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A Forest Per Worker: Quantifying the CO_2 Reduction Contribution of the Marginal "Green" (Migrant) Worker

SAM HUCKSTEP · JOHANN HARNOSS

Abstract

Workforce constraints are a widespread bottleneck to decarbonisation, hindering implementation and investment. In a novel exercise, we model the decarbonisation impact of the marginal contribution of a "green-skilled" worker in contexts of labour shortage across six countries in two occupations: an electrician installing residential rooftop solar photovoltaic (PV) panels, and a heating technician installing residential heat pumps, during the period 2024–2032. We find that the additional ("marginal") worker can contribute thousands of tonnes of CO_2 abatement, even when accounting for rapid grid decarbonisation. The marginal worker's contribution can have a monetised social value of hundreds of thousands of dollars. It is the equivalent of planting thousands of trees: a forest per worker.

On this basis, we argue that labour shortages must not be allowed to constrain decarbonisation activities. Where domestic training cannot meet demand, labour migration is a valuable policy tool. Because workers may make larger contributions in countries of origin than in countries of destination, however, we note that care must be taken to avoid implementation gaps caused by brain drain in countries of origin. Partnerships that combine training and labour migration partnerships can mitigate these risks.

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Acronyms

AC	Alternating current
AEA	Annual Emissions Allocation
DC	Direct current
GW	Gigawatt
HVAC	Heating, ventilation, and air conditioning
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt peak
NSDC	(Indian) National Skill Development Corporation
PV	(Solar) photovoltaic
SCGJ	(Indian) Skill Council for Green Jobs
STEM	Science, technology, engineering and mathematics
TESDA	(Philippines) Technical Education and Skills Development Authority
TVET	Technical and vocational education and training

Introduction

Workforce constraints are widely reported to be a key bottleneck in decarbonisation. Shortages of skilled workers are already reported to be constraining the implementation of decarbonisation plans and limiting investment (IEA, 2022; IEA, 2024). The International Renewable Energy Agency notes the challenge of a "critical skills gap" (IRENA, 2025: 87). The problem is expected to grow in the coming years as green transition deadlines draw closer.

As a key limiting factor in decarbonisation, a shortage of workers has a meaningful impact on carbon emissions and the achievement of targets. One recent analysis (Hambrecht et al., 2025) suggests that globally, workforce shortages could increase power sector emissions to 12 percent above 2030 pledges and more than 100 percent above 2045 commitments.

In this paper, we model for the first time the marginal decarbonisation contribution of an additional worker in contexts of labour shortage across six countries in two occupations: an electrician installing residential rooftop solar photovoltaic (PV) panels, and a heating technician installing residential heat pumps. We model a period of work from the start of 2024 to the end of 2032. We find that individual workers, if filling a labour shortage-induced implementation gap, can lead to thousands of tonnes of CO_2 abatement, even when accounting for broader grid decarbonisation. This decarbonisation has a monetised social value of hundreds of thousands of dollars: a solar panel installer working in Italy, for example, will contribute abatement with a social value of over US$280,000. It is the equivalent of planting a forest of trees: more than 6,500 trees would need to grow for 50 years to sequester the equivalent amount of carbon.

On this basis, we argue that if domestic training pipelines are insufficient to meet workforce demand for decarbonisation within the urgent timeframes required, legal, skills-based labour migration programmes should be used to ensure that implementation gaps do not persist. Our chosen countries comprise three possible countries of destination facing shortages (the United Kingdom, Germany, and Italy) and three possible countries of origin interested in agreeing training and migration partnerships (India, the Philippines, and Kenya). All three countries of destination are already, to varying degrees, leaning on immigration to meet decarbonisation workforce needs.

However, migration of "green-skilled" workers can also pose a carbon risk. High-income countries typically have lower carbon emissions per kilowatt-hour of generated grid electricity than lower-income countries, and also have more ambitious grid decarbonisation plans. Moving a "green" worker—for example, an electrician installing solar PV—from a lower-income country to a higher-income country could lead to a large *negative* impact on net decarbonisation. For this reason, we argue, countries of destination must take care when recruiting to ensure that they are not leaving an implementation gap in countries of origin, harming a global public good. Instead, they should target underemployed workers or collaborate with countries of origin to train more workers, ensuring that the global stock of skilled workers rises and that tasks crucial to decarbonisation are not left undone due to labour shortages.

In the first part of this paper, we set the context. We summarise the decarbonisation targets to which countries have committed; the shortages of skilled labour currently experienced and anticipated; and current use of labour migration policy.

In the second part, we show the results of an exercise in modelling the carbon emissions reduction contribution of a marginal worker across several scenarios. We briefly explain modelling parameters; more detail is available in the associated methodology annex.

In the final parts of the paper we provide policy suggestions. We propose four models of international recruitment and partnership, depending on conditions in the countries of origin and destination. We also provide broader policy conclusions, noting that underemployed workers, such as refugees without work rights, should be targeted for recruitment, and that harmonisation of curricula or qualification recognition should be a priority to ensure that reallocation of workers into implementation gaps can be facilitated.

Context

Decarbonisation targets

This paper focuses on six countries, all of which have stated commitments to reducing emissions:

- **The UK** targets a figure of 95 percent clean power generation by 2030 and a fully decarbonised electricity system by 2035 (Bolton, 2025a), on the way to net zero emissions by 2050 (Burnett and Stewart, 2025).
- **Germany** aims for 80 percent renewable energy generation by 2030 and carbon neutrality by 2045 (European Commission, 2024a).
- **Italy** aims for 71 percent renewable energy generation by 2030 (European Commission, 2024b) and carbon neutrality by 2050 (Erbach, 2024).
- **India** targets clean power generation contributing around 39 percent in 2026/2027 and 44 percent by 2032, with a further ~4 percent contributed by nuclear to give a total of roughly 48 percent (Ministry of Power, 2023).
- **The Philippines** aims for 35 percent renewable energy generation by 2030 (Climate Action Tracker, 2023), and a 75 percent reduction in greenhouse gas emissions by 2030 versus business-as-usual during the period 2020–2030 (NDC Partnership, 2025).
- **Kenya** aims to generate 100 percent of its electricity from clean energy sources by 2030 (CIF, 2024) and to cut overall carbon emissions by 35 percent by 2035 versus a business-as-usual scenario (Government of Kenya, 2025).

These high-level targets are enacted through interventions in markets to encourage rapid adoptions of new technological standards: for example, transitions from gas boilers to heat pumps, internal combustion engines to batteries, or single-glazed to double-glazed windows. They translate to technology-specific installation goals.

The UK, for example, has adopted the target of installing 600,000 heat pumps per year by 2028, rising to 1.6 million per year by 2035 (DESNZ & BEIS, 2023; Smalley and Sweeney, 2025). It has also set a target of increasing the total installation capacity of solar PV to 45–47 gigawatts (GW) by 2030, rising from 18.1 GW in 2025 (Hutton et al., 2025), and of nearly 80 GW of onshore and offshore wind (DESNZ, 2025). In **Germany**, the government has set itself a legally binding target of 215 GW of solar capacity by 2030 and around 400 GW by 2040, rising from 107.5 GW in July 2025 (Sternberg, 2025). It also targets 500,000 heat pump installations per year from 2024, with 6 million in operation by 2030 (BMWE, 2025). **Italy** aims for nearly 80 GW of solar capacity by 2030 (European Commission, 2024b), versus 40 GW in 2025 (Casey, 2025). It does not have a heat pump installation target, but does target sectoral renewables in heating increases expected to necessitate the installation of 8.6 million heat pumps by 2030 (Marchesini et al., 2025).

Lower-income countries have also adopted ambitious technology-specific targets. **India** targets 300 GW of solar capacity by 2030 (Rossi et al., 2025), and had installed 123 GW by August 2025 (MNRE, 2025a). Its PM Surya Ghar programme, a flagship federal initiative launched in 2024 and targeting the installation of 10 million residential rooftop systems by the end of 2027, will add 27 GW of new capacity (MNRE, 2025b). **The Philippines** targets 16.6 GW of solar capacity by 2029, versus a total 2.7 GW after a record annual solar deployment of 1.1 GW in 2024 (Rossi et al., 2025). **Kenya** targets 100 percent clean power by 2030; most renewable energy will be derived from geothermal and hydropower, but solar PV is also expected to make a major contribution (CIF, 2024), particularly through off-grid installations aiding the achievement of its universal energy access by 2030 (Kenya Power, 2025). Each installation of an off-grid household solar PV system is estimated to contribute emissions reductions of 431kg CO_2 per year (GOGLA, 2020).

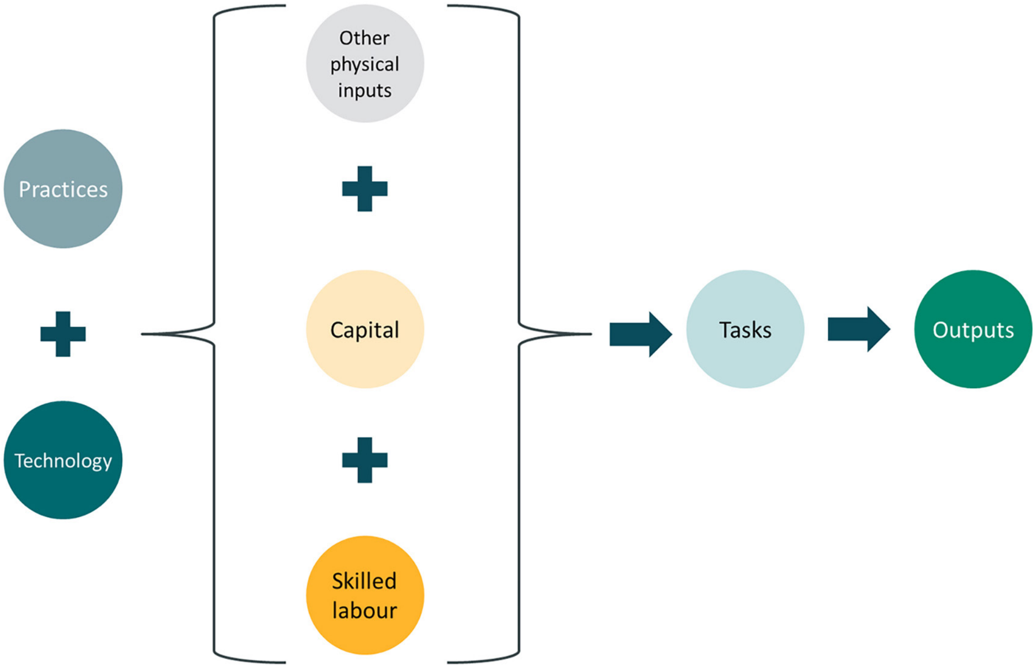
The role of labour in achieving decarbonisation targets

Decarbonisation policies represent major government interventions to correct longstanding market failures (see e.g. Altenburg and Rodrik, 2017). Due to the urgency of the need to redress high emissions, the industrial policies deployed have extremely tight timeframes for success.

This requires a coherent approach to solve numerous challenges simultaneously. Governments must ensure that there is sufficient public finance available to entice private finance into clean technologies; disincentivise the use of high-emissions fossil-based technologies; overhaul processes that could slow take-up, including permitting systems; rapidly improve electricity grids; address communications issues and misconceptions of ‘green’ technologies; support further technological innovations; and solidify supply chains—among other key bottlenecks that must be addressed (IEA, 2024b; Addison et al., 2025).

This set of interventions encompasses changes to the policy environment, the adoption of new practices, securing of physical inputs, and provision of capital. Within that, supply of labour is a crucial input without which the desired tasks will not be completed and desired outputs will not be achieved. Figure 1 summarises the interrelationship of key elements in production.

FIGURE 1. Visualisation of the production function



Source: Adapted from Granata and Posadas (2024).

As is evident in Figure 1, labour is not the only key input. The usefulness of other key inputs is, however, contingent on the supply of labour. In this paper, we focus on the decarbonisation impact of labour supply at the margin, and assume that other key variables in decarbonisation are addressed elsewhere in the policy system.

If these other variables fall away, labour demand will decline. This includes the presence of an enabling policy environment. Without policy interventions to drive consumer demand and ease the scaling of new technological take-up, there will not be a need for labour supply: decarbonisation-related tasks will not be viable within the timeframe needed, and emissions will not be lowered. For example, the UK faces an enormous need for a larger heat pump workforce to hit targets—but heat pump take-up is currently low, and incentivising greater rollout (and consequently higher labour demand) requires further policy assistance to rebalance price differentials between gas and electricity. Heat pumps need a price ratio of less than 2.5 to be perceived as attractive (Zackariat et al., 2025); in the UK and Germany, however, electricity costs over three times more than gas on a per unit basis (DESNZ, 2025b; SMARD, 2025). Levy reforms could increase the speed of the UK heat pump rollout by 60 percent (Sissons et al., 2025): when they occur, labour demand will spike.

Similarly, while solar PV is a cheap source of electricity across all countries of study, and its take-up is already happening at record scale (Rossi et al., 2025), further reforms are often still needed to accelerate it sufficiently. In Germany, for example, rooftop solar on residential buildings could provide up to 28 percent of the additional solar capacity needed to meet 2030 climate targets—but making this happen will require improved administrative processes and easier grid connections via smart meters (Fischer and Henger, 2025).

