Building a green future

Examining the job creation potential of electricity, heating, and storage in low-carbon buildings

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Building a green future: Examining the job creation potential of electricity, heating, and storage in low-carbon buildings

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ABSTRACT

Job creation is paramount when considering global transitions to low-carbon, clean-energy solutions. The building sector, critical to reducing greenhouse gas emissions on a global scale, has technologies available that rely on electricity rather than fossil fuels for energy and indoor heating and cooling. Solar photovoltaic, energy storage in the form of prosumer batteries, and heat pumps represent three readily deployable solutions to reduce carbon emissions in both new and retrofitted buildings. This study investigates the creation of jobs for each solution and then for all three combined across key countries in North America, Europe, and Asia. While other studies have explored aggregated job creation within nations, regions or globally, this first-of-a-kind study employs a micro-level approach examining six individual building archetypes: residential, hospital, hotel, office, retail, and education. Using the best available data as of 2022, the first-order assessment finds that more than 2 million new jobs and more than 141 million job years can be generated in Europe and the United States alone during the transition to net zero living.

1. Introduction

Job creation and the employment effects of different energy options are two of the most recurrent, and salient, social and political topics with respect to low carbon transitions. For example, job creation or disruption is a cornerstone of current debates about the innovation dynamics of net-zero economies, and whether they will foster massive 'creative destruction' or become 'motors of innovation' (Kivimaa and Kern, 2016). Jobs and employment feature prominently in adopted and pending government programs around the world (Boyle et al. 2021; Galvin and Healy 2020; MacArthur et al. 2020), especially those focused on 'green recovery' and 'building back better' (García Vaquero et al. 2021; Arnedo et al. 2021; Geels et al., 2022). In fossil fuel sectors, job losses and skill retraining remain a central issues in global deliberations about 'just transitions' and how frontline communities are affected by energy or climate policy (Lecocq et al. 2022; David and Schulte-Römer 2021; Gürtler et al. 2021).

Furthermore, the extent of job creation, or destruction, can shape the social acceptance and desirability of different low-carbon pathways and lead to social mobilization to support or oppose future energy transitions (Sovacool et al. 2022). In South Africa, fierce debates are ongoing about severe disruptions in coal producing provinces and labor emigration after an economy is decarbonized (Bohlmann et al. 2019). Hanto et al. (2021) add that while increases in renewable energy can produce net gains in employment to offset the decline in coal job losses, this is never certain and comprehensive plans for job transfers, policy formulations,

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; CGE, Computable General Equilibrium models; EU, European Union; GDP, gross domestic product; I/O, input-output; kW, kilowatt; MW, megawatt; NAIC, North American Industry Classification System; NDCs, Nationally Determined Contributions.; PV, Photovoltaics; USD, United States Dollar.

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and other support mechanisms are needed to protect global workers. More discrete but possibly longer lasting impacts on urban areas, such as overall employment in a service economy (e.g., solar installers) and manufacturing (e.g., EV or heat pump factories), are even more difficult to determine. Even improvements in energy efficiency can correlate with unemployment, as energy-efficient products improve productivity to the point where some workers lose their jobs. Energy efficiency improvements under some conditions reduce unemployment, but in other conditions result in an increase in unemployment (Agradi et al. 2022).

In this study, we examine how one aspect of the green transition – making buildings dependent on self-produced renewable energy – contributes to employment in the energy industry. Several studies explore job creation on an aggregate level within nations/regions or globally (Pai et al. 2021, Ram et al. 2020, 2022). Herein we take a micro-level approach, assessing job creation at the level of individual buildings of six archetypes: residential, hospital, hotel, office, retail, and education – all adopting rooftop solar PV to generate electricity, installing prosumer battery storage to capture any excess electricity unable to be consumed onsite, and heat pumps for building heating and cooling.

2. Defining and reviewing the employment effects of low-carbon energy

The academic literature utilizes various terms to describe and conceptualize employment or ‘green jobs.’ Barbieri and Consoli (2019) argue that “green employment” as a whole consists of work that takes place in industrial green processes (e.g. insulation, recycling), the production or delivery of green products and services (e.g., workers producing insulation panels, hybrid vehicles) as well as selected green industries (e.g. manufacturing of wind turbines). Using this broad definition, they estimate that green employment opportunities for regions such as the United States could be quite large, including up to 20 % of the total workforce (across industrial processing, products, services, and manufacturing). Cecere and Mazzanti (2017) frame green jobs instead as any employment activity that promotes innovation in green sectors such as environmental technology or sustainability as a whole. Karakul (2016) supposes that ‘green jobs’ are those that “reduce the environmental impact of enterprise and the economic sectors, ultimately to levels that are sustainable and contribute to the preservation or restoration of the quality of environment in agriculture and other industries and services sectors as well as administration while providing adequate wages, safe working conditions, protection of workers’ rights (and nature’s rights), social dialog and social protection.” King and Shackleton (2020) use the closely related term of ‘green collar jobs’ to refer to labor in businesses who produces or services contribute to improvements in environmental quality. Sulich et al. (2020) break down green job categories into the different classifications shown in Table 1.

The jobs created by different energy sources can also be differentiated as being direct, indirect, or induced. Direct job creation refers to sectors of the economy that are affected by direct economic activity due to higher investment. Indirect effects mainly include the materials and industry demand as a second-order effect. Finally, induced effects reflect the increased spending on consumer goods and services by those earning higher incomes due to the direct and indirect effects across the economy (Brown et al 2020). Brown et al. (2020) apply this approach to depict the various employment multipliers for different energy sector options shown in Table 2. As indicated in the table, energy efficiency options provide the most jobs per investment, followed by biomass and hydroelectric sources of electricity supply.

The methods and approaches for estimating green jobs and employment effects related to clean energy differ markedly, and can include different General Equilibrium Models (Computable General Equilibrium models, CGE) calibrated with different elasticities (Baldwin et al. 2020) as well as input-output (I/O) models such as IMPLAN which uses the North American Industry Classification System (NAICs) for jobs (Brown et al. 2020). Lesser (2010) noted a dominance of two particular approaches within the literature a decade ago. The first is the use of highly complex econometric models to estimate economic changes over time in response to different policy options, which are well suited to policy analysis and accounting for structural change. The second is I/O modeling, which traces the sales and purchases of goods across different sectors of the economy, well suited for assessing the impact of technology adoption (such as the addition of a wind farm or a new power

Table 1
Categories and descriptions of green jobs.

