26% of current operational carbon emissions) if public grid electricity could be replaced by RPV electricity. However, the actual contribution of RPVs to the reduction/decarbonization of household electricity is subject to large uncertainties due to both the momentary and seasonal mismatch between RPV supply and electricity demand. Future research could increase the temporal resolution of our model to better explore the real potential of RPVs for targeted electrification and decarbonization in the building sector.

1. Introduction

Globally, buildings account for 34% of energy consumption and 36% of carbon emissions (UNEP, 2024). Nearly 90% of Dutch buildings rely on natural gas for space heating and hot water (Visscher, 2019). The combined installation of heat pumps and rooftop photovoltaics (RPVs) is an important technology for electrifying buildings to displace natural gas and achieve climate neutrality by 2050 (Galvin, 2024a). Thanks to electricity subsidies and ever-decreasing costs (Wang et al., 2024), more than 18.8% of residential buildings in the Netherlands have RPVs (Slootweg et al., 2023), but this is far from enough to meet growing electricity demand caused by population growth and the installation of heat pumps. The installation of RPVs in the Netherlands is expected to increase significantly in the coming decades (Ouden et al., 2020). A systematic analysis of both RPV electricity generation and future electricity demand is crucial to better implement energy transition and decarbonization strategies in the building sector.

RPV electricity generation is mainly influenced by regional solar irradiation, PV technology, and suitable roof area (Bódis et al., 2019). Solar irradiation reflects the total solar energy received by the roof and can be obtained from meteorological stations (Assouline et al., 2017)and satellite observations (Mansouri Kouhestani et al., 2019). PV technology is mainly concerned with the panel efficiency, and the performance ratio, which describes the differences between the actual and theoretical energy output of PV systems (Gernaat et al., 2020). In contrast, the roof area suitable for PV installation is relatively difficult to calculate due to the lack of high-resolution roof data such as geometry, tilt angle, shading effects, and structural load-bearing capacity (Slootweg et al., 2023). Previous studies typically estimate suitable roof area by correlating roof area with socioeconomic indicators (e.g., population density, land area,

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GDP, and household expenditures) (Castellanos et al., 2017). Over the past decade, different types of data (e.g., LiDAR and GIS data) and modeling approaches (e.g., artificial intelligence) have been increasingly used to estimate suitable roof area, significantly improving the resolution of roof characterization (Walch et al., 2020). A more detailed introduction to roof area detection and modeling techniques can be found in several reviews, including assessment methods (Byrne et al., 2015) and GIS applications (Gassar and Cha, 2021).

Electricity demand forecasting is another important dimension in assessing the extent to which RPVs can meet electricity demand. Currently, two main approaches are used to forecast electricity demand: top-down and bottom-up models (Buffat et al., 2017). Top-down methods establish the correlation between statistical electricity consumption and socioeconomic indicators (e.g., GDP, population and household wealth) (Zhong et al., 2021). This type of model has the advantages of simplicity and data availability, but it ignores the heterogeneous characteristics of buildings, which limits its ability to capture the discontinuous changes in techno-economic conditions (Johansson et al., 2017). In contrast, bottom-up approaches extrapolate the electricity consumption of individual or archetypal buildings to the building stock level (Mastrucci et al., 2017). They can be further divided into the statistical method (also known as data-driven or black box) and the engineering method (also known as physics-based or white box) (Langevin et al., 2020). The statistical method typically uses regression or machine learning techniques to identify the mathematical relationship between energy consumption and building parameters (e.g., building age, floor area, and occupant profiles) (Amasyali and El-Gohary, 2018). The engineering methods use physical properties of the building envelope, climate data, and occupant data to calculate the heat transfer using thermodynamic principles (Buffat et al., 2017). Bottom-up models consider more end-use factors for building characteristics and environments, but have the disadvantage of requiring computational power and large amounts of technical input data from individual buildings or households (Yang et al., 2020).

Despite the rich literature on RPV electricity generation and electricity demand modeling, previous studies have mainly focused on estimating the RPV potential at a coarse spatial resolution to displace the current grid electricity consumption, largely ignoring the long-term impacts of population growth and different energy transition pathways on the future electricity demand of the building stock (Terry and Galvin, 2023). In the Netherlands, the large-scale installation of heat pumps to phase out natural gas will significantly increase future electricity demand (Ouden et al., 2020). In addition, the evolution of the building stock will change the spatiotemporal distribution of suitable roof areas for RPVs. However, existing building stock models mostly use top-down methods to track changes in building stock composition (e.g., building types and construction periods) and associated energy demand, without sufficient consideration of building heterogeneity and detailed technology changes. To our knowledge, no studies have focused on analyzing the potential of RPVs to meet the future electricity demand of the building stock, taking into full account of building stock turnover and different energy transition scenarios (e.g., renovation and building electrification).

Here we present an individual-building based dynamic building stock model capable of simulating building stock evolution, RPV electricity generation, energy demand, and carbon emissions. GIS data and archetypal buildings are used to derive the attributes (e.g., building geometries, envelope insulation levels, space heating systems and RPV systems) of more than 5 million individual residential buildings. Both RPV electricity generation and building electricity demand are updated annually with the evolution of the building stock. The model is applied to the Dutch residential building stock to answer the following research question:

To what extent can RPVs potentially meet electricity demand and reduce carbon emissions under different heat transition scenarios in the Dutch residential building sector?

2. Materials and methods

2.1. Model overview

The modeling process can be divided into three steps, as shown in Fig. 1. Step 1: Scenarios are defined to describe the different energy transition pathways of the building stock, mainly including renovation standards, heating system distribution and RPV installation. Step 2: Based on the principles of material flow analysis (MFA) (Müller, 2006), the dynamic building stock model is developed to simulate the evolution of the building stock (i.e., demolition, construction and renovation). Individual buildings are mainly characterized using the GIS data containing the location geometry and year of construction, and the archetypal building data containing the geometries and physical properties of representative buildings in the Netherlands. Step 3: Building energy models are used to simulate the energy demand for space heating and hot water, RPV electricity generation, and the electricity demand for appliances and lighting. Carbon emissions under different scenarios are calculated and compared to assess the decarbonization potential of the RPVs. More information on model details can be found in the following sections.

2.2. Scenario definition

This study defines four scenarios that differ in the distribution of heating systems and renovation standards (see Table 1). S0 follows a conservative development pattern, where the heating systems and renovation standards remain unchanged over the period 2020–2050. Both S1 and S2 describe the electrification of the building stock. S1 represents a moderate electrification situation, where most of the existing buildings are equipped with hybrid heat pumps, i.e., a combination of heat pump and natural gas boiler (Saffari et al., 2023), while S2 represents an ambitious electrification situation, where most of the existing buildings are equipped with fully electric heat pumps. The proportions of the different heating systems are derived from a report on the energy transition scenarios in the Netherlands (Ouden et al., 2020) and are assumed to increase linearly to the target proportions by 2050.