For labour *supply* to exist the policy environment must, furthermore, be predictable and reliable. Meeting decarbonisation targets requires policy that incentivises the completion of emissions-reducing targets, and in so doing creates sustained labour demand. Governments frequently state that this labour demand will create jobs to be filled by trained domestic workers. For this to happen, they must be trained to the level necessary in the required occupations. Training provision, however, frequently lags behind demand: training pipelines have multi-year lead times (apprenticeships typically take around four years to complete) and providers invest in training when demand looks durable (see e.g. Huckstep and Dempster, 2025). Where policy is perceived to be volatile or unpredictable, firms and training providers will rationally under-invest in training capacity, and potential trainees will doubt that credentials will be useful (see e.g. Barnes, 2025).

For this reason, reliable and predictable industrial policy is fundamental: companies, training institutions, and workforce entrants must anticipate sustained and predictable labour demand. The less reliable and predictable industrial policy is, the more likely it is that labour migration will ultimately be needed. Where there are fears of volatility of demand, the domestic training landscape will under-invest: investment and domestic supply might later catch up with demand, but there will be a period where migration is needed to act as a bridge. Sourcing workers to meet tight timelines will require international recruitment.

The scale of skilled labour shortages

As decarbonisation timeframes become tighter and the volume of tasks to be completed grows, the number of workers needed will rise and shortages will increase. This is challenging given that shortages are already widely reported to be hindering project implementation and increasing costs (see e.g. IEA, 2024; Huckstep and Dempster, 2025; Rossi et al., 2025).

In many countries, the decarbonisation drive must compete with other recruitment pressures. Alongside emissions reduction commitments, numerous governments have also pledged to rapidly increase their housing stock and to rearm. In the United Kingdom, for example, the Labour government's target of an additional 300,000 homes constructed per year has been estimated to require an additional 500,000 to 1 million additional construction workers—including in occupations required for achieving net zero emissions, such as electricians and heating technicians (Barnes, 2025). In Germany, the commitment to raise defence expenditure to over 2 percent of GDP has driven defence industry recruitment at a new scale; undersupply in key occupations shared with decarbonisation, such as welders, is already reported to be constraining expansion (Swaney, 2025).

Simultaneously, labour markets in countries of destination also face a structural demographic shift due to ageing populations (OECD, 2025). This is leading to large numbers of retirements within the period in which the labour force must instead be expanding.

In **the UK**, the qualified electrician workforce in England is estimated to have fallen by 26 percent during 2018–2024, with a further decline of around 32 percent anticipated if current trends persist, driven by falling apprenticeship numbers (a 10 percent year-on-year decline in 2024–25 alone) and rising retirements (JTL Training et al., 2025). There is a projected electrician shortfall of around 15,000 by 2030 (Eldred, 2025), with broader workforce gaps also anticipated across construction (CITB, 2025). The UK Government has highlighted shortages in multiple key occupations (DESNZ, 2025c), and numerous sector actors have warned of skilled workforce gaps in the tens or hundreds of thousands in the coming years (Huckstep and Dempster, 2025). These gaps are already reported to be driving up costs, leading to project delays, and disincentivising investment.

In **Germany**, energy and electrical trades are repeatedly registered as being in shortage in the Federal Employment Agency's labour market assessments (Bundesagentur für Arbeit, 2024b). The scale of the energy and electrical trades gap has been estimated at nearly 60,000 workers in 2025, in the context of a broader shortage of nearly 165,000 STEM (science, technology, engineering and mathematics) workers (Anger et al., 2025). In the medium term, these shortages are not projected to abate (Zika et al., 2024). Acute shortages are concentrated in trade occupations essential for rooftop solar PV installation and heat pump deployment: construction electricians and heating and air conditioning technicians are among the most in-demand 'bottleneck' roles, with an estimated shortage of 18,300 electricians and 12,200 heat and air conditioning technicians in 2024 (Büchel et al., 2025).

In **Italy**, recruitment difficulties are reported to be increasing in the electrical sector: in 2024, 73.6 percent of companies reported shortages. Shortages were also reported in other green transition-relevant occupations, including welders and engineers (Unioncamere-Excelsior, 2025). Italy anticipates significant workforce challenges due to the retirement of 2.9 million workers by 2028; the construction and manufacturing sectors are projected to be among those with the most challenging labour shortages, due in part to a shortfall of between 15,000–17,000 young people entering construction and electrical apprenticeships each year (Unioncamere-Excelsior, 2024).

Shortages in green transition-relevant occupations are not limited to high-income countries. Despite enjoying a demographic dividend, lower-income countries also face challenges.

In **India**, acute shortages in trained technicians are identified across solar PV, grid integration, and electric vehicle charging. In the context of a government target of electric vehicles contributing 30 percent of new sales by 2030, shortages of tens or hundreds of thousands of electricians and technicians are projected (Singh et al., 2025). Renewable energy projects are already reported to be being delayed by shortages of qualified workers; in government projections of shortages to 2028, multiple electricity generation roles, including in solar, are highlighted, with shortages of tens of thousands of solar PV installers expected in 2025. Shortages are reported to be both quantitative and qualitative, with major upskilling support needed (MSDE, 2025; RenewableWatch, 2025). India has invested in the buildout of the Skill Council for Green Jobs (SCGJ), which has scaled rapidly. The SCGJ aims to have trained one million workers across clean energy sectors by 2030 (IEA, 2023), in a broad range of occupations (see SCGJ, 2024). A sharp rise in demand is anticipated, especially in rooftop solar installation following a policy push (IEA, 2024c).

Kenya is also reported to face shortages of green transition-relevant skilled labour. In the most recent survey of skill needs by the Federation of Kenya Employers (2023), electrical skills were among the TVET (technical and vocational education and training) skills most reported to be in shortage—although, with only 21.1 percent of firms reporting hiring difficulties, shortages may not currently be acute. However, there is relatively little labour market information available relevant to Kenya's green transition skill gaps.

In **the Philippines**, manpower shortages and certification are highlighted as key challenges to its rapidly growing solar PV sector (Rossi et al., 2025). However, the pipeline of trainees is large: in 2024 the Philippines' Technical Education and Skills Development Authority (TESDA) reported over 92,000 graduates from electrical and electronic TVET courses and nearly 3,000 in heating, and nearly 5,000 trainers serving electrical education streams (TESDA, 2024a). Industry stakeholders report a shortage of electrical technicians, in part because the distributed energy sector struggles to compete with the more established power sector (TESDA, 2024b).

The role of labour migration

The role of immigration

In the context of under-developed domestic training pipelines, migration is a valuable pressure valve. It allows employers to meet labour demand within the mandated timeframes, avoiding project delays and cost overruns and buying time for the buildout of the training of new entrants or worker transitions. The fact that labour migration will need to have a role in achieving decarbonisation workforce goals is increasingly recognised, despite the increasingly difficult place of migration policy in the political landscape.

In **the UK**, labour migration policy adjustments introduced in 2025 focus access to Skilled Worker Visas on occupations relevant to the eight priority sectors of the 2025 Industrial Strategy, one of which is Clean Energy (DBT, 2025). The Industrial Strategy recognises that "changes to the skills system will take time to come to fruition", and that international recruitment will be needed in the interim. Numerous industry associations and companies have called for access to visas to avoid workforce bottlenecks (see e.g. Huckstep and Dempster, 2025; Barnes, 2025), and the House of Commons' Energy Security and Net Zero Committee (2025) has recognised that labour migration will be key to achieving policy goals. In the 2025 review of shortage occupations undertaken by the UK's Migration Advisory Committee, multiple roles relevant to the green transition are included, including electricians and heating and ventilation technicians (MAC, 2025). Several occupational pipelines are currently heavily supported by labour migration, including roofers and welders (Huckstep and Dempster, 2025).

Germany has explicitly linked the need for immigration reforms to decarbonisation-related workforce pressures (BMAS, 2024). Germany conducted significant reforms from 2023, relaxing access to immigration for applicants with vocational experience and reducing German language requirements while easing recognition of qualifications (Schneider, 2023). They also introduced a points-based 'Opportunity Card' allowing one-year (renewable) residence for jobseekers (Tollenaere et al., 2024). So far, increased visa grant rates have not fully translated into increased migration rates, possibly due to long visa processing times (Schultz and Mecke, 2024). Germany is also facilitating multiple pilot projects supporting both training and migration of workers with green transition-relevant skills, and has concluded several labour migration agreements (Sanderson, 2024; ZDH et al., 2024). Achieving decarbonisation is expected to require continued high levels of immigration (Büchel et al., 2025).

Italy has recently relaxed its immigration restrictions. The state labour-market intelligence system (Unioncamere-Excelsior, 2024) projects that between 2024 and 2028 around 640,000 immigrant workers will be needed. It has also moved to a programme of three-year labour migration quotas, setting access to non-seasonal visas according to a shortage list. For 2025, 70,720 non-seasonal visas were available (Ministero Dell'Interno, 2024). The 2025 list of occupations included several relevant to decarbonisation, including electricians and heating and ventilation technicians (Confindustria, 2024). Visas are also available outside the quota system for workers trained in ministry-approved vocational and civic-language programmes in non-EU countries (currently a list of 23) who also possess a job offer from an Italian employer (Ministero del Lavoro e delle Politiche Sociali, 2023). Confindustria, the national association of enterprises with 113,000 members, has suggested that Italy must prioritise training and integrating international skilled workers before they enter (Confindustria, 2025). Since 2023, Italy has also had a Migration and Mobility Agreement and joint working group with India (Ministero Degli Affair Esteri, 2024); in 2025 7,000 annual non-seasonal visas were allocated to India above the general quota (MEA, 2023).

The role of emigration

Just as all three high-income countries are increasingly recognising the importance of labour migration in the green transition, the three selected lower-middle-income countries are all prioritising facilitated labour emigration.

India is actively seeking labour migration agreements to promote the mobility of "green-skilled" workers (see e.g. Sarkar et al., 2025; Economic Times, 2024). Its SCGJ has worked closely with several other governments, notably Germany and Australia, on training for international labour markets (see e.g. SCGJ, 2024). Both the SCGJ and the National Skill Development Corporation (NSDC) have arms aimed at training workers to international standards, in collaboration with partner countries. In late 2025, India sought to reform its overseas mobility legislation to enhance cross-government policy coherence in the management of emigration (MEA, 2025).

Kenya has a large youth population, with high rates of youth unemployment (World Bank, 2024). Facilitated emigration has become a prioritised policy tool. In late 2024 Kenya agreed a new migration partnership with Germany (ILO, 2024). The agreement was warmly welcomed by Kenyan President Ruto, who suggested that he hoped 250,000 workers would move annually (Fox, 2024). By contrast, only around 1.25 million Kenyans are estimated to hold qualifications eligible for 'skilled worker' classification under Germany's migration system (Kaltner, 2024), suggesting that support in training is likely to be important. Kenya is now seeking to establish multiple further agreements, including with Canada (Mwangura, 2025), with a stated aim of exporting one million workers per year until 2028 (Ross and Martinez, 2025). In 2023 it established a National Policy on Labour Migration, seeking to better coordinate skills mappings, training provision, and international placements, and to establish bilateral labour migration agreements (Parliament of Kenya, 2023), approved in 2025 (Parliament of Kenya, 2025).

The Philippines has long been a major country of origin, with a longstanding deliberate focus on training workers for international labour markets as part of its national development strategy. Between 2006 and 2019, over 1 million workers were deployed internationally each year (Opiniano and Ang, 2024). The Department of Migrant Workers, created in 2021, provides coordination across agencies, streamlining the bureaucracy of emigration management. In the year to January 2025, nearly 40,000 'Craft and Related Trades Workers' (a group including electricians, welders, and other occupations relevant to decarbonisation) emigrated (DMW, 2025).

Quantifying the marginal decarbonisation contribution of an additional (migrant) worker

What is the marginal decarbonisation contribution of an additional worker in contexts of shortage? We estimate the marginal contribution of labour and report results (the change in avoided emissions from one additional installer) on a *per-additional-worker* basis. For brevity we refer to this as the "'marginal worker" effect. A marginal worker is understood to, in the first instance, be contributing to technology installations that would not happen if they were not present; or to be *bringing forward* installations that would otherwise only happen later, as labour supply catches up to green transition-driven demand.

We select two occupations: electricians installing residential rooftop solar PV, and HVAC (heating, ventilation, and air conditioning) technicians installing heat pumps in households. We choose these two occupation niches because they are: (a) contributing the installation of key technologies to the green transition; (b) recognised to be in widespread and growing shortage; and (c) relatively easily modelled: the technologies installed make discrete abatement contributions. Many other key occupations (including welders constructing offshore wind turbines, retrofit insulation installers, and linesworkers building out the grid) are also reported to be in critical shortage but are less easily modelled; future research could assess their per-worker contributions.