Section	Description of the group	Group characteristic proposed by the International Labor Organization
Agriculture, forestry, hunting and fishing	Silviculture and other forestry activities, excluding the acquisition of forest products Service activities related to forestry	Organic agriculture; sustainable forestry and soil, water, and wildlife conservation
Industrial processing	Manufacture of electric motors, generators, transformers, switchgear, and control of electricity Manufacture of batteries and accumulators Manufacture of wiring and wiring devices Manufacture of electric lighting equipment Manufacture of other electronic equipment	Energy efficient equipment, appliances, buildings and vehicles, and goods and services that improve the energy efficiency of buildings and the efficiency of energy storage and distribution.
Production and supply of electricity	Production, transmission, distribution, and trading of electrical energy	Electric energy from renewable sources or nuclear means
Water supply; sewerage, waste management, and remediation activities	Collection, purification, and distribution of water Sewage disposal and treatment Waste collection Waste treatment and disposal Materials recovery Remediation activities and other service activities related to waste management	Pollution mitigation; greenhouse gas reduction; recycling and reuse of goods, and associated services
Public administration and defense; compulsory social security	Public administration and economic and social policy	Governmental and regulatory administration; education, training

Source: Modified from Sulich et al. 2020:

Table 2
Comparison of employment multipliers across various energy sectors in the United States (full-time equivalent jobs/$million investment in $2015).

	Direct	Indirect	Induced	Total
Electric power generation				
Wind	0.47	1.49	1.62	3.58
Transmission & distribution	0.70	2.11	2.92	5.73
Fossil fuel	0.64	2.57	3.13	6.34
Solar	2.00	0.70	3.69	6.38
Nuclear	1.02	2.56	3.44	7.02
Geothermal	1.25	3.26	3.94	8.45
Hydroelectric	1.32	3.38	4.24	8.94
All other	1.87	3.40	5.05	10.32
Biomass	0.73	5.87	4.27	10.87
Energy efficiency				
Industrial	3.69	3.39	5.06	12.15
Residential	3.78	3.74	5.04	12.55
Commercial	4.07	3.48	5.10	12.64

Source: Brown et al. (2020). Note that the total values are correct; the sums of components shown may not add to the totals due to rounding.

plant). In their review of the literature, Lambert and Silva, (2012) concluded that various techniques were used across studies, including some that focus on the labor intensity of renewables, but others cost increases and availability of investments, and still others accounting for job losses, job quality, and skills. Analytical studies using extensive surveys were found to be more appropriate for regional studies, while input–output methods were better suited to national and international studies. Stavropoulos and Burger (2020) added in their review that while econometric/CGE and I/O models are all capable of estimating jobs or labor changes, they vary in their robustness: CGE methods are best at including most kinds of induced effects, whereas I/O methods can only address investment changes and consequent changes in income. Of the 30 studies examined, 22 reported only positive net employment effects, while 8 reported mixed positive and negative effects or negative net employment effects. In terms of methodology applied, 18 studies used an I/O analysis, 7 studies used CGE analysis, and 5 studies used analytical methods. Geographically, studies were conducted on the United States (9 studies) and Germany (8 studies). They found 7 studies that covered other countries and 6 studies covered a group of countries other than Germany and the United States.

The literature on job creation from clean energy technologies is equally varied; Table 3 presents an overview of more than two dozen studies published in the past two decades. These studies cover remarkably different technologies, from wind and solar power to energy efficiency and fossil fuels and even building renovations, transport, and desalination. Almost all studies find net positive job creation, and most are at the national scale. Most focus on one location only, meaning comparative work is rare. Many focus on one technology sector only (e.g., renewable energy). Most rely on a single model or method. The evidence base has a strong bias towards North America and Europe.

3. Estimating the global employment outcomes for low-carbon building archetypes

It is clear from the literature so far on jobs and clean energy that multi-technology studies, with a global reach and focus on multiple locations that utilize a diverse range of methods and data, are rare. Moreover, work on new buildings, or cities, compared to merely renovations and retrofits, is nonexistent, especially work that delves away from a national or top-down focus to a technology specific or bottom-up focus.

To address this gap, we examine the job creation potential of buildings and their configurations in future low-carbon cities. This involves looking intently at a transition from the buildings of today, which mostly rely on natural gas heating, with no digital controls or technologies, supplied by grids, to buildings of the future, which may use electric heat pumps, battery storage, and rely on a more distributed mix of generated energy. Table 4 captures some of the technologies specifically involved in the buildings of the future.

We model two building classes (today vs. future). Both building classes share the same physical characteristics in terms of energy intensity for various loads (heating, cooling, appliances), retrieved from the ASHRAE database. The building of the future differs from the building of today as the heating load is further electrified with heat pumps, digital controls are implemented to optimize energy use with occupancy, and distributed generation alongside storage is also deployed. We also create a distinction between existing buildings which undergo renovations (i.e., using a 1980 building profile from ASHRAE) and a new construction (i.e., using a 2018 profile). To give our results more granularity and robustness, we do this according to six building archetypes: residential single family (150 m2, 2 floors); office (45,000 m2, 10 floors); hospital (20,000 m2, 6 floors); hotel (4,000 sqm, 4 floors); retail (2,000 sqm, 1 floor); and education (20,000 sqm, 3 floors). The Schneider Electric study (2022) estimates carbon emissions savings, energy costs outcomes, and overall profitability of the additional investment. This study focuses on the creation of associated jobs for each archetype (both renovated and new).