Given the importance of renovation for energy savings in buildings, the conventional renovation standard (S1 and S2) is upgraded to an advanced renovation standard (S3) to investigate the impact of advanced renovation on reducing electricity demand. Conventional renovation represents a moderate renovation standard, while advanced renovation represents an ambitious renovation standard, i.e., the nearly-zero energy building (nZEB) standard. The Dutch regulation (Dutch Green Building Council, 2021) stipulates that all buildings constructed after January 1, 2021 are nZEBs. The U-values of renovation standards and new buildings are shown in Table S1 in the supplementary file.

2.3. Dynamic building stock model

2.3.1. Building stock characterization

The dynamic building stock model is based on individual buildings characterized by several attributes, mainly including building geometries (e.g., floor area and wall area), thermal properties of envelope components, heating systems, RPVs, energy demand and supply, and carbon emissions. Two main databases are used: the BAG (Basisregistratie Adressen en Gebouwen) GIS data (BAG, 2018) and the TABULA database (TABULA, 2017). The BAG data contains 5,092,511 residential buildings and their locations, heights, functions, and footprint area. The TABULA data contains the year of construction, envelope geometries, thermal properties, and heating systems of archetypal residential buildings in the Netherlands.

Based on the TABULA classification system, the Dutch residential buildings are divided into six construction periods (before 1964, 1965–1974, 1975–1991, 1992–2005, 2006–2014, and after 2015) and five types (single-family house, mid-terraced house, end-terraced house,

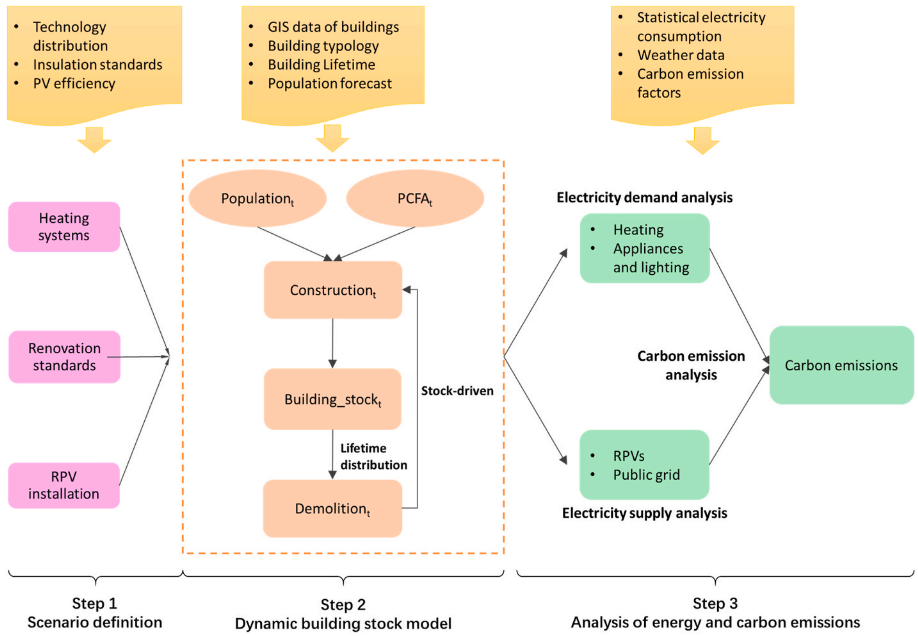

Fig. 1. The model procedure overview. PCFA is short for per capita floor area.

Table 1
Scenario definition. Percentages represent target shares of various technologies in 2050.

Buildings and technologies		Scenarios			
		S0	S1	S2	S3
Existing buildings	Heat networks	Keep current status	15%	15%	15%
	Hybrid heat pump		60%	0%	0%
	Electric heat pump		25%	85%	85%
	Renovation standard		Conventional	Conventional	Advanced
New buildings	nZEB	100%			

apartment building, and multi-family house). The physical properties and heating systems of the TABULA building archetypes are mapped to the individual BAG building according to the construction period and building type. Window and external wall areas are calculated using the window-to-wall ratios of the archetypes. Further technical details of the individual building characterization can be found in the authors' previous work (Yang et al., 2020).

2.3.2. Building stock evolution

The composition of the building stock is changed by demolition, construction and renovation activities. In this study, demolition and construction are modeled based on population and lifestyle using the stock-driven method (Müller, 2006), while renovation is modeled based on endogenously defined renovation rates using the activity-driven method (Hietaharju et al., 2021).

(1) Demolition

Buildings constructed before 1900 (accounting for 3.36% of all buildings) are considered historic buildings (Yang et al., 2022) and will not be demolished in the timeframe. The building lifetime is assumed to follow the Weibull distribution (Cao et al., 2019), whose density function is as follows:

$$f(x;\lambda,k)=\begin{cases}\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}}, x\geq 0\\ 0, x<0\end{cases} \tag{1}$$

Where x is the lifetime. k is the shape parameter of 2.95 (Deetman et al., 2020). The scale parameter λ is determined as follows:

$$\lambda = lifetime_{mean} \div \Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

Where $lifetime_{mean}$ is the mean life expectancy and its value is 130 years in the Netherlands (Deetman et al., 2020).

Lifetimes of buildings built after 1900 are randomly generated using the numpy Python package, following the Weibull distribution. Lifetimes below or above 1.5 standard deviations of the mean lifetime are filtered to avoid unrealistic lifetimes (Yang et al., 2023). The calculation details can be found in the attached Python code file. The demolition year (t_{dem}) is then determined as follows:

$$t_{dem} = t_{con} + t_{lifetime} \tag{3}$$

Where t_{con} is the year of construction, which is available for all the buildings in the BAG data.

(2) Construction

The new construction floor area in year t ($A_{con,t}$) is determined as follows (Müller, 2006):

$$A_{con,t} = PCFA_t \times P_t - S_{t-1} + A_{dem,t} \tag{4}$$

Where $PCFA_t$ is the per capita floor area in year t. Based on the BAG data and the population in 2020 (17.4 million (CBS, 2022)), its value is derived as 68.59 m^2 and assumed to be constant over the timeframe. P_t is the population in year t and its projection comes from the Statistics Netherlands (Centraal Bureau voor de Statistiek, CBS) (CBS, 2018). S_{t-1}

is the floor area stock of the previous year. $A_{dem,t}$ is the total floor area of buildings demolished in year t.

The total floor area of each type of new building ($A_{type,t}$) is determined as follows:

$$A_{type,t} = A_{con,t} \times PP_{type,t} \quad (5)$$

Where $PP_{type,t}$ is the proportion of a given building type in year t. Based on the BAG data, the current proportions of each building type are derived as follows: single-family house (12%), mid-terraced house (23%), end-terraced house (20%), apartment building (15%), and multi-family house (30%). These proportions are assumed to be constant over time.