We model the marginal worker's contributions in three high-income countries facing labour shortages: the UK, Germany, and Italy. We select these countries of destination because they are anticipated to face significant difficulties in sourcing sufficient workers for their decarbonisation goals, and because they are currently taking proactive policy approaches to try to connect immigration policy to their green industrial policy goals. We also model the marginal worker's contributions in three lower-middle-income countries: India, the Philippines, and Kenya. These are also facing skilled labour shortages, but are seeking to position themselves as potential suppliers of skilled labour to international markets. The marginal worker could be a domestic worker, but given recruitment pressures, we discuss them as though they are a migrant worker.

Our modelling covers the period 2024 to 2032. This is a key period for achieving decarbonisation targets, and a plausible period for labour migration. We take 2024 as the base year due to the fact that the most recent data for several key inputs, including grid emissions factors, is from that year. If applying this analysis to a migrant worker, we assume they arrived at the start of 2024 and work until the end of 2032. They may subsequently remain in the country of destination, and thus contribute to continued abatement, or may return to their country of origin to support what is likely by then to be an accelerating clean energy market.

Our modelling relies on a number of key assumptions and proxies. Further detail is available in the associated methodology document. Importantly, our approach:

- Assumes that grid decarbonisation rates meet stated government targets (also modelling 75 percent achievement of targets);
- Uses average grid emissions factors (carbon intensity of grid-drawn kWh), in the absence of reliable projections of marginal emissions factors; and
- Assumes varying and changing rates of labour utilisation, installation efficiency, and other key installation-related factors, specific to focus countries.

We assume that solar PV installations generate electricity that displaces grid electricity, and that heat pumps replace new high-efficiency gas condensing boilers. In general, we use conservative assumptions: the estimates generated are more likely to understate an installer's impact than to overstate.

A thousand tonnes of CO_2: The contribution of the marginal (migrant) worker

Solar photovoltaic panels and heat pumps are extremely carbon-efficient means of generating electricity and converting electricity to heat. A single installer, operating where otherwise installations would not take place, can make a major cumulative impact over the nine-year period studied. This is in large part because the emissions reduction effect is cumulative: PV systems and heat pumps continue to abate emissions beyond their year of installation.

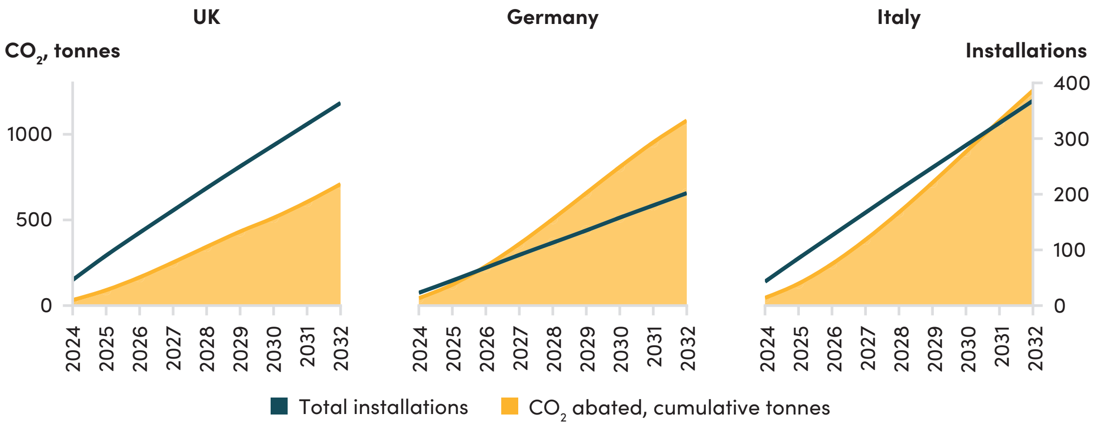
In Figure 2 we show emissions reductions, in tonnes of carbon dioxide, achieved by a marginal electrician facilitating the installation of rooftop residential solar systems (with a rising proportion of installations also including batteries). The anticipated number of installations over the time period varies, and is particularly affected by labour utilisation rates, the prevalence of batteries, the size of PV systems, and the prevalence of retrofit installations versus new-builds. In Germany, an electrician is projected to install 202 solar systems over the 2024–2032 period; in Italy and the UK, more than 360 are projected to be installed.

Large decarbonisation gains are projected in all countries: nearly 700 tonnes CO_2 in the UK, rising to over 1,000 tonnes in Germany and 1,200 tonnes in Italy. These figures assume that countries' stated grid decarbonisation targets are achieved, and thus that the carbon intensity of electricity displaced by solar PV additions is falling. (For this reason, abatement figures for the UK, which has highly ambitious decarbonisation goals, are relatively low for solar PV.) In the scenario modelled with goals only 75 percent achieved, grid carbon intensity is higher, and the abatement effect is therefore also higher. In this scenario over 1,400tCO_2 is abated in Italy.

FIGURE 2. The climate contribution of a marginal electrician

CO_2 emissions reduction contribution of an electrician installing residential rooftop solar PV

Decarbonisation scenario: Goals achieved ▼



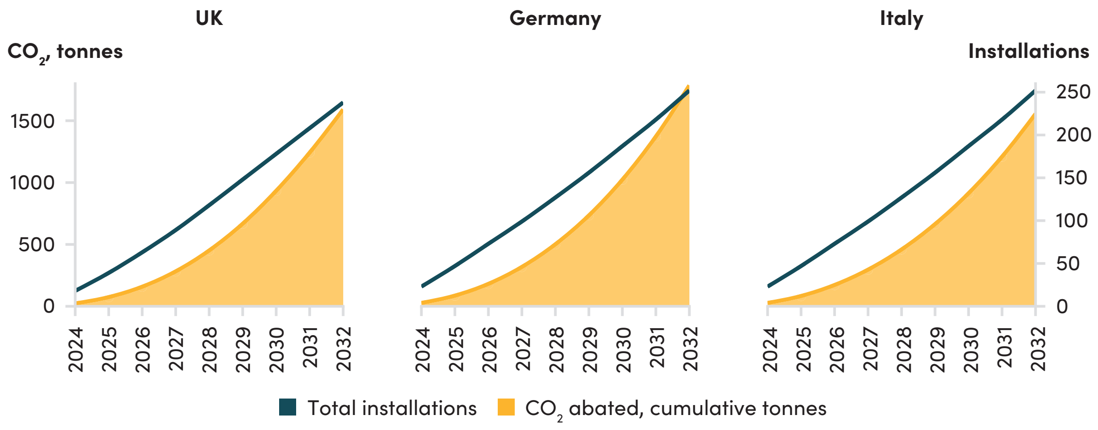
Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

Figure 3 shows emissions reductions achieved through heat pump installations. We conservatively assume the installation of new high-efficiency condensing gas boilers (rather than continued use of older low-efficiency boilers) as our counterfactual: despite this, the high carbon emissions of gas as a heat source, and the much higher efficiency of heat pumps, mean that heat pumps are still better for abatement than solar PV systems. In every country, the marginal worker's labour contributes over 1,500tCO_2 of abatement. Because they draw electricity from the grid, they become more efficient as system-wide decarbonisation continues. In the scenario in which grid decarbonisation targets are only 75 percent achieved, contrasting with solar panels, heat pumps' abatement contributions fall.

FIGURE 3. Emissions reductions through heat pump installation

CO_2 emissions reduction contribution of an HVAC technician installing heat pumps

Decarbonisation scenario: Goals achieved ▼



Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

At a certain point there will be a plateau effect as installed units come offline and must be replaced; for both solar PV and heat pumps, this occurs well after the period of study.

Why speed matters: 'Additional' vs. 'acceleratory' workers

Our base modelling scenario assumes that the marginal worker is *fully additional* throughout the period of study: the installations are assumed not to have otherwise been undertaken at all in the timeframe studied in the worker's absence. In this scenario, there is a persistent workforce bottleneck from 2024–2032. This seems a reasonable expectation given how much demand for workers is expected to grow, and given that labour supply is already widely reported to be a bottleneck. The width of the margin within which a worker can maximally contribute, without detrimentally competing with other workers, is projected to be large.

This marginal worker could be a migrant, but could also be a domestic worker. For the purposes of migration policy-setting coherent with decarbonisation policy, it will be important to assess whether migrant workers are needed to fill gaps, and how important a contribution they might make in complementing the domestic workforce in different labour supply scenarios.

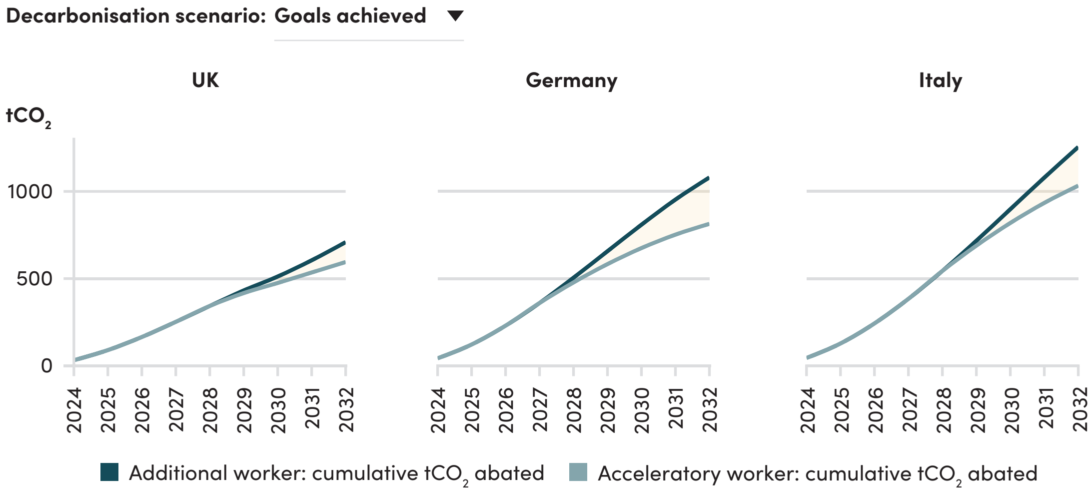
If domestic labour supply can rapidly ramp up in response to demand stimulated by the green transition, the contribution of a marginal migrant worker might be reduced. In a scenario in which demand is outstripped by supply, they could end up competing with domestic workers, rather than complementing them. In this case, their carbon emissions reduction contribution would be limited. As noted previously, this is far from the current situation and far from what is expected.

In a second scenario, we therefore model for an "acceleratory" worker. We assume that the (migrant) marginal worker's presence *brings forward*—accelerates—installations that would otherwise have taken place later, after domestic workforce supply responded successfully, but still with an unavoidable delay, to demand. We do this conservatively and simplistically: we assume governments initiated large-scale apprenticeship intakes in 2024 with high throughput, such that *all the workers that will be needed* begin to be trained, completing their apprenticeship the typical amount of time later. (In Germany an apprenticeship typically takes 3.5 years; in Italy and the UK it generally takes around four.)

In the "acceleratory" scenario, we show the contribution if the introduction of a migrant marginal worker brings installations forward by at 3.5 years or slightly more. We "cap" emissions reductions from installations at the end of this period, recognising that by then the new domestic pipeline would have caught up. For the years of the apprenticeship periods the "additional" (base) and "acceleratory" workers are the same, diverging after.

In Figure 4 we show this scenario for electricians installing solar PV systems. Despite the cap on the effectiveness of installations, the abatement contribution is still significant even if broader decarbonisation goals are achieved. In the UK an "acceleratory" worker still abates nearly 600 tCO_2, in Germany over 800 tCO_2, and in Italy more than 1,000 tCO_2 over the period.

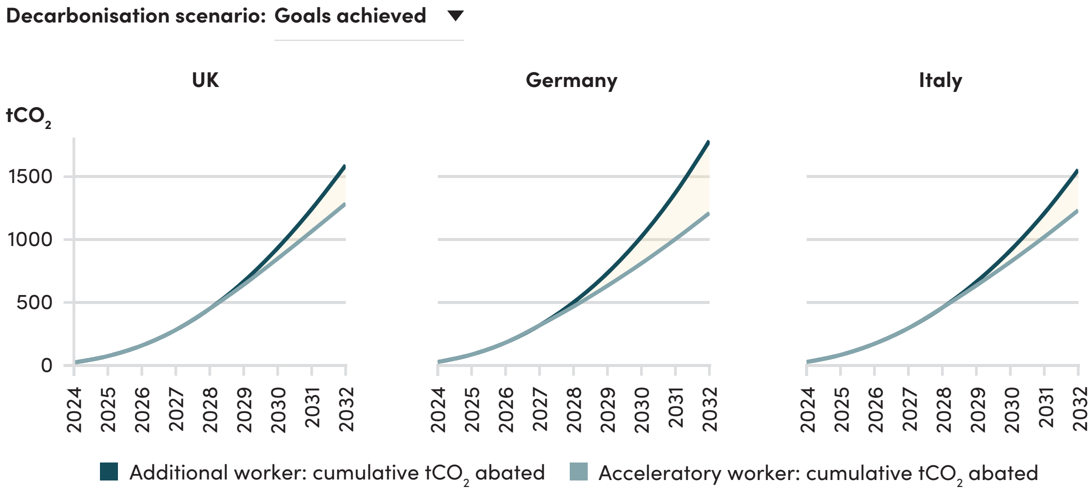
FIGURE 4. Solar PV: Additional vs. acceleratory worker



Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

In Figure 5 we show the "acceleratory" scenario for heat pump installers. For all countries, the 'acceleratory' worker still contributes over 1,200tCO_2 of abatement.