Schneider Electric (2022) conducted research on the costs of solar PV, heat pumps, and battery storage for each of the aforementioned archetypes in 19 regions globally.[5] We first estimate 6 m^2 of installed PV as having a capacity of 1 kilowatt (roughly 150–165 kW per square meter). We then use Ram et al. (2022) employment factors of jobs/MW to estimate total jobs per building. Finally, we use Ram et al.'s (2022) regional employment multiplier estimates for the year 2025 to adjust jobs created in the 19 regions globally for variations in labor productivity (1.0 for North America, 1.1 for Europe, and 1.6 for Northeast Asia). A virtue of the employment factor approach adopted by Ram et al. (2022) is its inclusion of jobs created across the value chain associated with energy technologies, and it incorporates modifications to capture the dynamic nature of job generation during energy transitions and accounts for differences regionally in trade and labor productivity (see the supplemental online methods materials for Ram et al. (2022) for more details on this approach). Note that we are not assessing or evaluating the employment factors that Ram et al. (2022) derived, but rather simply using them as robust, peer-reviewed estimates.

We report our calculations in jobs and job years. We employ the IEA definition here:

> *Jobs are reported as either job-years or jobs. The 'job-years' term is used to report the cumulative years of FTE over a period of time. The term 'jobs' is used to report employment during a single year or an average over a period. Job-years accounts for total employment created directly by a project making comparable employment that may spike during construction phases, then level off at much lower levels during operation, which may continue for 20 years or more. Jobs indicate how many people will be employed in certain industries during a specified period of time.*

The period of time a piece of infrastructure lasts varies from batteries to solar PV to heat pumps, but consistent with Ram et al. (2022), we assume that 'as and when energy plants are decommissioned and new energy plants replace the existing capacity, the operation and maintenance jobs continue to exist'. Therefore, we assume that the operation and maintenance jobs created in association with the buildings examined in our study will exist in perpetuity for those buildings. Note that Ram et al. (2022), whose employment factors we use here, estimate nearly identical employment factors in Europe and the United States (e.g., a multiplier of only 1.1 for Europe, and 1.6 for Northeast Asia over North America, as of the year 2025); these are the multipliers applied in our analyses here. However, not all employment factor analyses take this approach. Pai et al. (2021) cite employment factors that, for example, differ more than seven times between the US and Spain (see Table S1), although this assumes a utility-scale installation. The provision of separate rooftop PV employment factors by Ram et al. is a reason why we used those estimates in the first instance.

Our approach has some limitations. In our analysis, we assume that all self-generated PV is either consumed or stored, which leads to a clear oversizing of storage needs (notably in residential). In practice, models may differ with, for instance, reselling schemes (enabling individuals to resell their energy, hence less or no storage needed), alternative storage solutions (we have assumed stationary batteries, but one could also use thermal storage, storage from EVs, etc.). Furthermore, our building archetypes are not representative of the full stock of buildings in a given country. For example, our office building archetype is rather large. This is important to note because some of the largest number of jobs and job years created across the archetypes comes from office buildings, and this is predominantly due to their large size and requirements for heating

[5] Nine individual countries: Canada, Denmark, France, Germany, Italy, Japan, Netherlands, Spain, United Kingdom; four regions within the United States: Midwest, Northeast, South, and West; six regions within China: east, north central, northeast, northwest, south central, south.

Table 3
An overview of the recent literature on clean energy and job creation.

Study	Focus	Location (s)	Method	Finding
Arvanitopoulos et al. (2020)	Renewable electricity	United Kingdom	Vector Error Correction model of long-term employment impact of renewable technologies	The positive employment impact for renewables is greater than the employment impact for natural gas or nuclear power; a 1 GWh increase in renewable electricity supply creates 3.5 jobs
Blanco and Rodrigues (2009)	Wind energy	European Union	Survey of wind energy companies	Wind energy deployment created 104,000 jobs in 2008
Brown et al. (2020)	Electricity generation (including fossil fuels, renewables, and nuclear power), energy efficiency	United States	IMPLAN model	Calculates direct, indirect, and induced employment effects per $ million of investment, finding that energy efficiency has the most (12.64) whereas wind power the least (3.58)
Bulavskaya and Reynes (2018)	Renewable energy	Netherlands	CGEM ThreeME (Multi-sector Macroeconomic Model for the Evaluation of Environmental and Energy policy) Model	Renewable energy transition will create almost 50,000 new jobs by 2030 and add almost 1% of GDP
Cantore et al. (2017)	Energy efficiency, renewable energy	Africa	Scenario analysis of direct and indirect job coefficients (jobs/GWh/year)	Energy savings and renewable energy generates net positive employment compared to a reference scenario; costs per additional job created decrease with increasing levels of both energy efficiency and renewables
Costantini et al. (2018)	Energy Efficiency	European Union	Econometric analysis of a sector-based panel dataset for 15 EU countries From 1995–2009	Energy efficiency has a positive effect on net employment, even in energy intensive industries
Dalton and Lewis (2011)	Renewable energy	Ireland	Calculates jobs/MW installed for one year as well as jobs/cumulative MW installed	Renewable energy can provide up to 177 jobs per million head per installed MW cumulatively
Dvořák et al. (2017)	Renewable energy	Czech Republic	Input/output modeling with data from EurObserv'ER	Biomass and waste energy processing offer the highest employment per MWh, which benefits employment in (economically fragile) rural areas
Garrett-Peltier (2017)	Energy efficiency, renewable energy, fossil fuels	Global	Input-output model	An average of 2.65 full-time-equivalent jobs are created from $1 million spending in fossil fuels, while that same amount of spending would create 7.49 or 7.72 FTE jobs in renewables or energy efficiency; every $1 million shifted from brown to green energy will create a net increase of 5 jobs
Heinbach et al. (2014)	Renewable electricity, heat pumps, biofuels	Germany	IÖW model	Renewable energy adds €9.3 million of municipal value and 166 jobs per average municipality; Manufacturing and operation and maintenance are the two largest sources of value
Heinbach et al. (2017)	Solar photovoltaics	Netherlands	WeBEE model	About 2000 jobs were present in the PV sector of the Netherlands in 2015, related mostly to installation work (> 70%) and trade
International Renewable Energy Agency (2021)	Renewable energy	Global	Input-output model	Renewable energy contributed 12 million jobs in 2020 (39% of which were in China), 4 million of these jobs were in solar PV and 32% of all jobs were held by women
Jacobson et al. (2019)	Wind energy, solar PV, hydropower (wind-water-solar energy)	143 countries	Scenario analysis	Renewable energy creates 28.6 million more jobs than a business as usual scenario
Kammen et al. (2004)	Renewable energy, coal, gas	United States	Scenario analysis	Investments in renewable energy produce as much as 10 times as many American jobs than comparable investments in fossil fuel or nuclear technologies
Lehr et al. (2012)	Renewable energy	Germany	PANTA RHEI model	Renewable energy expansion will increase net employment by 150,000 by 2030, and gross employment to 500,000 to 600,000
Llera et al. (2013)	Solar photovoltaics	Spain	Value chain approach	The manufacturing, installation, operations, and maintenance jobs associated with solar energy in Spain surpassed 19,800 in 2010
Malik et al. (2021)	Renewable energy	Global (in line with the Paris Agreement NDCs)	Scenario analysis moderated by employment factors	A 1.5∘C-compatible scenario results in a net increase in jobs through gains in solar and wind jobs in construction, installation, and manufacturing, despite significant losses in coal fuel supply; eventually leading to a peak in total direct energy jobs in 2025. In the long run, improvements in labor productivity decrease total direct energy employment, but total jobs are still higher as operation and maintenance jobs replace fuel supply jobs
Malik and Bertram (2022)	Solar energy and wind energy	India	Energy employment model and energy scenarios	Gains from renewable energy job and value creation take place away from existing coal regions, raising equity concerns and political constraints