(3) Renovation

As buildings in the same neighborhood tend to have similar construction times and technologies, the Dutch government has developed a neighborhood-based approach (Klimaatakkoord, 2020). Municipalities, together with residents and homeowners, determine the best solution for a given neighborhood in terms of renovation and heating systems. Therefore, the order of renovation is considered at the neighborhood level according to the weighted average U-values of the neighborhoods, which are determined as follows (Yang et al., 2022):

$$U_{neighborhood} = \frac{\sum_{1}^{N_{neighborhood}} A_{building} \times U_{building}}{\sum_{1}^{N_{neighborhood}} A_{building}} \quad (6)$$

Where $N_{neighborhood}$ is the number of buildings in a given neighborhood. $A_{building}$ is the floor area of a building in the neighborhood. $U_{building}$ is the weighted average U-value of a given building, which is determined as follows:

$$U_{building} = \frac{\sum_{1}^{N_{element}} A_{element} \times U_{element}}{\sum_{1}^{N_{element}} A_{element}} \quad (7)$$

Where $N_{element}$ is the number of envelope elements. Here its value is five, which includes roof, external wall, window, door, and ground floor. $A_{element}$ is the area of the envelope element. $U_{element}$ is the U-value of the envelope element.

2.4. Analysis of energy and carbon emissions

2.4.1. RPV electricity generation

The amount of electricity generated by the RPV on the roof of a given building (E_{RPV}) is calculated as follows (Gernaat et al., 2020):

$$E_{RPV} = G \times \eta \times R_{performance} \times A_{suitable} \quad (8)$$

Where G is the annual solar irradiation (Table S3), which is taken from the KNMI (Royal Dutch Meteorological Institute) (KNMI, 2024). η is the efficiency of the solar panel, which here is 17% (Gernaat et al., 2020). Panel efficiency degrades with age, so a degradation factor of 0.005 per year is assumed (Bódis et al., 2019). $R_{performance}$ is the performance ratio that reflects the difference between the actual electricity yield and the nameplate electricity yield under standard test conditions. Its average value in the Netherlands is 71% (Meng et al., 2022). $A_{suitable}$ is the roof area suitable for PV installation.

The BAG building footprint area (ground floor area) is assumed to be equal to the roof area (Fakhraian et al., 2021). However, only a fraction of the roof area can be used for PV installation due to shading from neighboring buildings and trees, the load-bearing structure, and unfavorable favorable roof orientation and slope (Slootweg et al., 2023). Currently, about 18.8% of residential buildings in the Netherlands are equipped with RPVs (van Groesen, 2024). However, there is great uncertainty about the proportion of buildings suitable for RPVs, with values ranging from 35% (Zhang et al., 2023), 40% (Defaix et al., 2012), 50% (Jamal et al., 2014), 55% (Slootweg et al., 2023) to 64% (Bódis et al., 2019). In Europe, about half of the roofs (49–64%) are suitable for the installation of RPVs (Bódis et al., 2019). This study assumes that the proportion of buildings installed with RPVs will gradually increase to 55% by 2050 (Slootweg et al., 2023). An extreme situation (100% of roofs installed with RPVs) is defined to estimate the maximum electricity generation potential of RPVs. As all new buildings in 2021–2050 are nZEBs, they will all be equipped with RPVs. Due to other uses (e.g., air conditioning, chimneys, and ducts), a further reduction factor (60%) is assumed to account for the net useable roof area (Bódis et al., 2019).

2.4.2. Electricity demand

Energy consumption in the Dutch residential sector includes three main end-use categories: space heating, hot water, and appliances and lighting (EuroStat, 2024). The energy demand for space heating and hot water in existing buildings is simulated using a heat demand model (Yang et al., 2020) developed according to EN ISO 13790. The effect of energy efficiency renovations is assessed on a building-by-building basis. For new buildings, the energy for space heating and hot water is estimated using the energy intensities of the TABULA building archetypes (TABULA, 2017).

Electricity is mainly consumed by appliances and lighting (EI_{al}), electric heat pump (E_{ehp}), hybrid heat pump (E_{hhp}) and electric water heater (E_{ewh}), so the total electricity demand is calculated as follows:

$$E_{elc} = E_{ewh} + EI_{al} + E_{ehp} + E_{hhp} \quad (9)$$

The electricity consumption of the electric water heater is estimated using the method of (Yang et al., 2020). The electricity consumption of appliances and lighting (EI_{al}) is estimated by multiplying the building floor area by the electricity intensity (kWh/m^{2}a) differentiated by building type and year of construction, which is derived from the BAG database and the CBS statistical electricity consumption reported at the postcode level (CBS, 2023). The electricity intensity per building type is shown in Table S2. The calculation method is as follows:

$$E_{al,i} = EI_{al} \times A_{building,i} \quad (10)$$

Where $E_{al,i}$ is the electricity demand of building i. EI_{al} is the electricity intensity of appliances and lighting. $A_{building,i}$ is the floor area of building i.

Taking into account improving energy efficiency and increasing types of household appliances, the electricity for appliances and lighting is adjusted as follows, according to an energy transition report for the Netherlands (Ouden et al., 2020):

$$E_{al,t} = \sum_{1}^{N_{total,t}} E_{al,i} \times (1 + 0.01 \times (t - t_0)) \times \left(1 - 0.10 \times \frac{t - t_0}{t_{end} - t_0}\right) \quad (11)$$

Where $E_{al,t}$ is the total electricity demand for appliances and lighting in year t. $N_{total,t}$ is the total number of buildings in year t. t is the time step and t_0 is the start year 2020. t_{end} is the end year 2050. 0.01 is the growth in electricity consumption of appliances and lighting per year (Ouden et al., 2020). 0.10 is the total electricity savings from efficiency improvements by 2050 (Ouden et al., 2020).

For the buildings heated by all-electric heat pumps, the electricity consumption of electric heat pumps (E_{ehp}) is calculated as follows:

$$E_{ehp} = \frac{E_{heating}}{3.5} \quad (12)$$

Where E_{ehp} is the electricity consumption of the electric heat pump. $E_{heating}$ is the energy demand for space heating. The coefficient of performance (COP) of the electric heat pump is 3.5 (Verhagen et al., 2021).

For the buildings heated by hybrid heat pumps, the electricity consumption of the hybrid heat pumps (E_{hhp}) is calculated as follows:

$$E_{hhp} = \frac{E_{heating}}{3.5} \times 0.65 \tag{13}$$

Where 0.65 is the proportion of space heating energy supplied by the heat pump (Ende, 2017).

2.4.3. Carbon emissions

Energy-related carbon emissions are reported in kg CO_2-eq (IPCC, 2013) and calculated as follows:

$$C = E \times F_{carbon} \tag{14}$$

Where E is the energy quantity. F_{carbon} is the carbon emission factor from the ecoinvent database 3.6 (cut-off system model) (Wernet et al., 2016). The Dutch government plans to significantly increase the share of renewable electricity technologies (e.g., solar and wind) to reach the climate neutral target by 2050, which will significantly reduce the carbon emission factor of public grid electricity. In this study, the progressively reduced carbon emission factors for public grid electricity are used and can be found in Table S5.