FIGURE 5. Heat pumps: Additional vs. acceleratory worker



Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

These results suggest that even where migrant workers are only anticipated to be needed in the short term while the domestic labour supply scales up to meet policy-driven demand, their contributions are sufficiently significant that the avoidance of workforce-related bottlenecks should be a priority.

The need for care: Ensuring net emissions reduction

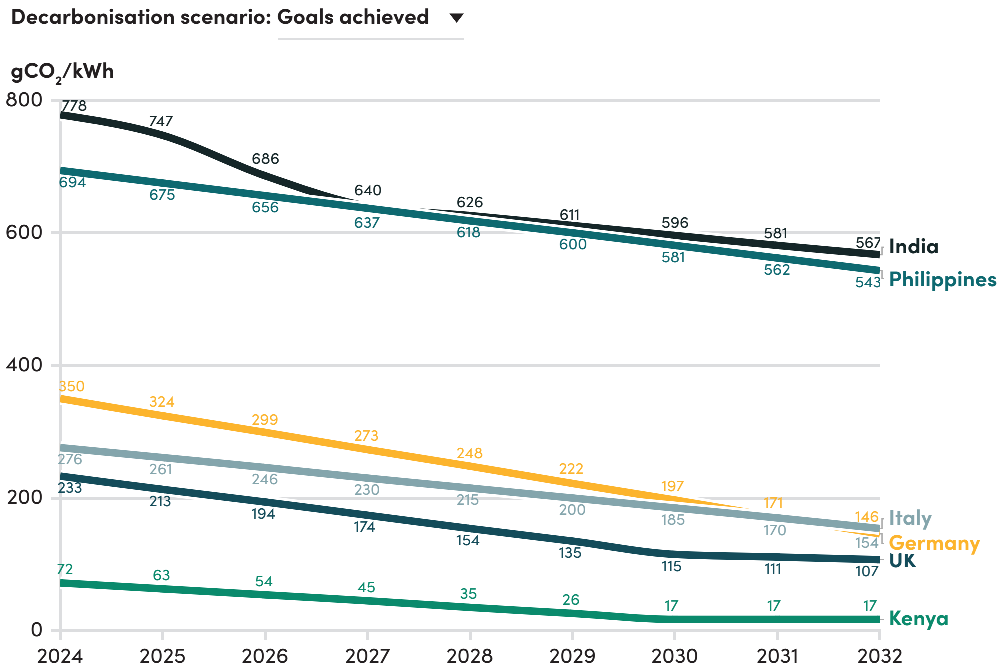
Grid carbon intensities (the amount of carbon emitted with ever kilowatt-hour of electricity generation) vary significantly across countries. This is potentially significant when seeking to maximise the net decarbonisation impact of labour reallocation. A migrant worker contributing marginal labour can evidently make a large impact for decarbonisation in a country of destination; but if that impact would have been larger in their country of origin, their relocation will have a net negative effect on carbon reduction.

To explore this we compare the decarbonisation impact of marginal labour across countries of destination and origin. We use grid carbon intensity figures from Ember (2025). These are average emissions factors, used as a proxy for marginal emissions factors in the absence of adequate data. (This may either overstate or understate decarbonisation contributions depending on the technology and country.) We project future emissions factors on the basis of declared country decarbonisation goals, also projecting partial (75 percent) achievement of stated goals.

Of the six countries, Kenya has the lowest grid carbon intensity in 2024, in large part due to high generation from geothermal, hydropower, and other renewable sources. India has the highest, followed by the Philippines, each emitting two or more times the gCO_2/kWh of the UK, Germany, and Italy.

Figure 6 shows projected average grid carbon intensity from 2024–2032.

FIGURE 6. Grid carbon intensity, 2024–2032



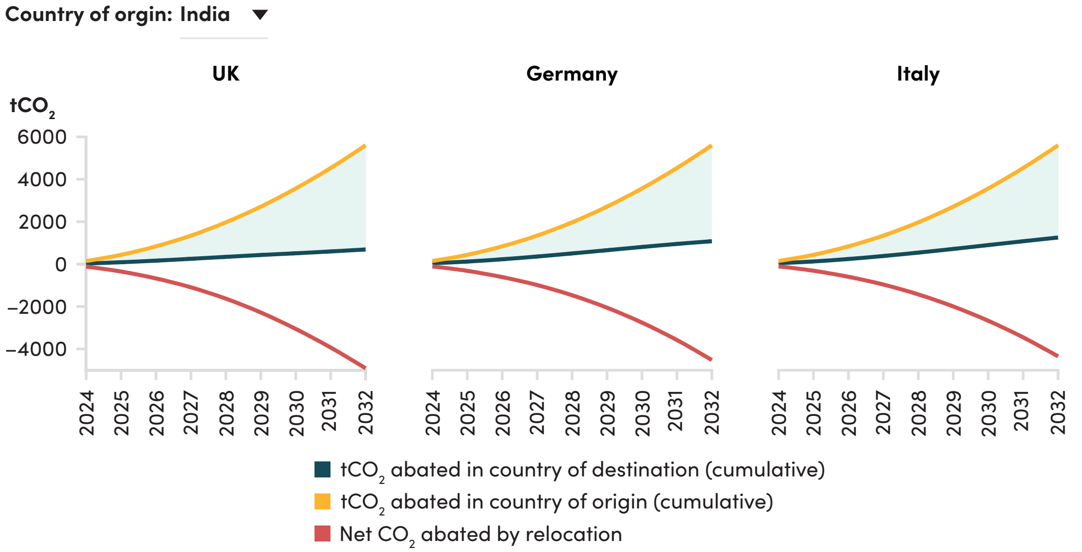
Sources: Decarbonisation targets are derived from national commitments. Carbon intensity is derived from Ember (2025) constituted from energy-source emissions by proportion of generation for use in modelling. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

The wide variance in grid carbon intensity results in corresponding variance in the abatement impact of technologies lowering carbon emissions. Each solar panel installed in India will, if it displaces grid-drawn electricity, have a much greater carbon emissions reduction effect than one installed in the UK.

Countries of origin, as noted earlier, also face workforce shortages. This can potentially pose a problem. If a migrant worker is equally marginal in both the country of origin and the country of destination, the discrepancy in grid carbon intensity may mean that, even if we assume lower productivity and installation rates in the country of origin, their abatement contribution would be much larger remaining in place rather than moving to fill a bottleneck role in a high-income country facing a workforce crisis.

In Figure 7 we show the difference between the carbon emissions reduction contribution made by a marginal worker in countries of destination and countries of origin. In Kenya, where solar installations are predominantly off-grid and are estimated to displace around 430kgCO_2 per year (GOGLA, 2025), there is little risk of a net carbon deficit (although care still needs to be taken to avoid harming energy access goals). In India and the Philippines, by contrast, the departure of a migrant worker that is equally marginal in both country of origin and country of destination could leave an abatement gap of 4–5,000tCO_2 by 2032.

FIGURE 7. The potential penalty of moving a marginal solar PV installer

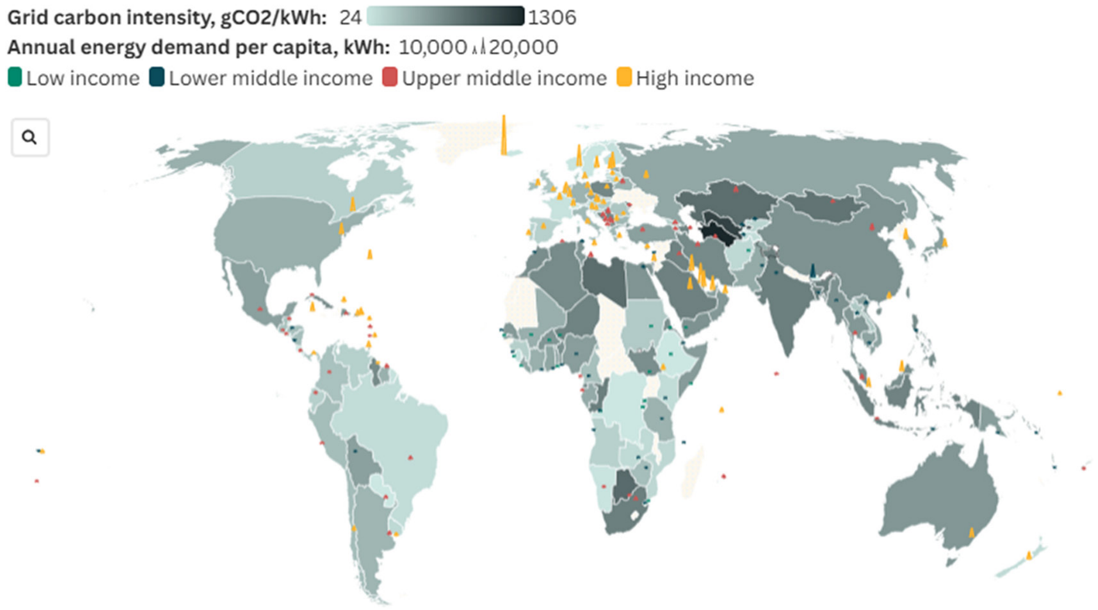


Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

This does not mean that labour migration of electricians and other workers from these countries should be ruled out. It does, however, mean that attention must be paid to ensuring that countries of origin are not left without necessary workers.

Figure 8 shows grid carbon intensity and energy demand per capita in 2023. Many potential migrant countries of origin, such as Morocco, Egypt, India, or the Philippines, have grid carbon intensity multiple times higher than most—but not all—potential countries of destination.

FIGURE 8. Grid carbon intensity and energy demand per capita, 2023



Source: Ember (2025). Note that this is a static version of an interactive graphic. The full map can be accessed on the CGD website.

Recruitment from countries of origin with high carbon intensity of energy generation should be handled with particular care. They may have surplus or underemployed workers, but where they don't, training support by the country of destination may be needed to ensure that recruitment does not leave an abatement deficit. Equally, recruitment from countries with low energy provision per capita, in need of expanded clean electricity access, should also be undertaken carefully to avoid negative development outcomes.

A forest per worker: Comparing the marginal worker's contribution to other benchmarks

To place the contribution of a marginal "bottleneck" worker in context, we compare their abatement contribution to the number of trees that would need to be planted to capture the equivalent amount of carbon emissions avoided. We use figures from the UK's Woodland Carbon Code (UK Forestry

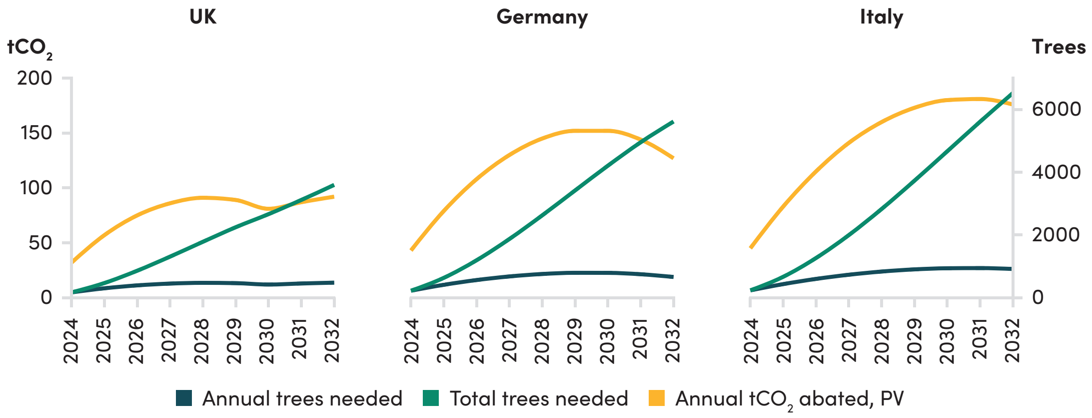
Commission, 2025), and assume the planting of new native woodland for a 50-year lifespan (West, 2024)—the accounting lifespan most relevant to decarbonisation timeframes. Because sequestration is vulnerable to reversal (a tree might later be burnt or rot), this comparison is only illustrative: direct abatement should be prioritised over offsetting (Axelsson et al., 2024).

Figure 9 shows the equivalent value in tree-planting of a marginal solar PV electrician's work. In the UK, installations undertaken during the period 2024–2032 would have the equivalent decarbonisation contribution of planting over 3,500 trees; in Italy, it would be the equivalent of more than 6,500. In India and the Philippines, high grid carbon intensity pushes the equivalent number of trees to nearly 30,000. (Note that as the carbon intensity of displaced grid electricity falls, the *annual* abatement of the stock of installed solar PV systems also plateaus and falls, despite continuing additions.)