(continued on next page)

Table 3 (*continued*)

Study	Focus	Location (s)	Method	Finding
Meijer et al. (2012)	Energy efficiency (building renovation)	European Union	Literature review	Housing renovation programs can create between 280,000 to 1,480,000 new jobs in the building sector by 2020
Mirasgedis et al. (2014)	Energy efficiency (in buildings)	Greece	Input-output modeling coupled with adjusted earnings gain approach	Building energy efficiency measures generate €0.11 to €0.23 million per €1 million invested; they also result in lifetime energy cost savings of 10–24% per building
Pai et al. (2021)	Renewable energy, fossil fuels, nuclear power	Global	A global dataset of job intensities across 11 energy technologies and five job categories in 50 countries with an integrated assessment model under three shared socioeconomic pathways	Under a well-below 2 C scenario, 84% of jobs are located in the renewable energy sector (11% are fossil fueled and 5% I nuclear power); although fossil fuel jobs decline, losses are compensated by gains in solar and wind manufacturing
Papoutsoglou et al. (2022)	Electric vehicles	European Union	Digital trace data	Jobs indirectly related to the electric vehicle industry account for 6.7% of total EU employment
Ram et al. (2020)	Renewable energy, energy storage (batteries)	Global	Employment factor approach and the LUT energy transition model	Direct jobs increase from about 21 million in 2015 to nearly 35 million in 2050; Solar PV, batteries, and wind power are the major job-creating technologies.
Ram et al. (2022)	Renewable energy, heat, transport, and desalination	Global	Value chain analysis moderated by labor intensities and employment factors	Direct energy jobs increase substantially from approximately 57 million in 2020 to nearly 134 million in 2050; value chains in renewables and sustainable technologies are more labor intensive than fossil fuels
Raupach-Sumiya et al. (2015)	Renewable energy	Germany and Japan	IÖW model	Renewable energy provided 344,000 to 378,000 jobs
Rostami et al. (2022)	Energy storage	Global	Data envelopment analysis	The energy storage technologies with the greatest job creation potential are Super Magnetic Energy Storage, lithium ion batteries, and hydrogen fuel cells
Scott et al. (2008)	Energy efficiency (buildings)	United States	Input-output modeling (ImSET model)	By 2030, energy efficiency can increase employment by up to 446,000 jobs, increase wage income by $7.8 billion, and reduce needs for $207 billion in capital stock
Sterzinger and Svrcek (2004)	Wind energy	United States	Scenario analysis	Every 1000 MW of wind power creates 3000 jobs in manufacturing, 700 jobs in installation, and 600 in operations and maintenance
Wei et al. (2010)	Energy efficiency, renewable energy, carbon capture and storage, nuclear power	United States	Analytical model of net employment impacts	Low-carbon energy sources create more jobs per unit than coal and natural gas; aggressive energy efficiency measures and renewables could create more than 4 million jobs by 2030

Source: Compiled by the authors. Note: studies are listed alphabetically. GDP = gross domestic product. EU=European Union. MW=megawatt. NDCs=Nationally Determined Contributions.

and cooling. In the case of retrofits, there may be several stages of retrofits (notably for heating and cooling), and this may have an impact on actual job creation as a result. Finally, due to the lack of reliable data, we do not include the impact of digitalization on job creation.

A final clarification is that the employment factors used herein to calculate the jobs created by each building only account for jobs *created*, not also jobs lost. However, Ram et al. (2022) demonstrate that during the transition from fossil fuels to renewables, more jobs are created in fossil fuel decommissioning than are lost in operations and maintenance for gas turbine power plants or coal power plants. Pai et al. (2021) reveal that although 80 % of all jobs lost in the energy industry due to a switch from fossil fuels to renewables are expected to be in extraction, jobs created through wind and solar will substantially outnumber jobs lost to extraction.

3.1. Electricity (solar PV)

Our calculations for electricity estimate the number of jobs created by installing solar PV on all available roof space for each of the aforementioned archetype buildings. We use the floor space of each building, multiplied by the building's floor to roof ratio, multiplied by an estimate of the percentage of roof space suitable for solar PV installation (Schneider Electric, 2022).

Jobs[1] = Building floor space (m^2) x floor to roof ratio x roof space for PV x employment factor[2]

[1] Here 'jobs' refers to jobs or job years; we ran separate equations for each.

[2] Employment factors vary across regions; drawn from Ram et al. (2022).