The carbon emission reduction potential ($C_{reduction}$) is considered as a substitution of public grid electricity and is calculated as follows:

$$C_{reduction} = \begin{cases} \left(F_{carbon\_grid} - F_{carbon\_RPV}\right) \times E_{RPV}, E_{elc} \geq E_{RPV} \\ F_{carbon\_RPV} \times E_{elc}, E_{elc} < E_{RPV} \end{cases} \tag{15}$$

Where F_{carbon_grid} is the carbon emission factor of public grid electricity. F_{carbon_RPV} is the carbon emission factor of RPV electricity.

3. Results

3.1. RPV electricity generation

We show that the western coastal area of the Netherlands receives more solar energy than the inland area (more than 1100 kWh/m^2), although the absolute differences between the cities are not large (Fig. 2a). There are large differences between the suitable roof areas of the cities (Fig. 2b). The cities with the most suitable roof areas are Amsterdam (3.86 km^2), Rotterdam (3.76 km^2) and The Hague (3.39 km^2). Fig. 2c shows that the ratio of suitable roof area to floor area is mostly above 10%, while the ratio of suitable roof area to floor area is below 6% in Amsterdam, Rotterdam and The Hague. The reason for this is that these cities have more high-rise buildings than other cities, meaning that these cities have more floor space for electricity consumption but less space for RPV installation. Fig. 2d shows that the total suitable roof area will increase slightly before 2041 and then remain relatively stable, mainly due to slower population growth and an increasing share of high-rise buildings in new construction. The majority of existing buildings will remain in use until 2050, and new buildings account for only a small proportion of the roof area, highlighting the importance of exploring the roof area of the current building stock.

In Fig. 3a, the electricity generated by RPVs is 3.87 TWh at the

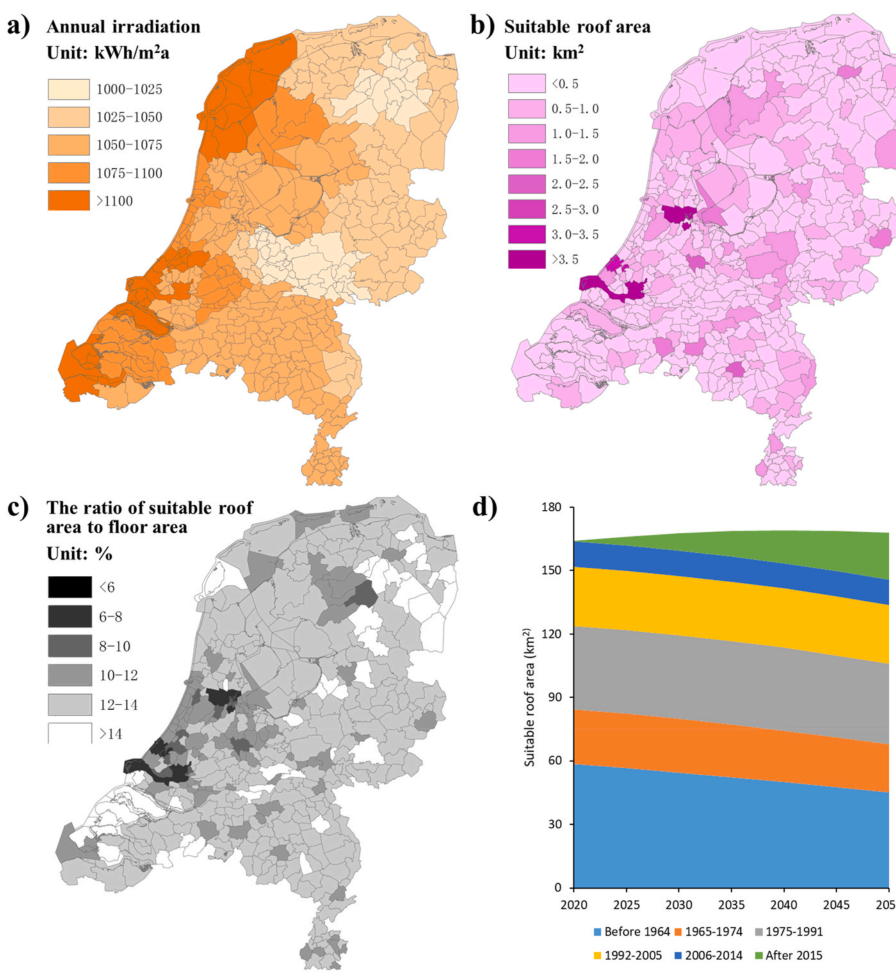

Fig. 2. Solar irradiation and suitable roof area. a) shows the spatial distribution of solar irradiation in different cities. b) shows the spatial distribution of suitable roof area. c) shows the differences in the ratio of suitable roof area to floor area between cities. d) shows the development of suitable roof area differentiated by building age.

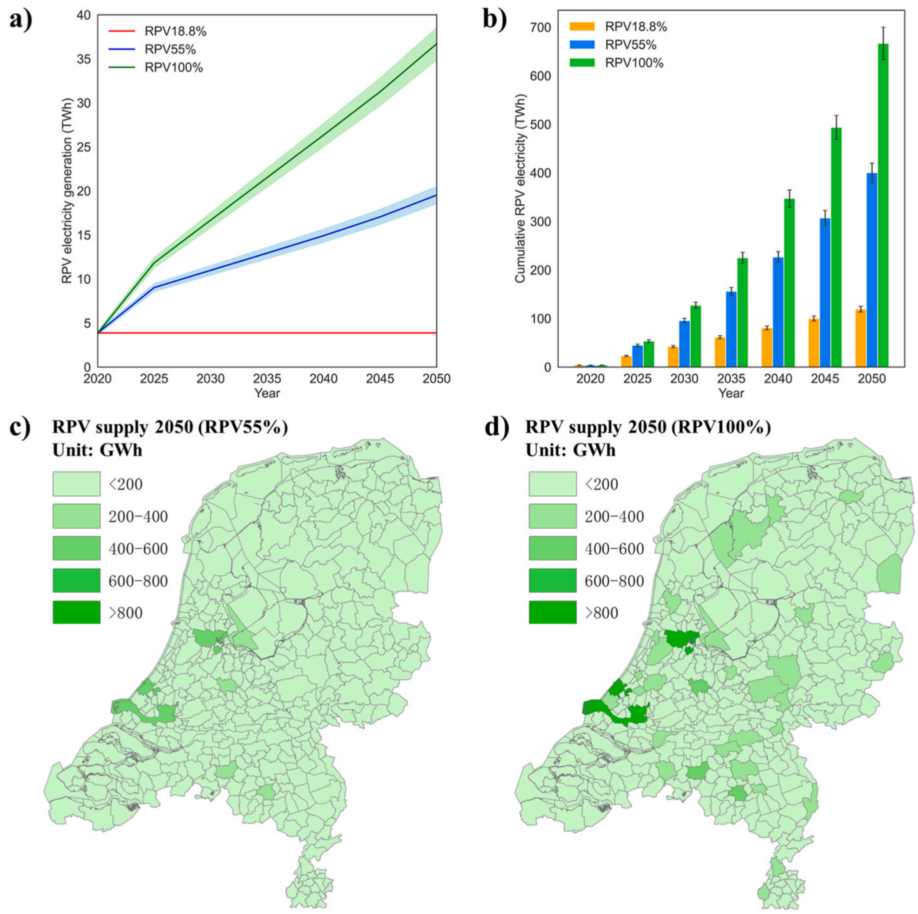

Fig. 3. RPV electricity supply. a) shows the RPV electricity generation at different RPV installation rates. b) shows the cumulative RPV electricity generation at different RPV installation rates. c) and d) show the spatial distribution of RPV electricity generation in 2050. "RPV55%" means that 55% of the rooftops are installed with RPVs, and "RPV100%" means that all the rooftops are installed with RPVs. The shaded bands in a) and whiskers in b) represent the sensitivity intervals given by 5% percentage variations.