FIGURE 9. Tree-planting needed to match solar PV abatement

Trees needed to equal annual and cumulative abatement of a solar PV installer's work

Country category: Country of destination ▼



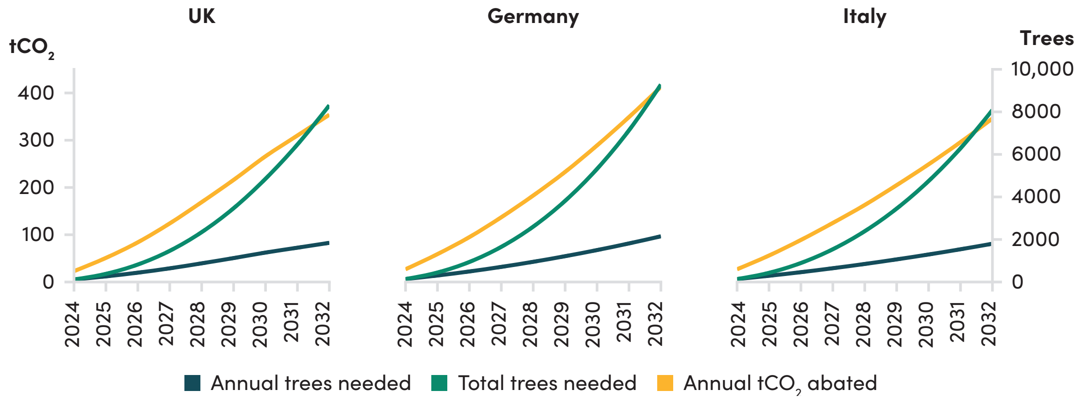
Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

The equivalent figure for heat pumps is larger still, ranging from over 8,000 in Italy to over 9,200 in Germany (Figure 10). (We don't model the country of origin scenario for heat pumps, given that heating technicians in the country of origin are likely to be installing air conditioning units. These may make a valuable adaptation contribution, but would cause emissions rather than contribute to abatement.)

FIGURE 10. Tree-planting needed to match heat pump abatement

Trees needed to equal cumulative abatement of a heat pump installer's work

Goals achieved ▼



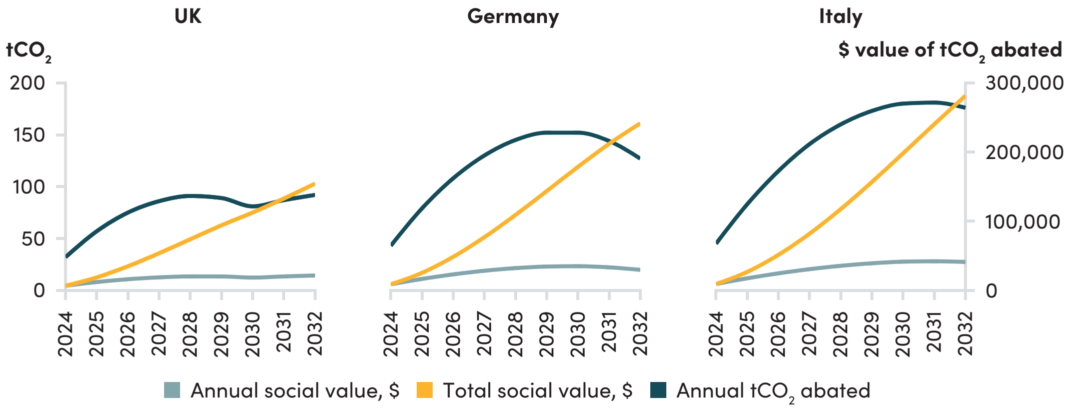
Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

The marginal worker's abatement contribution can also be expressed in monetary terms, using the social cost of carbon (an estimate of the global social value of avoiding the long-term damages from one additional tonne of CO_2). We use the social cost of carbon values used by the US Environmental Protection Agency under the Biden Administration, which calculates a US$190 value in 2020, rising to US$230 in 2030 and US$270 in 2050 (EPA, 2023). These figures suggest significant social value returns from facilitated labour migration to fill bottleneck roles. The work of a marginal electrician installing rooftop solar PV is estimated to have a value of between approximately US$150,000 and US$280,000 in countries of destination, and in excess of US$1.2 million in India and the Philippines (Figure 11). In Kenya, where off-grid solar installations abate roughly 430 $kgCO_2$/year, values are lower.

FIGURE 11. The monetised value of solar PV abatement

Social value (US$) of CO_2 abatement contributed by the work of one marginal electrician installing residential rooftop solar PV

Country of destination ▼



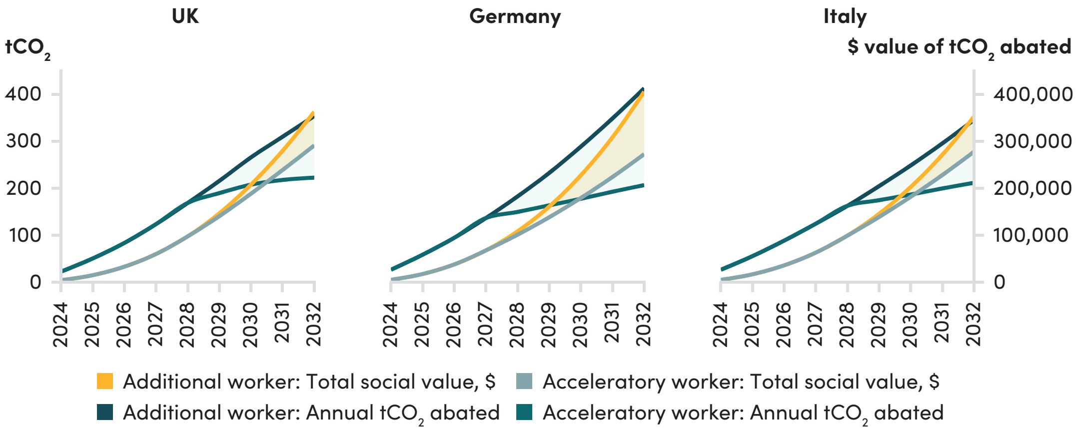
Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

For heat pumps, in line with higher emissions reduction benefits, monetised values are higher. In Figure 12 we show the social value of the marginal heating technician's work, showing how social value varies with decarbonisation and 'acceleratory' versus 'additional' worker scenarios. In a scenario in which decarbonisation goals are achieved, the marginal 'additional' worker's decarbonisation contribution would be valued at more than US$330,000 in each country, rising to over US$400,000 in Germany; the 'acceleratory' worker's contribution would be valued at around US$270,000.

FIGURE 12. The monetised value of heat pump CO_2 abatement

Social value (US$) of CO_2 abatement contributed by the work of one marginal heating technician installing residential heat pumps

Decarbonisation scenario: Goals achieved ▼

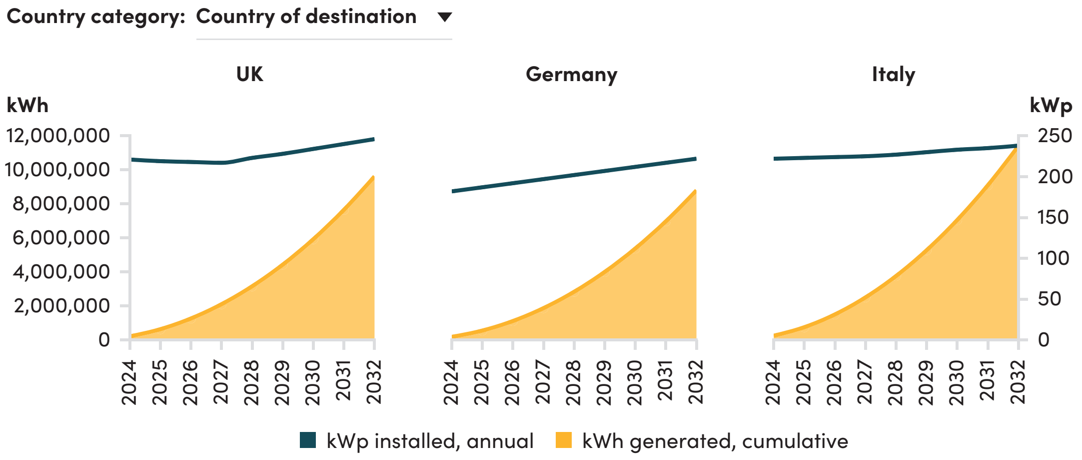


Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

Gas imports reduced, costs avoided: Co-benefits of filling workforce gaps

Carbon abatement contributions are a global public good. However, marginal workers also contribute more local goods, benefiting households directly or contributing to national treasuries. Firstly, there is the benefit of greater energy generation or efficiency. A marginal electrician is estimated to install more than 200 kWp of rooftop solar capacity each year: this generates a total of around 10 million kWh of electricity by 2032, reducing generation needs from other sources.

FIGURE 13. Electricity capacity and generation: A worker's solar PV installations

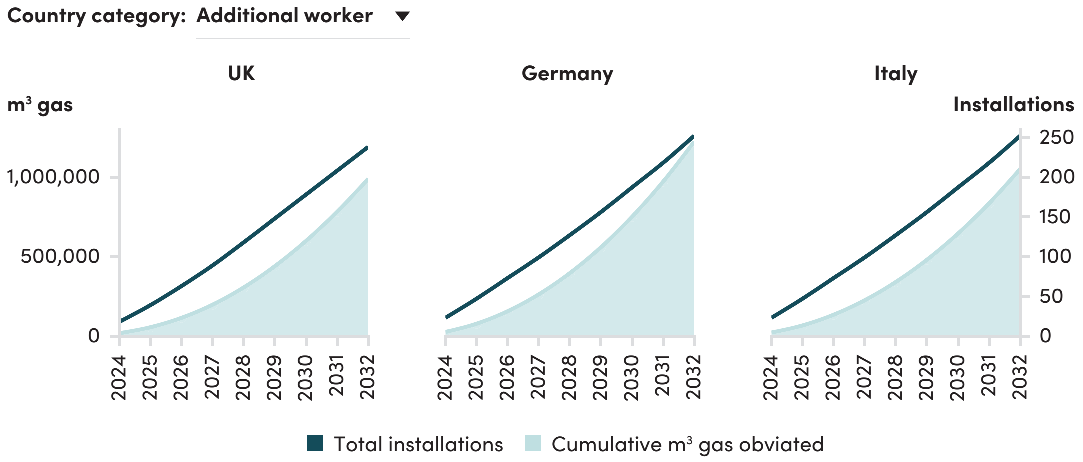


Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

In the context of persistently higher electricity prices due to supply chain and geopolitical disruptions (Bolton, 2025b; Eurostat, 2025), rooftop solar PV installations can, with appropriate financing support, save household consumers money (e.g. DESNZ, 2025d).

Heat pumps can also save consumers money, if installed within the right policy setting (see e.g. Sissons et al., 2025; Harrison, 2025). They will also reduce the amount of gas needed to be produced or imported, a valuable factor in the context of a continuing fragile global liquid natural gas market (see e.g. IEA, 2025). A marginal heating technician is estimated to install a total of around 240 household heat pumps during the period 2024–2032: cumulatively, this obviates the need for around 1 million m^3 of gas in the UK and Italy, and more than 1.2 million m^3 in Germany.

FIGURE 14. Gas saved by a worker's heat pump installations, m^3



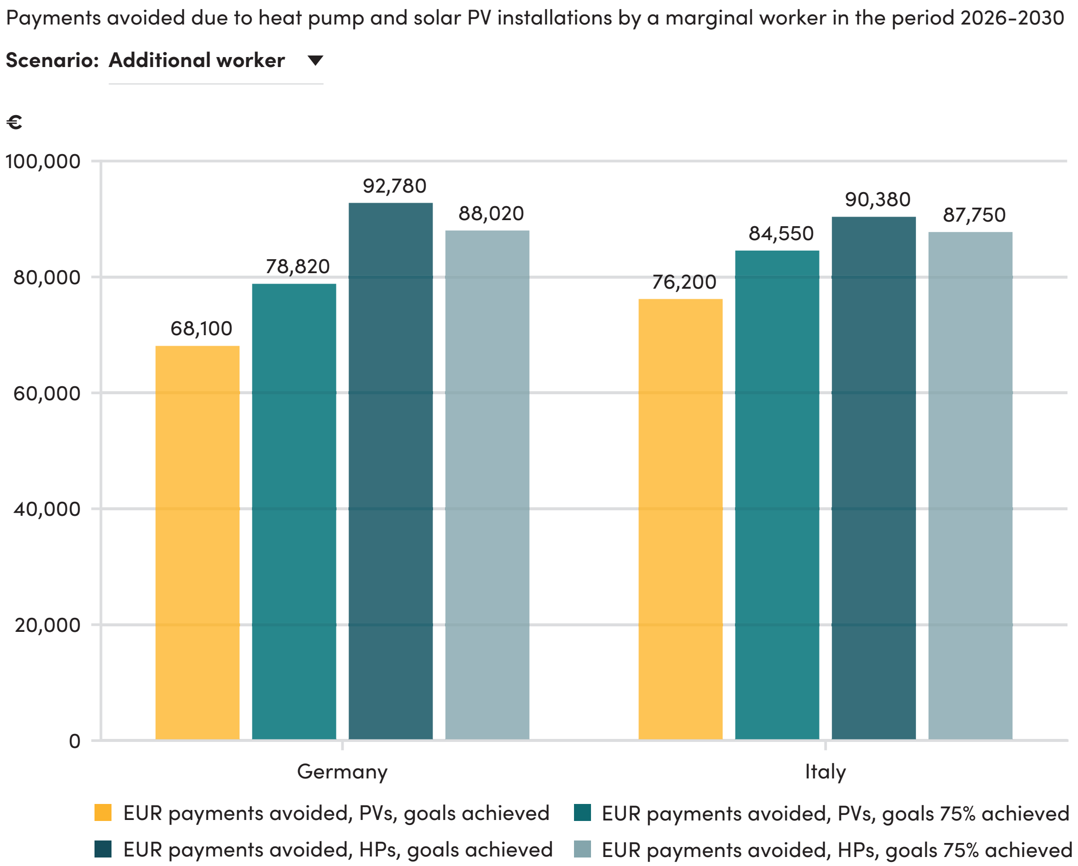
Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

For Germany and Italy, which are under the EU's legally binding Effort Sharing Regulation, there is potentially a direct financial incentive to ensure that a shortage of "bottleneck" workers does not lead to breached emissions pledges. For each tonne of CO_2 emitted over an agreed ceiling set under the Effort Sharing Regulation, EU Member States must purchase an Annual Emissions Allocation (AEAs) from another Member State that has a surplus, within a restricted market (European Commission, 2023). (Funds from sales are expected to be used nationally for climate-related purposes; it is not clear what will happen if no other Member States have sufficient sellable AEAs.) Both Italy and Germany are projected to heavily overshoot their limits under the Climate Change Regulation, with an estimated combined 246 Mt CO_2e deficit for 2021–2030 (Transport and Environment, 2024). (Germany alone is expected to have a deficit of 226 Mt CO_2e (Umwelt Bundesamt, 2025).)