With separate estimates for existing structures and new builds, we present 12 archetype estimates for jobs and for job years created. We estimate the jobs created by solar PV by using an employment factor from Ram et al. (2022) for the number of jobs and job years created per MW of installed capacity. Using the Ram et al. (2022) multipliers for jobs based on regional variations in labor productivity, we calculated slightly different estimates of solar PV per region (Tables S2 and S3).

3.2. Heating (heat pumps)

Our calculations for heating estimate the number of jobs created by using heat pumps to provide for the full heating/cooling needs of the archetype buildings. We use the floor space for each building multiplied by the load demand (W/m2) multiplied by employment factors (job years or jobs, adjusted per watt) from Ram et al. (2022). For load demand, we use the maximum estimated demand for heating or cooling (Schneider Electric, 2022), whichever is higher.

Jobs[1] = Building floor space (m^2) x load demand (W/m^2) x employment factor[2].

Table 4
Example comparison of operating energy, cost, and carbon for a ten-story, 45,000-m^2 office building in Canada today and in the future.

	Carbon Intensities (gCO_2/kWh)		Cost (USD/kWh)
Natural gas	200		0.03
Grid Electricity	0.134		0.11
Distributed Electricity	-		-
	Today	Future	Technology, Approach, Benefits
Average Energy Intensity (kWh/m^2)			
Heating (space + water)	79	33	Heat Pumps
Cooling	12	12	
Lighting, ventilation, water, appliances, cooking, other	107	107	
Total	198	152	
		106	Digital Controls for Efficiency in combination with heat pumps can decrease energy intensity by 46%
Total Energy Demand (GWh/ year)			
Gas demand	3.53	-	
Electricity demand	5.38	4.77	
Total	8.91	4.77	
Distributed Generation			
Available surface for PV (m^2)	-	450	Solar PV compensates for grid electricity
PV production (kWh/m^2/year)	-	197	
Total (GWh/ year)	-	0.0887	
Spending (USD/m^2)			
Natural gas	2	-	Energy spending can decrease by 26% implementing available technologies which also decrease carbon emissions by 56%
Electricity	13	11	
Carbon Emissions ($kgCO_2/m^2$/year)	**32**	**14**	

Source: Schneider Electric (2022)

[1] Here 'jobs' refers to jobs or job years; we ran separate equations for each.

[2] Employment factors vary across regions; drawn from Ram et al. (2022).

For each building archetype in each region, we use heating and cooling loads that account for all coils and zone conditioning (outside of electric heating when present); we divide these values by the surface area of the building to get a load in W/m2 (Schneider Electric, 2022). Due to differences between global regions in heating and cooling needs and regional variations in labor productivity, we calculated individual estimates of heat pump jobs per region (Tables S4 and S5).

3.3. Storage (batteries)

Our calculations for battery storage estimate the number of jobs created by using batteries to store energy generated by solar PV. We start with Schneider Electric (2022) estimates for dimensioning of storage required to retain solar production that exceeds building use, based on the expected electricity consumption of each building archetype in the 19 regions. We then multiply this by the employment factors for jobs and job years created by prosumer battery storage (Ram et al. 2022).

Jobs[1] = ($\int$ *PV production [kW], for each archetype and region, when PV production [kW] > demand [kW]*) x employment factor[2].

[1] Here 'jobs' refers to jobs or job years; we ran separate equations for each.

[2] Employment factors vary across regions; drawn from Ram et al. (2022).

Note that for seven archetypes, zero storage is reported due to Schneider Electric's calculations that production will never exceed use in these buildings. For dimensioning of battery storage in particular, there was substantial variation across regions for all archetypes except for residential (Tables S6 and S7). Finally, we apply the same regional labor productivity multipliers to battery storage from Ram et al. (2022) as we apply for solar PV and heat pumps.

3.4. Synthesis across solar PV, heat pumps, and batteries

Having individually estimated job creation from the three low-carbon technologies, we now combine those estimates to provide an overall assessment of job creation provided by retrofit or new construction of each archetype building (Tables S8 and S9). Overall, across the regions on aggregate, the greatest number of job years and jobs come from retrofitting existing educational buildings, or from new educational buildings, depending on the region (due to particularly high heating load demand in educational buildings and potential for substantial battery storage for new educational buildings in some regions; Fig. 1). The next highest number of job years comes from new and existing office buildings, but in this instance, the driving influence is high heating and cooling load demand and the relatively large footprint of these buildings). In some regions, jobs per building from new retail are also quite high, and even higher than from new or retrofitted office buildings, due to potential for battery storage for excess electricity generated from solar PV.

Job creation for each of the six archetypes and within the 19 regions studied was considered on a per building basis. Across both jobs and job years, residential and hotel archetypes had less job creation compared to retail, hospital, office, and education. This is not to suggest that their overall impact would be lower, but rather, in context of the per building analysis, our finding indicates the type of dedicated or shared labor coverage that would be required for each building. Fig. 1 compares the potential jobs (top panel) and the job years (bottom panel) created for new builds versus retrofits on a per building basis. Residential and hotel archetypes are relatively close to the 1:1 line, indicating retrofits and new builds would create a similar number of jobs and job years, though very slightly in favor of new builds. Yet, per building, the impact is less compared to other archetypes suggesting the intuitive situation where a single residential or hotel building would not generate a dedicated job, but rather would require a labor force that supports residential and hotel archetypes across multiple buildings. Additionally, the total building stock being considered would then serve as a multiplier for the total impact of job creation.

Fig. 1 also shows that hospital and office archetypes would create a similar number of job years across all regions for retrofits and new builds, although the jobs per building is slightly higher for retrofits in most regions. New constructions show an increased number of jobs and job years for each retail building, indicating that retrofits for this archetype would not create as much job creation in the regions studied. Finally, education building archetypes have the relatively highest impact on jobs and job years per building basis. Education buildings are the most geographically dependent when considering whether a retrofit or new build would create more jobs. For example, Spain was analyzed to have over 75 job years created per new education building, but less than 40 for retrofits. A renovated building in China Northeast was analyzed to create over 3.5 jobs, but less than 2.25 jobs for a new build. As plotted in Fig. 1 by dark green circles, the education archetype did not produce a general trend of creating more job years in retrofits or new builds, but typically favored retrofits for the creation of new jobs per building.