current RPV installation rate (18.8%). By 2050, RPV electricity generation has the potential to increase up to 19.52 TWh (at 55% RPV installation rate) and 36.71 TWh (at 100% RPV installation rate). The cumulative RPV electricity generation will reach 119.26 TWh, 400.11 TWh, and 666.69 TWh in 2050, depending on the RPV installation rate. Fig. 3c and d show that there are large differences between the RPV electricity generation of different cities. Large cities such as Amsterdam, Rotterdam, and The Hague generate the most electricity (more than 400 TWh), while the RPV electricity generation of most cities is below 200 GWh, which is in line with the spatial distribution of suitable roof areas in Fig. 2b.

3.2. Residential electricity demand

Fig. 4a shows that the electricity demand increases in all scenarios. The annual electricity demand of scenarios S1 and S2 in 2050 is about 30% higher than the reference scenario (S0). However, the difference in electricity demand between scenarios S1 (43.98 TWh) and S2 (45.11 TWh) is very small, meaning that an ambitious installation of fully electric heat pumps instead of hybrid heat pumps (combination of heat pump and natural gas boiler) leads to a limited additional electricity consumption. The electricity demand of scenario S3 in 2050 (37.01 TWh) is much lower than that of scenario S2, demonstrating the great need for advanced renovation of the existing building stock to save electricity for heat pumps. The comparison between scenarios S0 and S3 shows that the ambitious installation of electric heat pumps combined with advanced renovation causes only 8% of the increase in electricity demand in 2050. In Fig. 4b, the large-scale installation of heat pumps significantly increases the electricity demand for heating. Compared with 2020, the electricity demand for heating in scenario S0 increases by 88%, mainly due to the electricity consumption of electric heat pumps in newly built nZEBs. However, this is much less than in the other scenarios, where the heating-related electricity demand increases by about 12 times (S1), 13 times (S2) and 4 times (S3), respectively. Fig. 4c shows the large variation in electricity demand in the residential sector between the cities. Annual electricity demand is mostly below 100 GWh, while some large cities require more than 600 GWh per year, such as Amsterdam (1420.36 GWh), Rotterdam (1185.75 GWh), The Hague (1036.29 GWh) and Utrecht (600.23 GWh).

3.3. RPV electricity supply vs. residential electricity demand

Overall, the RPV electricity supply is significantly lower than the electricity demand, regardless of the heat transition scenarios (Fig. 5a). In fact, the RPV electricity supply in 2050 is even much lower than the electricity demand in 2020. However, the RPV electricity supply is much higher than the electricity consumption of widely installed heat pumps. Fig. 5b shows that the electricity deficits in "S0+RPV55%", "S3+RPV55%", and "S3+RPV100%" decrease over time. Differently, the electricity deficit in "S1+RPV55%" and "S2+RPV55%" first decreases and then gradually increases, which means that the RPVs cannot cover the electricity if only 55% of the buildings are equipped with RPVs and the buildings are only renovated to conventional standard. "S3+RPV100%" shows that if both RPVs and heat pumps are installed

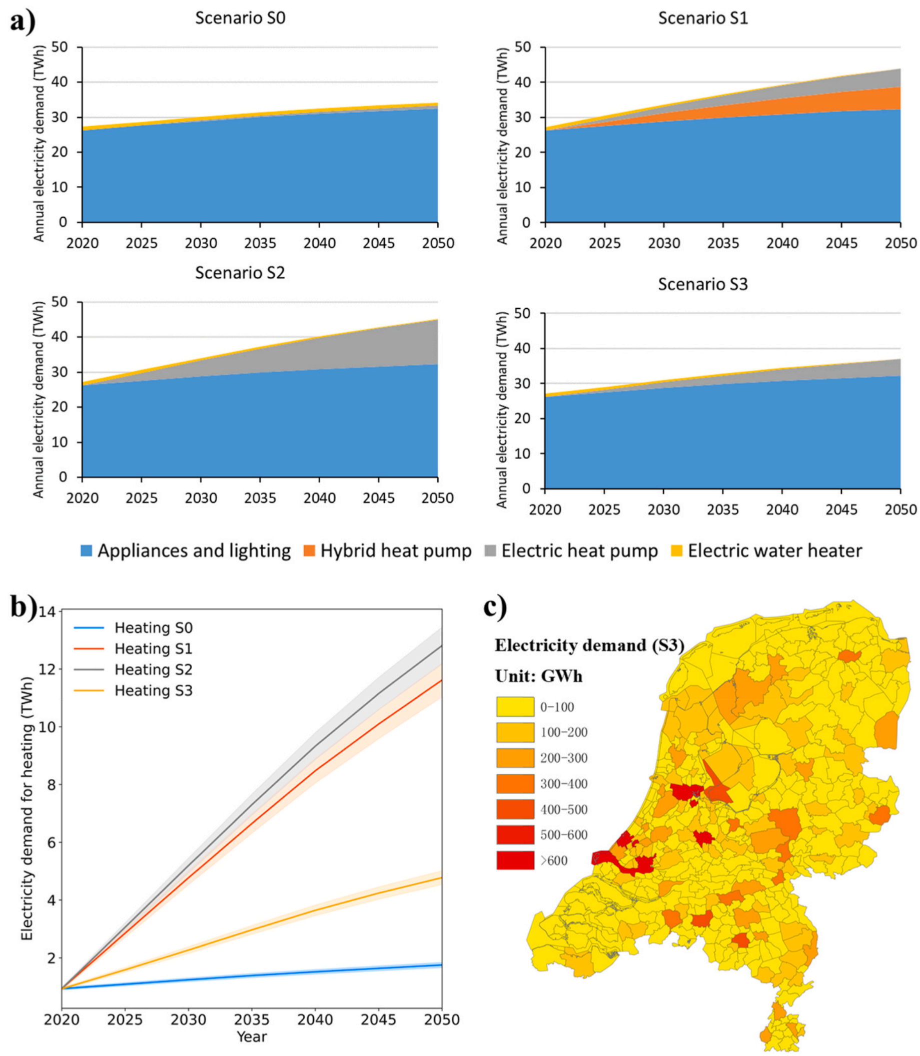

Fig. 4. Electricity demand in the future. a) shows the change in electricity demand under different scenarios. b) shows the electricity demand for space heating and hot water. c) shows the spatial distribution of electricity demand under scenario S3 in 2050. The shaded bands in b) represent the sensitivity intervals given by 5% percentage variations.

on a large scale and buildings are renovated to the advanced standards, RPVs have the potential to cover 99% of residential electricity demand in 2050, demonstrating the importance of advanced renovation and further exploitation of roof space for RPV installation. Fig. 5c shows that the electricity deficits exist for all cities and that 84% of the cities have electricity deficits below 60 GWh, with the exception of some large cities such as Amsterdam (851 GWh), Rotterdam (677 GWh) and The Hague (588 GWh). Fig. 5d shows that when all roofs are equipped with PV, 98% of the cities have electricity deficits below 60 GWh. In about half of the cities, RPV electricity generation is higher than residential electricity demand. However, cities such as Amsterdam (445 GWh), Rotterdam (287 GWh) and The Hague (225 GWh) still have significant electricity deficits.