There is no transparent market price for AEAs. Proxies derived from prices in related EU carbon markets are often used, and suggest that an AEA could be priced at around EUR 122 (US$143) by 2030, with an anticipated average value of EUR 99 (US$116) for the period 2027–2030 (BloombergNEF, 2025). Germany and Italy would need to buy AEAs in or ahead of the 2032/33 compliance window for excess carbon emitted during the mechanism's 2026–2030 accounting period.

During the 2026–2030 accounting period, the emissions abatements enabled by a marginal worker would, at an EUR 99 AEA value, total well over EUR 60,000 (US$69,000) in both Germany and Italy (Figure 15). This is the cost both countries would need to pay for additional emissions that could, if labour shortages are a limiting factor, be abated with the addition of workers. Where labour bottlenecks are preventing carbon-reducing installations, both countries therefore have a clear direct fiscal incentive to fill roles, including through the use of targeted labour migration.

FIGURE 15. Effort Sharing Regulation payments avoided



Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

The amounts calculated to be saved are likely to be many times greater than the costs of international recruitment, even where training or similar support is provided to the country of origin. If this is the case, coherency across policy areas and cost centres becomes still more important to realise both abatement opportunities and savings.

Carbon emissions resulting from migration do not pose a risk

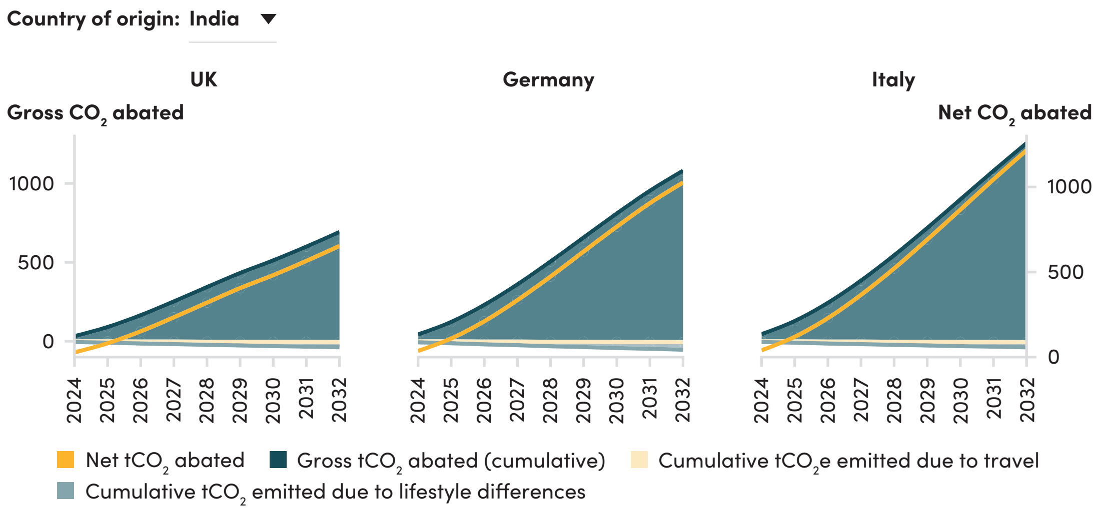
Migration is not without carbon costs in its own right. International air travel is estimated to emit around 150gCO_2e per kilometre (Ritchie, 2023). We compare workers' decarbonisation contributions with the carbon cost of their relocation, using estimates of travel-related CO_2 emissions produced by the International Civil Aviation Organization. We adapt these CO_2 figures to account for additional heating effects caused by other factors, prominently radiative forcing, following a methodology developed by the UK's Department for Transport (DfT, 2024). We assume that a migrant worker visits their country of origin every two years.

We also calculate the increased carbon emissions caused by lifestyle differences between countries of origin and countries of destination. To do this, we take adjusted net differences between per capita emissions, also incorporating emissions embodied in trade.

The carbon costs of migration are not insignificant. A migrant from the Philippines to the UK, for example, would cause emissions of over 1.6tCO_2e in their initial outbound flight, while lifestyle emissions would also be estimated to go up by around 5tCO_2 per year.

In the context of the marginal worker's decarbonisation contribution, however, the carbon costs of migration are far outweighed. Even in the UK, where the targeted grid decarbonisation trajectory limits the abatement contribution of the marginal solar installation, the carbon costs of migration still equal less than 10 percent of a marginal migrant installer's abatement. In Italy, against 1,255tCO_2 abated by a solar PV installer, the net abatement across the period of an installer moving from India would be 1,216 tonnes (Figure 16).

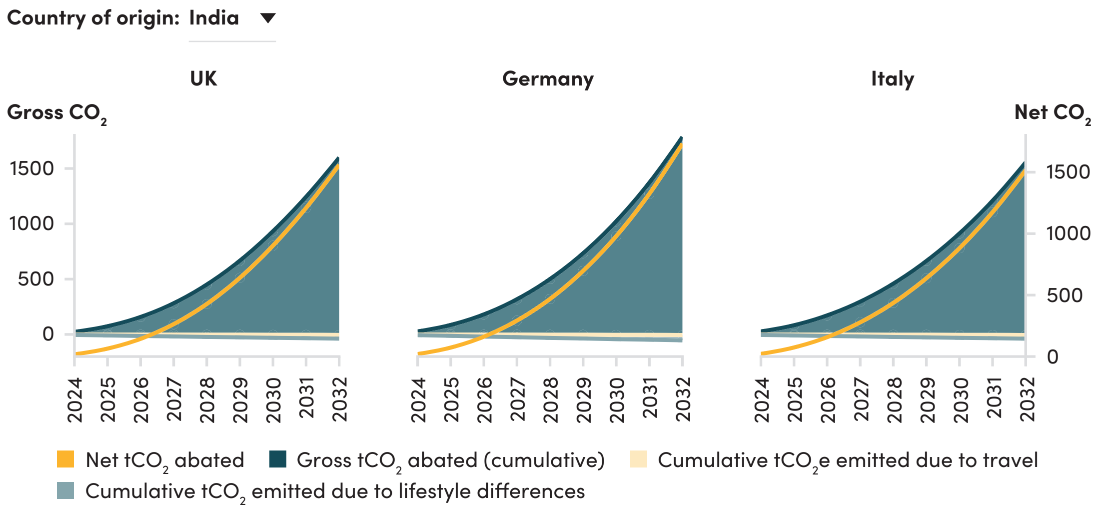
FIGURE 16. CO_2 abatement of solar PV installation, net migration emissions



Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

Unsurprisingly, the abatement contribution of a heat pump installer net of migration carbon costs is still greater. In the context of 1,500–1,700 tCO_2 abated, 30 to 60 tonnes due to migration are almost a rounding error (Figure 17).

FIGURE 17. CO_2 abatement by a heat pump installer, net migration emissions



Note: For modelling assumptions and data sources, please see the explanation in the methodology. Note that this is a static version of an interactive graphic. The full chart can be accessed on the CGD website.

Implications for labour migration policy

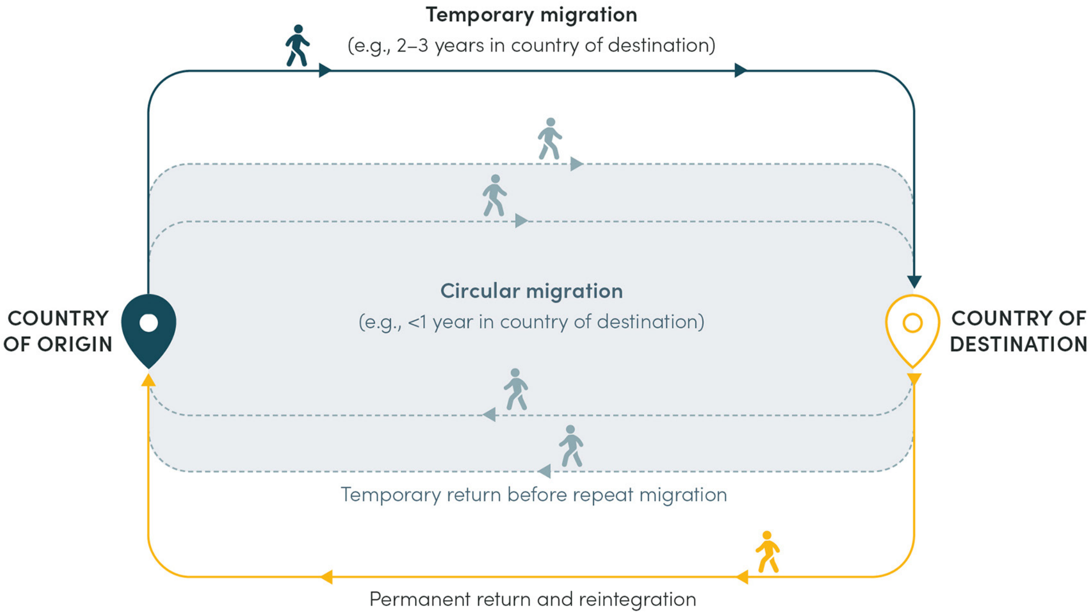
Given the decarbonisation contribution that can be made by qualified workers in contexts of labour shortage, better mechanisms for increasing supply and effectively allocating it to areas of high demand are crucial. Labour migration will have a crucial role to play in supplying the workforce needed at the margins. At the same time, as noted, the possibility of contributing to a global public *bad* means that multiple migration models need to be considered. We provide four non-mutually exclusive options.

Option 1: Recruit as normal

Some countries of origin may have surplus workers who, if remaining in situ, would be underemployed or unemployed. In these cases, international labour migration can allow them to be reallocated to locations in which they can contribute more productively. This may be because a country of origin has an overly-scaled training pipeline; because it suffers an economic downturn, leading projects to be cancelled and workers to be freed up; because it hosts a skilled refugee population unable to contribute due to lack of work rights; or because its fossil sectors scale down before green sectors scale up, leaving workers with transferable skills underemployed. Where this is the case, international recruitment can take place as normal without the need for fears of a decarbonisation gap being left in the country of origin. This is not expected, however, to be the normal scenario.

These workers could be recruited into temporary visas, in which they remain in the country of destination for a fixed period of time (for example, 3 years) before returning to the country of origin (Figure 18). In some cases, where jobs are not in demand year-round, a circular model (in which workers repeatedly migrate to the country of destination before returning) may be suitable, but in decarbonisation-related sectors this is likely to be rare. Fixed-term migration can usefully respond to limited-duration surges in tasks due to policy interventions, or can fill non-structural workforce gaps while domestic training ramps up. It may have the advantage of providing workers with increased skills or employment to high-demand decarbonisation in countries of destination before they return to assist growing clean growth in countries of origin. In some contexts, it may also be more politically palatable than longer-term migration. On the other hand, shorter-term migration may also be less attractive to employers in the country of destination. In some contexts, migration with a path to permanency will be both politically acceptable and structurally necessary.

FIGURE 18. Fixed-term migration model



Source: Dempster and Huckstep (2024).

Option 2: Recruit into apprenticeships

Many countries, such as the UK (Huckstep and Dempster, 2025), are struggling to increase the provision of domestic training: they may even have excess demand for training unmatched by supply. In Germany, however, a confluence of factors means that there are tens of thousands of apprenticeships unfilled by domestic workforce entrants (Bundesagentur für Arbeit, 2024a).