3.5. Jobs created through archetype retrofits across regions

Following our calculations at the micro-level (i.e., scale of each individual building), we made a very initial investigation into how many

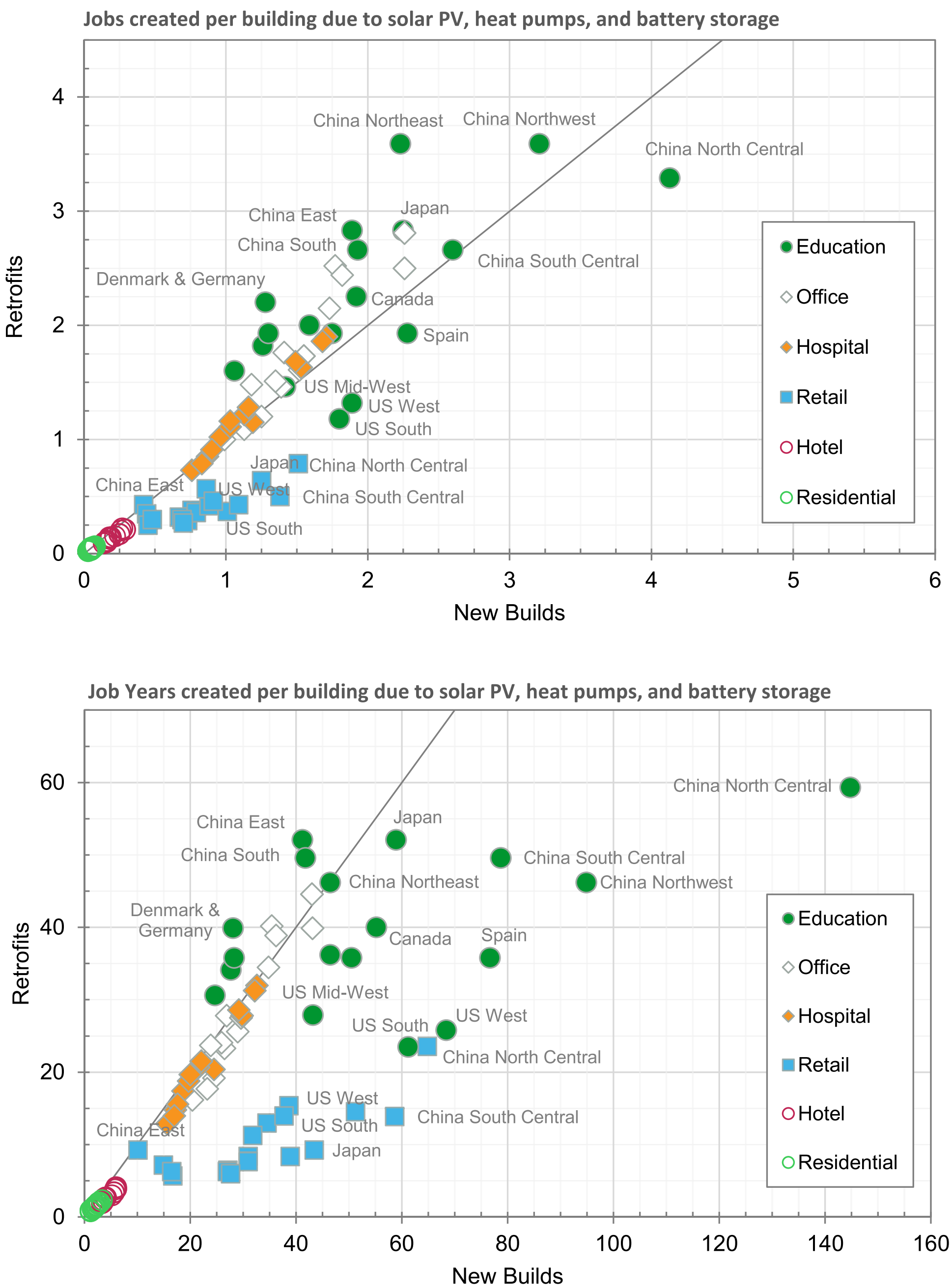

Fig. 1. Predicted job creation per building, accounting for the use of solar PV, heat pumps, and battery storage combined. *Note:* New builds vs retrofits for jobs (top) and job years (bottom) per building for each of the six archetypes and eighteen regions in this study. The solid line is an equal potential of jobs or job years for a given retrofit or new build. Deviation from the 1:1 line indicates more potential for new builds, below the line, or retrofits, above the line. Select regions labeled for interest, the complete data set is available in Supplementary material. (Jobs measures continuous jobs supported through operations and maintenance. Job years measures the number of years of work for one person, involved in manufacturing, construction, installation, and decommissioning).

jobs the retrofits we describe herein could create across the regions we include in our analysis. We estimate job creation in two scenarios – when 10 % of eligible buildings in our archetype categories are renovated (early in the transition) and when 100 % of such buildings are renovated (the end of this transition). Many countries globally have goals or legally mandated timelines for net zero set at the year 2050, making this a reasonable timeline for 100 % renovation of eligible buildings, according to the solar PV, heat pump, and (possibly, for certain regions) battery scenarios described above. This is a first, conservative, attempt that is constrained to retrofits to existing buildings (we were unable to obtain reliable data on estimates of future building needs), and only in our seven countries in Europe and four regions in the United States (we could not locate data on the other regions). Additionally, because some historic buildings will be unable to be renovated, some will not be suited to renovation architecturally, and because some buildings will be demolished, we only account, somewhat arbitrarily, for 80 % of total current building stock as being eligible for renovation (in both our aforementioned 10 % and 100 % estimates).