3.4. RPV decarbonization potential

Fig. 6a shows that annual carbon emissions decrease in all scenarios but carbon emissions from electricity are significantly reduced when more electricity is supplied by RPVs. The annual carbon emissions of “S3+Grid” in 2050 are much lower than those of “S1+Grid” and “S2+Grid”, demonstrating the large contribution of advanced renovation to reducing carbon emissions. In Fig. 6b, the annual carbon emissions in 2050 in “S0+Grid” decrease by about 30% compared to 2020, mainly due to the increasing share of renewable electricity in the public grid electricity, although the annual electricity demand will increase (Fig. 4a). The reduction in annual carbon emissions in “S1+Grid” (9%) and “S2+Grid” (7%) is much lower than in “S0+Grid”, mainly due to the large-scale installation of heat pumps. Annual carbon emissions are reduced by 81% in “S3+RPV100%+Grid”, meaning that advanced renovation combined with the large-scale installation of heat pumps and RPVs has great potential for advancing the building stock towards the carbon neutral target. Fig. 6c shows that there are large differences in the decarbonization potential between cities. The decarbonization potentials are between 40% and 50% in most cities, while the decarbonization potentials are below 40% in several cities such as Amsterdam (31%), Rotterdam (34%), The Hague (34%) and Rijswijk (28%). If all the rooftops are equipped with RPVs (Fig. 6d), the annual decarbonization potential can reach more than 80% in 91% of the cities, except for cities such as Rijswijk and Amsterdam, where the decarbonization potential is still below 60%.

4. Discussion

This study presents a bottom-up dynamic building stock model to assess the RPV potential for electricity reduction/decarbonization in the building sector. The parametric characterization of individual buildings

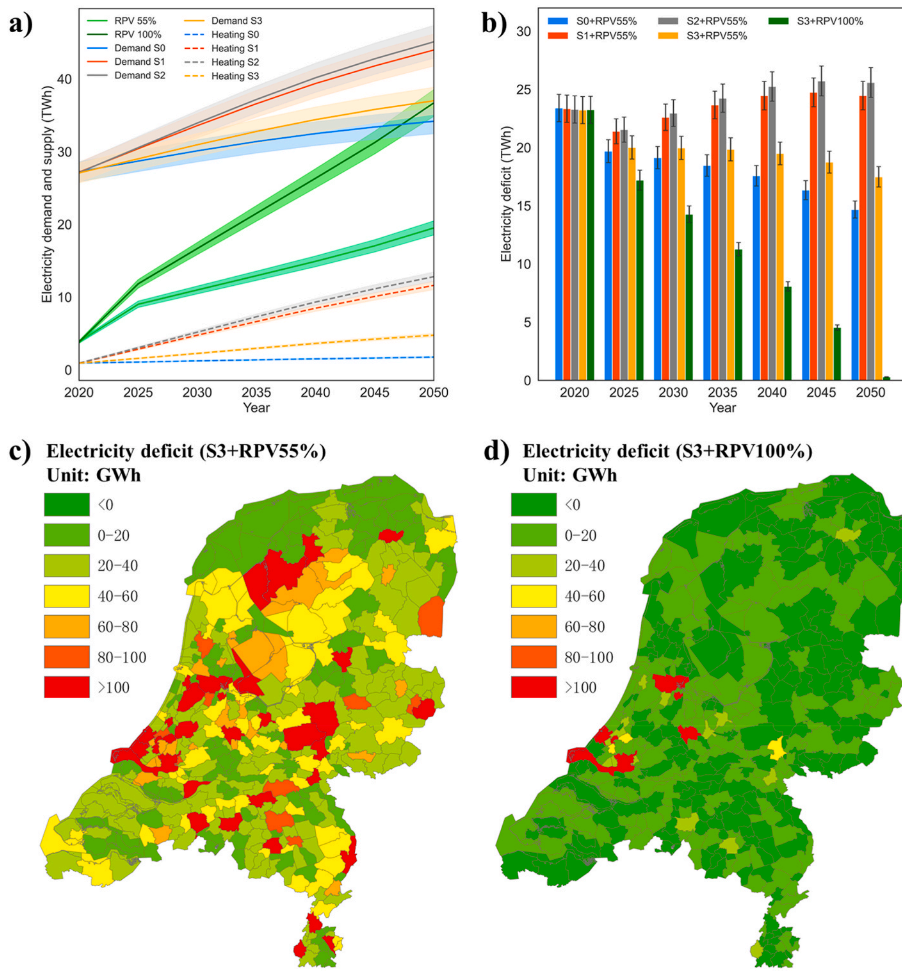

Fig. 5. Relationship between RPV electricity supply and building electricity demand. a) shows the total electricity demand, heating electricity demand, and RPV electricity generation over time. b) shows the electricity deficit over time. c) and d) show the spatial distribution of the electricity deficit of scenario S3 at different RPV installation rates. The electricity deficit refers to the annual electricity demand of the buildings minus the annual electricity production of the RPVs. The shaded bands in a) and whiskers in b) represent the sensitivity intervals given by 5% percentage variations.

makes it possible to track technical changes at the individual building level, such as the renovation and installation of heat pumps and RPVs. To the best of our knowledge, this is the first study to evaluate the potential of RPVs to reduce/decarbonize electricity in the building sector, considering the impact of heating transition scenarios on electricity demand. The strengths of this study are the high-resolution description of individual buildings and the integration of the dynamic building stock model, the RPV electricity generation model, and the building energy demand model.

4.1. RPV potential to meet electricity demand

Our study shows that RPVs can generate 19.52 TWh of electricity in 2050, while their potential to meet electricity demand is also influenced by the heat transition scenarios. RPVs can potentially meet 57% of the electricity demand if the building stock follows a conservative pattern (scenario S0). The installation of heat pumps will significantly increase the electricity demand, with RPVs potentially meeting about 43% of the electricity demand if the building envelope is renovated to conventional standards. The comparison between scenario S2 and scenario S3 shows that advanced renovation can reduce the annual electricity demand by 18%. If the advanced renovation is combined with the installation of electric heat pumps and the simultaneous exploitation of the full potential of RPVs ("S3+RPV100%+Grid"), RPVs can generate 36.71 TWh, i.e., 99% of the electricity demand.