Where country of destination training capacity persistently outstrips local demand, unfilled apprenticeships can be filled by international youth assisted in accessing migration pathways. This is a model that is already being tested in Germany by organisations including the employer association Bauverbande (Schneider, 2023), the Nepal Secretariat of Skills and Training (NSST, 2025), an educational body, and the non-government organisation Malengo (Malengo, 2025).

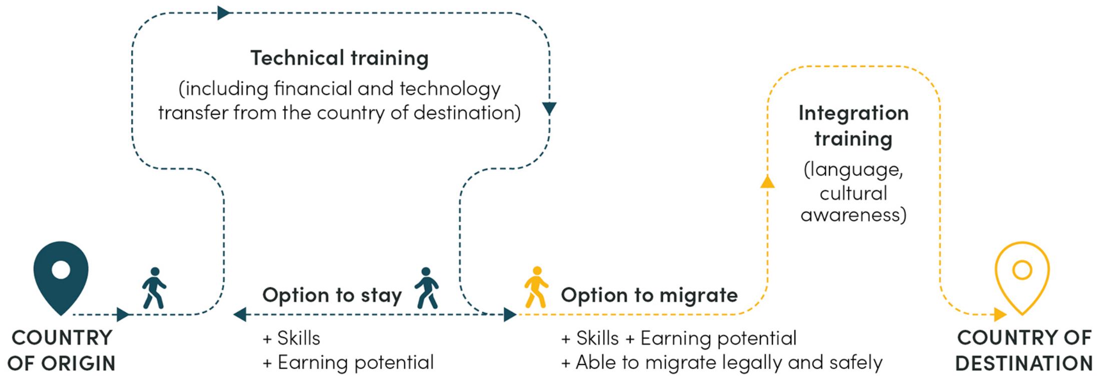
This approach fills labour market gaps in the country of destination, and does not risk leaving the country of origin with skill gaps: participants moving internationally are not yet skilled, and receive training in the country of destination. It is likely that Germany, with an apprenticeship system with excess capacity, is a rare case, although similar dynamics on a much smaller scale are also reported in Austria (BMWET, 2024) and Switzerland (News Service Bund, 2024).

Option 3: Global Skill Partnerships

Where both the country of destination and a potential country of origin have predictable labour shortages in the same occupations, programmes that pair training and migration—including models such as the Global Skill Partnership—can be valuable. The Global Skill Partnership model (Figure 19) sees the country of destination provide technology and finance to train a cohort of workers in the country of origin, before part of the cohort is supported in migrating. The model allows the country of destination access to a reliable and predictable pipeline of workers trained to the standards needed, reducing risks related to credential recognition problems.

The model also obviates the risk of skill gaps left in the country of origin causing a decarbonisation deficit. Instead, because of the partial-cohort migration outcome, the total stock of skilled workers is increased in both countries. This "dual track" system is the defining characteristic of the Global Skill Partnership model.

FIGURE 19. Global Skill Partnership model



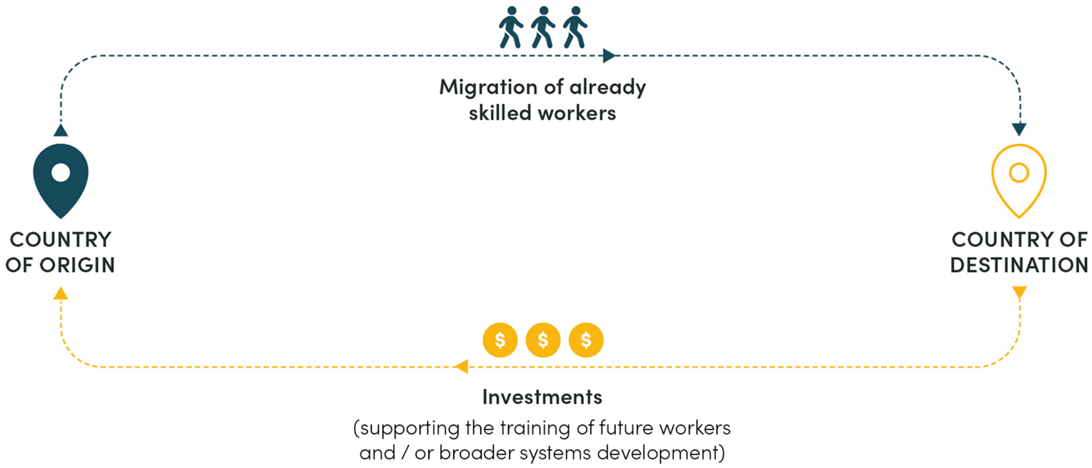
Source: Dempster and Huckstep (2024).

Option 4: Recruitment with parallel investments

In some cases, countries of origin may not face labour-related bottlenecks –they may have sufficient workers already trained, or have adequate training pipelines in place to replace emigrating workers—but may require other forms of support. In a final migration model, the country of destination expands the migration of pre-trained workers while also providing investments to the country of origin to support future training or the development of broader systems. These investments could, for example, be in labour market intelligence, the quality of training facilities, or necessary equipment for post-training activities.

This model (Figure 20) could be applicable for contexts in which a Global Skill Partnership is not suitable, possibly because establishing one would be too expensive or time-consuming, or because skill needs are unaligned. It has the greatest potential when the country of destination has pressing shorter-term skill shortages, and where the country of origin has non-workforce needs with which the country of destination can support. In this way a partnership could benefit both countries in their clean energy transition.

FIGURE 20. Parallel Investments model



Source: Dempster and Huckstep (2024).

BOX 1. Supporting training for international labour markets

Recognition of qualifications remains a persistent challenge to international reallocation of workers. Given the decarbonisation contribution that can be made by qualified marginal workers, it is crucial workers can easily reallocate to areas facing decarbonisation workforce bottlenecks. For this reason, countries of destination have a strong reason to support the training of workers in countries of origin *for international labour markets*, creating a pool of skilled workers able to access international mobility to contribute to decarbonisation where needed.

Countries of destination can benefit from a sure supply of workers—a form of insurance against labour supply shortfalls—but trained workers could also remain in the country of origin to support electricity access and/or emissions reduction, *or move elsewhere* to an area of high demand. Training investments with international standards are thus an investment into the broader decarbonisation ecosystem.

This is a relatively new model, but one that is already starting to see adoption. Australia is partnering with India to expand solar PV workforce availability, training 2,000 solar technicians to international standards through the 2024 India-Australia Renewable Energy Partnership. The partnership is expected to support Australian needs while also providing "a talent pool for roles across the world" (DCCEEW, 2024). Similar partnerships could be sought by other countries of destination.

A push towards globally recognised standards is also championed by industry bodies. The Global Solar Council, in partnership with the Global Wind Organisation, has created the Global Solar Training Standards Initiative (Rossi et al., 2025). Released in July 2025, the standards are intended to provide standardised training modules allowing training providers to equip workers with universally trustworthy skillsets that can be transferred across contexts. Thus far, the effort has focused on utility-scale solar (GWO, 2024); pilots have taken place in the United States, Germany, and the UK (Energy Live News, 2025).

Policy conclusions

The absence of a 'green-skilled' worker can have a large carbon emissions implication at the margin. Ensuring that workforce supply is adequate to the task should therefore be a major policy priority. The domestic workforce should provide the vast majority of the skilled workers needed. But for most countries, training capacity will not scale to the extent needed at the speed needed (see e.g. Hambrecht et al., 2025). Where this is the case, the use of labour migration policy can ensure that workforce gaps do not lead to implementation gaps.

While labour migration is an increasingly difficult area of policy politically, these findings support the use of targeted labour migration to supplement domestic workforce supply. Across high-income countries seeking to decarbonise rapidly, the thousands of migrant workers needed to fill labour gaps are likely, on the basis of this paper's modelling, to contribute to the abatement of millions of tonnes of CO_2.

Several policy conclusions can be derived.

Where domestic labour pipelines alone cannot meet needs, international recruitment should be facilitated. From a carbon emissions reduction standpoint, labour migration is not a tool that can be set aside. This requires coherency between reliable green industrial policy, workforce development policy, and immigration policy, informed by strong labour market intelligence.

International recruitment must be conducted with care to ensure that it does not leave decarbonisation gaps in countries of origin. Because of differences in grid decarbonisation levels, a worker can often make a greater contribution at the margin in a country of origin than a country of destination. Because the climate is a global public good, this recruitment would therefore be harmful to the country of destination.

Underemployed workers should be targeted for recruitment. Many workers will not be equally marginal in countries of origin and destination: international recruitment will often not leave a gap. Partnerships can be agreed with countries with surplus pre-trained populations. Equally, some populations, such as refugees unable to work in host countries, may have necessary skills but be unable to use them (see Dempster et al., 2025). Recruiting under- or unemployed workers will maximise the net decarbonisation gain from workforce reallocation.

Training and migration partnerships with countries of origin can mitigate risks. Partnerships that increase the total stock of workers before helping some to move to where they're needed can benefit both destination and origin countries. For the country of destination, such a partnership can serve as a form of insurance and as a contribution to broader decarbonisation. If they do need workers, they have a known supply whose training they have ensured is to the standard required. If they do not, the workers can go where they are needed: in the green transition they are unlikely to go unemployed. This is a model being tested by Australia in partnership with India.

Given the value of a marginal skilled worker, training and migration partnerships are a good use of climate finance. Without skilled workers, decarbonisation cannot happen. An individual's abatement contributions can run into thousands of tonnes of CO_2: preventing workforce bottlenecks is a good use of climate finance.

Harmonise curricula and qualification recognition procedures to facilitate workforce mobility. International reallocation of workers to countries with skill bottlenecks is crucial for decarbonisation. Difficulties in recognising training standards, however, frequently delay or derail mobility. Harmonisation of curricula to international standards and improvements to credential recognition should be priorities for standard-setting and recognition bodies at the international and national levels. Mutual recognition or service level agreements and overseas assessment partnerships could help at the bilateral level.

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Methodology

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Methodology: Solar panel installation abatement

Our primary scenario is of a worker installing residential rooftop solar photovoltaic systems, whose presence in the country of destination labour market is wholly additional throughout the period of study: they are performing work that would otherwise not have been done. The range of factors considered is shown in Table 1.

TABLE 1. Modelling factors in solar PV installations

Embodied Emissions Factors	Solar PV Operational Factors	Battery Operational Factors	Installation Factors	Decarbonisation
PV embodied carbon (kg/kWp/year)	Solar system kWp average	Battery prevalence	Working days per year	Grid electricity gCO_2/kWh: decarbonisation goals achieved and 75 percent achieved
Battery embodied carbon (kg/kWp/year)	kWh/kWp·yr capacity (yield)	Electricity round-trip rate	Hours/kWp: new build and retrofit rates	
Decrease rate of embodied carbon (batteries)	Degradation rate	Efficiency rate (electricity lost during round-trip)	New build vs. retrofit prevalence	
Decrease rate of embodied carbon (solar PV)	Generation (kWh/yr)	Battery size (kWh)	Learning rates: battery and solar PV	
	Export curtailment rate		Hours/kWh: battery installation rate, DC and AC	
	Rebound rate		Labour utilisation rate	

Formulae: ‘Additional worker’ scenario

We use the following formulae to calculate abated emissions, with values following the assumptions set out in the subsequent sections.

Annual displaced electricity per installation

$$D_y = C_y \cdot Y \cdot \phi_y$$

With

$$O_y = G_y \cdot (\theta_y^{bat} \cdot f_y^{bat}) \cdot \eta^{rt}$$

$$Q_y = G_y \cdot (1 - \theta_y^{bat} \cdot f_y^{bat}) \cdot (1 - \gamma)$$

Such that

$$\phi_y = \frac{O_y + Q_y}{G_y}$$

- D_y: Displaced kWh per new system in year y.
- ϕ_y: Effective displacement factor
- O_y, Q_y: kWh used via batteries, via export
- $G_y = C_y \cdot Y$: Gross annual generation.
- Factors: battery share (θ_y^{bat}), battery round-trip efficiency (η^{rt}), curtailment (γ), rebound (ρ), share of a system's generation routed via battery (f_y^{bat}).

Installation time per system

$$t_y^{tot} = \frac{\left(\sigma_y^{new} h_y^{new} + \sigma_y^{retro} h_y^{retro}\right) \cdot C_y}{8} + \frac{\left(\sigma_y^{new} h_y^{bat,DC} + \sigma_y^{retro} h_y^{bat,AC}\right)}{8} \cdot \theta_y^{bat}$$

- PV time (first term) + battery time (second term).
- $h_y^{new}, h_y^{retro}, h_y^{bat}$ decline each year by fixed rates to embed learning.

Installations and capacity added

$$I_y = \frac{W}{t_y^{tot}} \cdot u_y$$

$$C_y^{add} = I_y \cdot C_y$$

$$C_y^{cum} = \sum_{k=1}^{y} C_k^{add}$$

- I_y: Systems installed per worker in year y.
- W: Working days per year.
- u_y: Worker utilisation rate.
- C_y^{add}, C_y^{cum}: New and cumulative capacity.