For our analysis below, we use estimates of the total number of buildings in each of the six building categories we include above.[6] Additionally, because the building archetypes in our study are on the larger end in terms of size (floor area), we only include estimates of jobs created for buildings this size or larger in each of the categories. The EIA data we use provides information on the percentage of buildings in each size range for each building type (e.g., 22 % of retail buildings are in the

[6] Data from https://ec.europa.eu/energy/eu-buildings-database_en; https://www.eia.gov/consumption/commercial/data/2018/#b11-b14; https://www.eia.gov/consumption/residential/data/2015/index.php?view=characteristicshttps://www.bpie.eu/publication/europes-buildings-under-the-microscope/.

size range of our archetype, and 2 % of all healthcare buildings are in the size range of our hospital archetype). The European Commission data does not offer a similar breakdown across size ranges, so we use the same percentages of buildings from the US for the seven European countries. This is likely an overestimation, as building sizes in Europe tend to be smaller than in the United States, but the job creation estimates for all eleven regions we examine here are still all quite conservative, due to: (1) leaving out any of the smaller buildings of each building type (over 99 % of all buildings of that type for education and office), and (2) only accounting for renovations and not at all for new buildings (which, in many cases, have more potential for job creation than renovations do [Tables S8 and S9]).

For residential buildings we take a different approach, due to not having data on percentage of single family dwellings over and under 150 square meters. Although we acknowledge that jobs created by retrofitting a home are not linearly associated with floor area, for a best estimate, we take the average square meters of floor area for a single family dwelling in each country, divided by 150 square meters, to generate a factor by which to adjust the job estimates in each region (Table 5).

A further limitation of this preliminary analysis is the data on existing building stock employs different methodologies across the US and European data, using broader definitions of what is classified as offices and hospitals in Europe, and with lack of clarity on what is counted as retail and hotels in both data sets. For example, the EU Data Observatory data reveals 23,000 healthcare buildings in the Netherlands, and the US Energy Information Administration data shows same number of healthcare buildings in the Northeast United States, even though there are 265 % as many single family dwellings in the US Northeast. This reveals that there are differences in how the data is recorded across the different regions (e.g., what counts as healthcare facilities? Small offices vs larger clinics and hospitals). For hotels, the Netherlands shows 10,000 compared to 63,000 in the US Northeast. Clearly there are variations in data provision across the EU and US data sets, although the same methodology was applied for data collection within the four US regions and then within the seven Europe regions. Our numbers here are initial estimates that both point to broad potential for job creation, but also toward data needs for more precise estimation.

The figures herein are order of magnitude estimates (Tables 6 and 7). Again, the total number of jobs created is likely higher because all building sizes are ultimately eligible for such renovation. Because of the different approach to calculating jobs created from residential renovations, we are including all eligible residential properties. This helps explain why the employment numbers for residential are so much higher compared to the other archetype categories.

4. Discussion and conclusion

The results offer a micro-scale view of job creation from low-carbon buildings through renewable energy retrofits or the addition of renewable electricity and heating to new buildings. We worked with an integrated technology company (Schneider Electric), conducting its own analysis of green building costs and carbon savings, to determine the number of jobs per building provided by these additions.

The type of building that prompts the largest magnitude of job creation varies based on global region and whether one examines jobs or job years. Our results reveal that the highest number of job years is 144.8 – for new education buildings built in North Central China. This is driven by the large amount of roof space available for solar PV on new education buildings and the ability for solar produced in this region to exceed required use in an education building, meaning relatively large dimensioning of battery storage. The highest number of jobs for any of our archetype buildings and regions analyzed is 4.13 – again, new education buildings in North Central China. Buildings in China (or northeast Asia generally) create more jobs than elsewhere, because we use a multiplier of 1.6 over North American jobs, based on labor productivity differences (Ram et al. 2022).

In general, across the regions, we see the greatest potential for job creation in green buildings using the technologies discussed herein coming from: (1) heat pump use for large buildings and (2) battery storage in geographic regions and building types that generate solar in excess of demand, allowing for storage. For heat pumps, solar PV, and batteries, the largest share of job years comes from construction and installation. Solar PV itself contributes more moderately to job creation than battery storage or heat pumps. This is mainly due to limitations in the amount of space available for rooftop solar PV on many types of buildings. For example, although we estimate office buildings at 45,000 m^2, due to the assumption of 10 stories and an estimated 10% of roof space in existing buildings (that is, not new buildings) available for solar installation (Schneider Electric, 2022), this means the space available for solar PV is only 1% of the office building floor space. With less solar PV installed, the jobs created will be fewer, and this further reduces the potential for battery storage because electricity use always exceeds production. New builds can be intentionally designed for rooftop solar PV, substantially increasing the installed capacity of solar PV, as seen in the differences in jobs created between retrofits and new builds in Tables S2 and S3.

In terms of national policy, understanding the potential for a green energy transition to create employment is very important. Such data could potentially incentivize politically conservative audiences, who might not feel strongly about green energy otherwise, to favor a green energy shift (Whitmarsh and Corner, 2017). On a local level, or within the board room of a company interested in specific building projects, jobs estimates for single buildings or a small set of buildings, are likely more useful and relevant compared to regional, national, or global estimates. We offer our estimates here as an initial attempt to fill this gap in the extant literature.

The job creation potential of low-carbon buildings, could be a significant co-benefit that is not widely validated in the current literature. Even using fairly conservative estimations, that is, presuming that only relatively large buildings in our five archetype categories (and 80 % of all residential buildings) are retrofitted with solar PV, heat pumps, and battery storage, and using data only available for Europe and the United States, low-carbon buildings could generate more than 3.5 *million* new jobs (See Fig. 2) and 141 *million* job years. Although this level of employment creation would not be expected until late in the transition towards net zero, even 10 % renovation of eligible buildings discussed herein would create 0.4 million new jobs and 14 million job years. These numbers are only first-order initial estimates; they do not account for possible job losses in other sectors of the economy. They are also incomplete and indicative of a lack of reliable data on buildings for other world markets, notably China. Our estimates across archetypes and regions for total jobs created (Tables 5 and 6) reveal the bulk of job creation coming from the residential sector due to the very conservative estimations for commercial buildings in this initial analysis. Recall that estimates for residential buildings used average floor area, rather than the percentage of buildings within a certain size range (as we used for

Table 5
Average floor area (square meters) of single family dwellings, by region.