There are differences between our study and some previous studies due to calculation methods, assumptions and site characteristics. According to a Deloitte report for the Netherlands (Broersen et al., 2018), 892 km^2 of roof area is suitable for RPVs and 50% of the total electricity demand can be supplied by RPVs. 98% of the residential electricity demand can be supplied by RPVs, which is much higher than in our study. The reason may be that it assumes that all the residential roofs are covered with RPVs, while our study assumes that only 55% (Slootweg et al., 2023) of roofs are suitable for RPVs. For some other countries in the Europe, the results are similar to our study. Gomez-Exposito et al. (2020) conclude that RPVs could supply almost 45% of the electricity demand in Spain. In a residential district in Germany, the comparison between RPV electricity production and measured electricity production shows that 35% of the electricity can be supplied by RPVs (Strzalka et al., 2012).

It is worth noting that the percentages of RPVs meeting electricity demand in this study are the potential rather than the actual amounts, as the time profiles of RPV electricity generation may not match with the time profiles of lighting, appliances and heat pumps, including both momentary and seasonal mismatches. Thus, the self-consumption of RPV electricity (i.e., public grid electricity displaced by RPV electricity) would be much lower than the total amount of electricity generated by RPVs. The self-consumption rate of RPV electricity, i.e., the actual share of RPV electricity consumed by the households, varies considerably between studies carried out in different countries, e.g., 50–70% in the

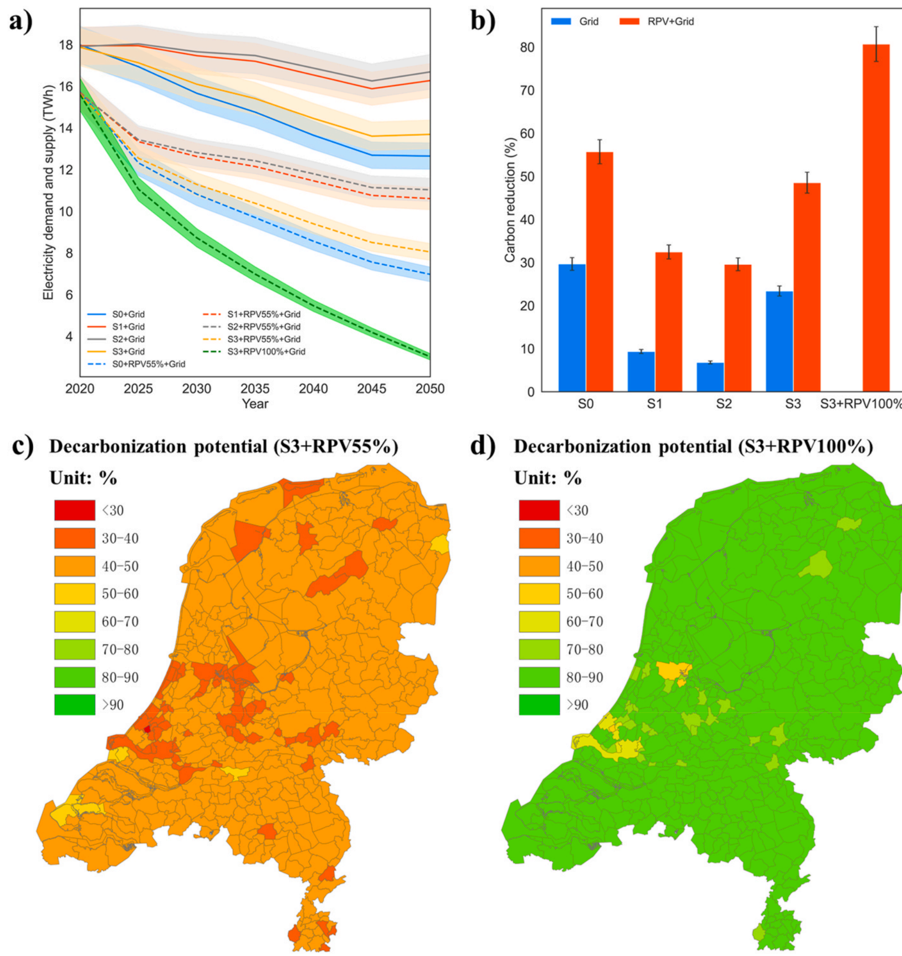

Fig. 6. Decarbonization potential of RPVs. a) shows the comparison between annual electricity-related carbon emissions under different scenarios. b) shows the decarbonization potential of different scenarios by comparing 2050 with 2020. c) and d) show the decarbonization potential at city level for different RPV installation rates. The shaded bands in a) and whiskers in b) represent the sensitivity intervals given by 5% percentage variations.

Netherlands (Jager-Waldau et al., 2020), 30% in Japan (Jager-Waldau et al., 2020), 41.96% in Australia (Z. Wang et al., 2023), 8–30% in Spain (Torres-Rivas et al., 2022), 21.4% in Sweden (Gudmunds et al., 2020) and 30% in the France (Thebault and Gaillard, 2021). There are also considerable uncertainties in the projected residential electricity demand and the carbon emission factor of public grid electricity in 2050, which may also introduce uncertainty in our results. Our sensitivity analysis (see Fig. S3) shows that the carbon emissions associated with residential electricity in 2050 are very sensitive to the future electricity demand and the carbon emission factor of grid electricity, and quite sensitive to the self-consumption rate of RPV electricity. This implies the importance of improving the estimation accuracy of these variables.

4.2. The key role of reducing electricity from appliances and lighting

Appliances and lighting will continue to dominate the total electricity demand (Fig. 4a). Electricity generated by RPVs can hardly cover the electricity demand of households unless the electricity demand for appliances and lighting is significantly reduced. However, reducing the electricity demand for appliances and lighting is a challenge. Many appliances (e.g., refrigerators, washing machines, and microwaves) have a relatively long lifetime, and their sales and market penetration are also influenced by complex macroeconomic factors (Heeren et al., 2013). Therefore, the large stock of existing energy-inefficient appliances will remain in use and their energy efficiency is likely to be improved only through end-of-life replacement. In addition, the diffusion of electric vehicles (EVs) will further increase residential electricity demand (Zhong et al., 2024). Lifestyle changes could be important strategies, such as controlling the growth in per capita floor area and encouraging electricity-saving behavior.

4.3. Policy implications

Our study has important implications for RPV deployment, heat transition, and decarbonization in the Dutch residential building sector. The results show that there is no big difference between moderate heating electrification (scenario S1) and ambitious heating electrification (scenario S2) in terms of electricity demand growth. Renovation plays a crucial role in mitigating the increase in electricity demand for space heating. Therefore, direct installation of all-electric heat pumps combined with advanced renovation is recommended to decarbonize the building stock. The results can be applied to neighboring countries with similar building technologies, space heating systems and climate as the Netherlands, such as Germany and Belgium.

The study also shows that the ratio of suitable roof area to floor area has a significant influence on the RPV potential for electricity reduction/decarbonization. It can be used as an important indicator to determine which city has the greatest opportunity to achieve electricity self-sufficiency in the building sector if RPV electricity is fully exploited, especially for countries like the Netherlands where spatial differences in solar irradiation are not very large. In large cities with more high-rise buildings (e.g., Amsterdam, Rotterdam and The Hague), the ratio of suitable roof area to floor area is less than 6% and their potential electricity self-sufficiency rate is around 40%, which is much lower than the national average level (53%). Thus, small cities with low-rise buildings have a better chance of achieving electricity self-sufficiency through PV, if PV electricity is fully exploited, than large cities with many high-rise buildings. However, large cities such as Rotterdam (4.1%), Amsterdam (4.2%) and The Hague (5.4%) currently lag far behind in terms of RPV installation (van Groesen, 2024). In Westerveld (a municipality with 19, 661 inhabitants), on the other hand, more than 38.4% of residential buildings have RPVs on their roofs (van Groesen, 2024). The use of RPVs in large cities should be encouraged to keep pace with small cities.

4.4. Limitations and research opportunities

Despite the strengths of our model in providing important insights into the potential of RPVs to reduce/decarbonize electricity, the following limitations can be improved in future research.

(1) There is a significant temporal mismatch between RPV electricity generation and electricity demand as well as a mismatch between building characteristics and the COP of heat pumps (Galvin, 2022a), so a large proportion of the electricity generated by the RPVs cannot be used directly by the buildings. However, our model uses a method with low temporal resolution (yearly basis) to estimate the annual electricity demand and RPV electricity generation. In addition, the COP actually depends on the insulation level (e.g., U-values) of the building envelope, the heat distribution system, and the temperature difference between the rooms and the heat source (Terry and Galvin, 2023), while our study uses a seasonal heat pump COP (3.5). Therefore, our model cannot capture the instantaneous match/mismatch between the electricity demand of the building and the electricity generation of the RPV. The actual impact of RPVs in displacing grid electricity and reducing carbon emissions would be less optimistic than the results of our study (see Fig. S3), as the gaps due to the time mismatch between RPV supply and building electricity demand would have to be filled by public grid electricity. Future research can integrate the hourly building electricity demand model with the hourly RPV electricity generation model to determine the actual amount of RPV electricity consumed by buildings and the corresponding decarbonization potential (Galvin, 2022b). Electricity storage technologies (e.g., batteries) and smart dispatch systems are regarded as important strategies to address the match-mismatch issues with shared RPVs in multi-apartment buildings by analyzing how electricity is generated, stored, and distributed, and how far we are from electricity self-sufficiency if RPVs are installed at scale (Galvin, 2024b). However, they can only balance the electricity demand of households and RPV electricity generation for short periods. There is an even bigger winter-summer mismatch, i.e., low RPV electricity productivity vs. high heat demand from heat pumps in the winter, as well as high RPV electricity productivity vs. low electricity demand in the summer (very few residential buildings with air conditioning systems in the Netherlands). Unpredictable mismatches in the medium term, for example due to cold grey days without wind, will further aggravate the mismatch. Therefore, not only the momentary mismatch, but also the seasonal mismatch influences the level of self-consumption of electricity from RPV.

(2) This study uses a fixed proportion of suitable roofs from the literature, i.e., 55% (Slootweg et al., 2023), to derive the suitable roof area for RPVs. However, the exact suitable roof area is difficult to calculate due to the lack of high-resolution data on roof characteristics such as slope, orientation, load-bearing structure, and shading from trees and neighboring buildings. Future research is needed to determine which buildings are suitable for PV installation (e.g., identification by building type and age) and how much roof area can be used. The increase in PV panel efficiency due to technology development and the actual performance of RPVs (C. Wang et al., 2023) should also be considered. In addition, facades have about three times the surface area of roofs and can also be installed with PV systems, which can significantly increase the electricity productivity of buildings (Fath et al., 2015). Future research could explore the full potential of building-integrated PV (BIPV) electricity generation and assess the synergistic effect of public electricity transition and large-scale deployment of onsite PV on residential carbon emissions (Galvin, 2024a).

(3) This study uses a constant per capita floor area (68.59 m^2), which varies over time and across regions, which may lead to uncertainties in the modeled trend of building stock development. In addition, population development and migration are inhomogeneous between cities. Future research can develop city-specific dynamic building stock models with the changing per capita floor area and urbanization rate to better capture the spatiotemporal building stock evolution.

(4) Large-scale advanced renovation and installation of heat pumps and RPVs requires support from stakeholders such as homeowners, tenants, and government, while this study only considers their potential from a technical perspective. Future research could look at the micro-level considerations to determine whether RPVs and heat pumps are economically feasible and how many homeowners are willing to install them in their buildings (Galvin, 2024a).

(5) Residential electricity demand is strongly related to the population, appliance use, and the energy efficiency of lighting and appliances. In addition, there are already many EVs in the Netherlands (Statista, 2024), and the share of households with EVs is expected to increase significantly in the coming years (IEA, 2024). However, our model did not include the increase in electricity consumption caused by EVs, which may underestimate future electricity demand. Future research can conduct a more systematic study (e.g., including EVs) to better project the development trend of residential electricity demand.

5. Conclusion

This study presents a bottom-up building stock model capable of assessing the RPV potential to meet electricity demand and reduce carbon emissions. Individual buildings are characterized by a set of attributes, such as geometries, thermal properties, and technical systems, which allow the changes in annual electricity demand and RPV electricity generation to be captured as the building stock evolves. In contrast to previous studies that have mainly focused on estimating RPV electricity generation, our study considers the impact of electrification of space heating systems (e.g., heat pumps) on the RPV potential to meet electricity demand. The results show that large-scale installation of heat pumps will significantly increase electricity demand in the residential sector, while appliances and lighting will continue to dominate electricity consumption. In order to reduce the electricity demand induced by heat pumps, extensive renovation is required. The electricity generated by RPVs, if fully utilized, can potentially meet all residential electricity demand. Ambitious installation of RPVs and heat pumps together with advanced renovation can potentially reduce annual carbon emissions by about 12.6 Mt CO_2-eq (81%). Our study can provide policy makers with critical insights for the transition to a sustainable energy system and the targeted decarbonization of the building sector. Future research is recommended to consider socio-economic factors and to increase the spatiotemporal resolution of the energy demand models and the RPV generation model to explore the true potential of RPVs for electricity supply and decarbonization.

CRediT authorship contribution statement

Xining Yang: Writing – original draft, Software, Methodology, Funding acquisition, Conceptualization. **Han Wang:** Writing – review & editing. **Mingming Hu:** Writing – review & editing. **Zhi Cao:** Writing – review & editing. **Chunbo Zhang:** Writing – review & editing. **Xiaoyang Zhong:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144587.

Data availability

Data will be made available on request.

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