Region	Average floor area	Adjustment factor for jobs estimate (area / 150 sq. m.)
Denmark	93	0.62
France	70	0.47
Germany	74	0.49
Italy	64	0.43
Netherlands	87	0.58
Spain	37	0.25
United Kingdom	76	0.51
US Midwest	212	1.41
US Northeast	194	1.29
US South	180	1.20
US West	166	1.11

Table 6
Job years (000′s) created per region due to retrofitting buildings with solar PV, heat pumps, and battery storage.

Archetype	US Mid-west	US NE	US S	US W	Denmark	France	Germany	Italy	Netherlands	Spain	UK
Residential	24,704	15,506	40,897	21,873	621	8001	5248	3460	1847	2562	3818
Hospital	24	35	62	46	3	241	149	71	25	69	43
Hotel	22	12	28	19	5	41	25	42	2	43	28
Office	407	257	723	250	124	661	603	786	156	622	984
Retail	310	102	670	420	20	237	426	312	17	713	102
Education	201	127	288	310	57	487	373	164	35	143	178
TOTAL	25,669	16,039	42,667	22,918	830	9668	6825	4834	2082	4153	5153
10% of total	2567	1604	4267	2292	83	967	683	483	208	415	515

Table 7
Jobs (000′s) created per region due to retrofitting buildings with solar PV, heat pumps, and battery storage.

Archetype	US Mid-west	US NE	US S	US W	Denmark	France	Germany	Italy	Netherlands	Spain	UK
Residential	674	449	975	481	18	262	153	103	48	60	113
Hospital	0.2	0.3	0.5	0.4	0.03	2.2	1.3	0.6	0.2	0.6	0.4
Hotel	2.7	1.3	3.2	2.2	0.6	5.1	3.0	5.4	0.2	5.4	3.5
Office	1.5	1.0	2.7	0.9	0.5	2.5	2.3	2.9	0.6	2.3	3.7
Retail	26	11	41	26	2	25	46	31	2	52	11
Education	0.8	0.6	1.2	1.3	0.3	2.1	1.6	0.7	0.1	0.6	0.8
TOTAL	705	463	1024	511	22	299	207	144	51	122	132
10% of total	71	46	102	51	2	30	21	14	5	12	13

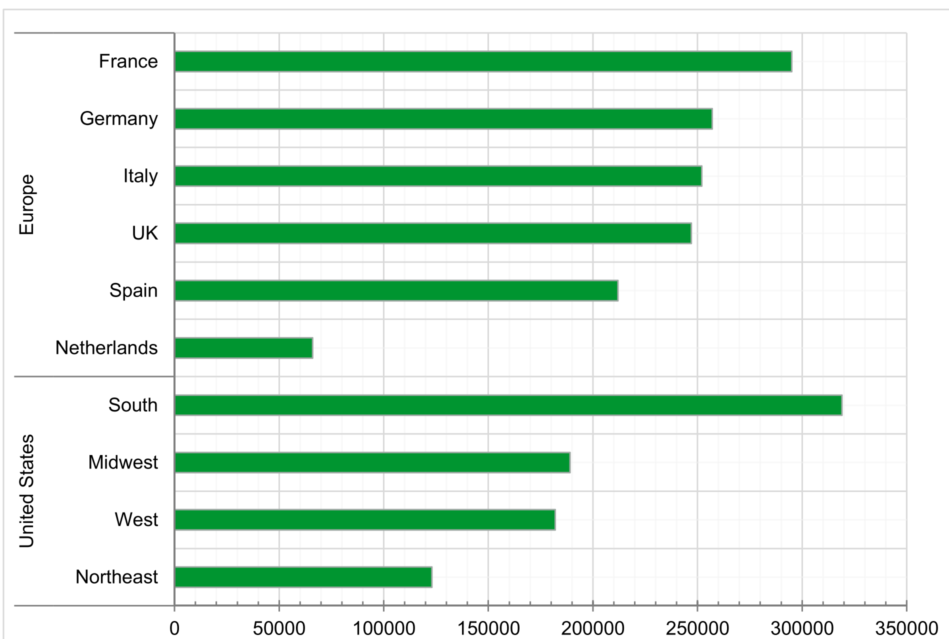

Fig. 2. Job creation potential of low-carbon buildings in Europe and North America.
Source: Authors, based on the analysis presented in Section 3.

the other five building archetypes; this difference was due to the nature of data available from the US EIA and European Commission).

When providing our estimates for job creation, we remain aware of the assumptions and restrictions included in our calculations. The amount of rooftop solar that we use to calculate job creation is highly dependent on the building types, sizes, and floor to roof space ratios we have included in our analysis. Our data, from Schneider Electric, of amount of roof space suitable for solar PV represent reasonable estimates, but the real availability of roof space will clearly vary widely, especially for existing edifices (not new build), due to equipment installed on roofs, shared areas, and roof orientation. We have taken key assumptions herein that we consider to represent average conditions. Additionally, we use robust multipliers from the peer-reviewed literature for estimating jobs created across geographic regions, but we explain above that these estimates vary quite widely across academic studies. Further, we only account for job creation, not jobs lost (particularly relevant in fossil fuel extraction), which should be a focus of future research in this area.

We do not include job creation estimates from digitalization, smart controls, and efficiency. These subjects offer additional pathways for job creation related to building decarbonization, but may also have a systemic impact on battery storage sizing and electricity demand which are subject to future research. Additionally, future research on methodology and standardization to assess the impact building decarbonization will have on jobs is highly relevant. Other research which enables a higher resolution of building stocks and their suitability for decarbonization technologies will improve the accuracy of the associated job creation potential. Approaches including the use of GIS and/or satellite data offer the promise to fill information gaps in regions where no data is available.

This study represents an initial introduction to micro-scale estimates of jobs created from manufacturing, construction, installation, operations, maintenance, and decommissioning of solar PV, heat pumps, and battery storage in new buildings and existing, retrofitted buildings. We examine job creation in 228 categories – six types of buildings (residential, hospital, office, retail, hotel, and education) each across new and existing structures, each in 19 different regions globally. Estimates of jobs and job years created per building can be useful for informing companies, communities, and governments seeking to engage in building projects about the effect their projects may have.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.tej.2023.107274.

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