Cohort-corrected displaced electricity

$$E_y^{disp} = \sum_{k=1}^{y} (C_k^{add} \cdot Y \cdot (1-d)^{(y-k)} \cdot \phi_k$$

- E_y^{disp}: Displaced electricity in year y, adjusted for degradation and using each cohort's own effective displacement factor.
- d: Annual PV degradation rate (set at 0.5 percent).

Net CO_2 abatement

Countries with grid-tied/hybrid PV installations:

$$A_y = \frac{1}{10^6}\sum_{k=1}^{y}(E_y^{disp}\cdot\alpha_k) - \frac{1}{1000}(J_y^{cum}\cdot\epsilon_y)$$

Kenya (off-grid PV installations):

$$A_y = \frac{1}{1000}(J_y^{cum}\cdot K) - \frac{1}{1000}(J_y^{cum}\cdot\epsilon_y)$$

- A_y: Net CO_2 abatement (tonnes) by year y.
- α_k: Grid carbon intensity in cohort k (gCO_2/kWh).
- J_y^{cum}: Cumulative installation-years.
- ϵ_y: Annual embodied emissions per system (kg/yr).
- K: Fixed estimated abatement per system-year in Kenya (431 kg/CO_2/yr).

TABLE 2. Symbols: 'Additional worker' scenario for solar PV modelling

Symbols	Meaning
y	Year of installation (2024…2032)
C_y	PV system capacity per installation (kWp)
Y	Yield per unit capacity (kWh/kWp·yr)
G_y	Gross annual generation (kWh)
O_y, Q_y	kWh used via batteries, via export
f_y^{bat}	Share of a system's generation routed via battery
θ_y^{bat}	Share of installations with batteries
η^{rt}	Battery round-trip efficiency
γ	Export curtailment rate
ρ	Rebound rate
ϕ_y	Effective displacement factor
h_y^{new}, h_y^{retro}	Hours/kWp for new-build and retrofit
$h_y^{bat,DC}, h_y^{bat,AC}$	Hours for DC and AC battery installation
$\sigma_y^{new}, \sigma_y^{retro}$	Shares of new-build vs retrofit installs
t_y^{tot}	Total installation time per system (days)
W	Working days per year
u_y	Working days per year (230)
I_y	Installations completed per worker (per year)
C_y^{add}, C_y^{cum}	Added and cumulative PV capacity (kWh)
E_y^{disp}	Cohort-adjusted displaced electricity
d	Annual degradation rate
α_k	Grid carbon intensity in cohort year k (gCO_2/kWh)
J_y^{cum}	Cumulative installation-years
ϵ_y	Embodied emissions per system (kg/yr)
K	Kenya-specific fixed abatement per system (431 $kgCO_2$/yr)
A_y	Net CO_2 abatement (tonnes)

Formulae: ‘Acceleratory worker’ scenario

In a secondary scenario, we calculate the marginal worker’s contribution with the assumption that domestic labour force supply will catch up with demand during the period of study. For this scenario, we assume perfect catch-up after the amount of time taken to train a new worker via an apprenticeship. This varies between countries:

- **UK:** an apprenticeship to become an installation and maintenance electrician typically takes around 54 months, plus a six-month period of end-point assessment (Skills England, 2025a); we assume an average of 4.5 years.
- **Germany:** an electrician apprenticeship typically takes 3.5 years (Bundesagentur für Arbeit, 2025b).
- **Italy:** an electrician apprenticeship typically takes 3 years for the basic qualification, with a 4th year required to be a responsible technician allowed to certify electrical work (and potentially subsequent years also required, depending on the scale of an installation) (ISPO, 2025). We assume an average length of 4 years.

This is a conservative approach: given that demand is likely to be scaling more rapidly than supply in the approach to 2030, 100 percent catch-up is unlikely.

To do so, we adapt the modelling conducted for the ‘additional worker’ scenario. We designate τ as the amount of time taken to complete an apprenticeship and be able to install solar PV, and impose a τ-year cap on the abatement contribution and embodied carbon amortisation of each installation cohort

Note that our assumption of a fixed τ-year ‘head-start’ window for accelerated installations abstracts from learning: in practice learning rates would mean that a ‘catch-up worker’ entering in year τ would be slightly more productive than a year-1 worker, so full catch-up would occur in a little under τ years. We retain the simple cap for transparency; it is a conservative simplification that will slightly overstate the duration of the acceleratory effect relative to a fully explicit learning model by a few percent per year. Given much larger uncertainties elsewhere in the modelling (such as with regard to policy choices and grid decarbonisation, for example), we do not consider this to be likely to significantly bias results.

For the first τ post-installation years (for $y \le i + (\tau - 1)$), the two scenarios yield identical annual results. Differences only arise when the earliest cohorts become older than τ years:

$$E_y^{add} - E_y^{acc} = \sum_{i \le y-\tau} \left(N_i \cdot d_i \cdot \frac{g_y}{g_i} \right)$$

$$B_y^{add} - B_y^{acc} = 1000 \sum_{i \le y-\tau} (N_i \cdot e_i)$$

The net annual difference is thus

$$A_y^{add} - A_y^{acc} = \frac{\Delta E_y \cdot I_y^{goal,75\ percent} - \Delta B_y}{10^6}$$

Note that because per-worker annual installation volumes are assumed to increase over time due to learning rates, the largest cohorts are those installed towards the end of the period of study. Their τ-year windows extend beyond the end of our modelling horizon, so annual net abatement remains positive in 2032. If the horizon were extended to include the full τ-year windows for final 'accelerated' cohorts, annual net abatement would converge towards zero as the baseline catches up.

Cohort activity window (τ-year cap)

$$1_{i,y}^{(\tau)} = \begin{cases} 1, if\ i \le y \le i + (\tau - 1) \\ 0, otherwise \end{cases}$$

- i, y: cohort year, current year

Annual displaced electricity (kWh) in year y

$$E_t = \sum_{i \le y} (N_i \cdot e_i \cdot 1_{i,y}^{(\tau)})$$

- E_y: annual displaced electricity (acceleratory)
- N_i: Installations completed in cohort i
- e_i: Annualised embodied carbon per addition (cohort i)

Annual embodied-carbon flow (grams CO_2e) in year y

$$B_y = 1000 \cdot \sum_{i \le y} (N_i \cdot e_i \cdot 1_{i,y}^{(\tau)})$$

- B_y: Annual embodied grams CO_2

Annual net abated CO_2 (tonnes) in year y

$$A_y^{goal} = \frac{E_t \cdot I_y^{goal} - B_y}{10^6}$$

$$A_y^{75\ percent} = \frac{E_y \cdot I_y^{75\ percent} - B_y}{10^6}$$

- $I_y^{goal}, I_y^{75\ percent}$: Grid intensity in year y, varying by grid decarbonisation scenario
- A_y^{goal}, $A_y^{75\ percent}$: Annual net abated CO_2 in year y, varying by grid decarbonisation scenario

Cumulative net abated CO_2 (tonnes) to year y

$$C_y^{goal} = \sum_{s=2024}^{y} A_s^{goal}$$

$$C_y^{75\ percent} = \sum_{s=2024}^{y} A_s^{75\ percent}$$

- $C_y^{goal}, C_y^{75\ percent}$: Cumulative net abated CO_2 (tonnes)

TABLE 3. Symbols: 'Acceleratory worker' scenario for solar PV modelling

Symbol	Meaning
τ	Years taken to train as an apprentice
i, y	Cohort year, current year
N_i	Installations completed in cohort *i*
d_i	Displaced electricity per addition
g_y	Cumulative PV yield factor in year *y*
$I_y^{goal}, I_y^{75\ percent}$	Grid intensity in year *y*, grid decarbonisation at goals and 75 percent
e_i	Annualised embodied carbon per addition (cohort *i*)
$1_{i,y}^{(\tau)}$	τ-year activity indicator for cohort *i* in year *y*
E_y	Annual displaced electricity
B_t	Annual embodied grams CO_2
$A_y^{goal}, A_y^{75\ percent}$	Annual net abated CO_2
$C_y^{goal}, C_y^{75\ percent}$	Cumulative net abated CO_2

Installation rates

We assume that each worker will work 230 days per year. This assumes 52 5-day weeks, from which is subtracted 30 days for public holidays and vacations.

The US National Renewable Energy Laboratory (Cook et al., 2023), in an unusually detailed time-and-motion study, finds that retrofit installation of residential rooftop PV typically takes around 6.9 worker-hours per kW and 3.8 worker-hours per kW for new dwellings, with a typical crew size of 2 to 5 workers. In this case, a crew of three workers would take 11.5 hours (1.4 working days) to install a 5 kW solar PV system via retrofit, and 6.3 hours (0.8 working days) to install a 5 kW solar PV system in a new build.

In the absence of country-specific estimates for most countries, we adjust these figures as a basis for calculations. This is an assumption, and actual times will vary across contexts: time per kW is significantly affected by roof type and complexity (e.g. clay tiles versus asphalt shingles; the pitch of the roof; the number of storeys; etc.). It will also be affected by market practices and regulations, such as whether there are burdensome scaffolding safety regulations in place, whether components are pre-assembled, etc.

Speeds elsewhere may be higher. In Germany, installation has previously been estimated to take 4.3 worker-hours per kW (Calhoun et al., 2014): German installers 'are simply able to do each of these discrete activities two to four times faster than any benchmarked U.S. installers', in part due to more favourable architecture and to greater standardisation eliminating most pre-installation work (Morris et al., 2013). In Australia, residential solar PV installations are estimated to take 6.1 hours/kW (Calhoun et al., 2014).

We assume the following installation rates and changes. We assume for all that a three-person team conducts installations, and that the electrician is present throughout.

- **UK:** 7.5 h/kW for retrofits, and 3.9 h/kW for new builds, adapting Cook et al. (2023) to account for more stringent scaffolding regulations (see e.g. HSE, 2025) and more fragmented roofs.
    - We calculate that in 2024 there was a 78 percent/22 percent split between retrofits and new builds (Simkins, 2025 and MCS, 2025b). We assume that this will rise to a 70 percent/30 percent split by 2027 due to 2025 legislation requiring that all new builds have solar panels installed (Pickard, 2025), before falling to 80 percent/20 percent by 2030 and thereafter as the retrofit market grows.
- **Germany:** 4.3 h/kW average (Calhoun et al., 2014).
    - We assume a current split between retrofit and new builds of 95 percent/5 percent remaining stable throughout the period, on the basis that 65 percent of German house owners plan to install solar PV by 2029 (Collins, 2025).
- **Italy:** 6.5 h/kW for retrofits, and 3.9 h/kW for new builds, adapting Cook et al. (2023) to account for greater market development and anticipated standardisation.
    - We assume a current split between retrofit and new builds of 95 percent/5 percent following the retrofit-oriented 'Superbonus' scheme, rising to 90 percent/10 percent to meet 'near-zero emissions buildings' obligations by 2027 (see e.g. Bardi, 2025) and remaining at this level thereafter.
- **India:** 7.1 h/kW average for retrofits and 4.3 h/kW for new builds, adapting Cook et al. (2023) to account for more diverse roof types (Sethi and Kosmopoulos, 2025) and less standardisation.
    - We assume a current split between retrofit and new builds of 97 percent/3 percent due to the incentives of household-level retrofit policies (MNRE, 2024), rising to a 90 percent/10 percent split by 2030 and thereafter with the assumption that integration of solar into new builds will increase.
- **Philippines:** 7.5 h/kW for retrofits, and 4.3 h/kW for new builds, adapting Cook et al. (2023) to assume more varied rooftop architecture (local sources suggest longer installation times, e.g. Solaric, 2025) and less standardisation.
    - We assume a current split between retrofit and new builds of 95 percent/5 percent due to a lack of policy regarding solar PV installation on new builds, rising to a 90 percent/10 percent split by 2030 and thereafter with the assumption that integration of solar into new builds will increase.

- **Kenya:** 7.5 h/kW for retrofits and 4.3 h/kW for new builds, adapting Cook et al. (2023) to account for limited market development and less standardisation.
    - We assume a current split between retrofit and new builds of 98 percent/2 percent in a retrofit-dominated market, rising to a 90 percent/10 percent split by 2030 and thereafter with the assumption that integration of solar into new builds will increase.

Battery installations

Battery installations increase labour time, often significantly. Analysis by NREL (2022) suggests that in the US a 12.5 kWh battery takes an additional 20 worker-hours (typically a crew of a licensed electrician and an assistant) to install if a DC-coupled battery, and 32 additional hours if an AC-coupled battery. In Australia, battery installation is reported to take 1 to 2 days (16–24 worker-hours if a crew of 2) for a standard storage system (5–10 kWh), and “a few days longer” if a large system (CEC, 2019: 19).

Given that little information is available about how installation times scale with battery size, we assume a fixed installation time of 6 h as a floor (due to commissioning, connection, software set-up, etc. required regardless of battery capacity), and add 1.12 h labour for each average kWh. This reflects the fact that additional kWh require the installation of additional units, but do not change base setup times. Following NREL (2022)’s DC/AC split, we estimate translations from DC capacity to AC capacity at a 1:1.6 rate.

This gives, for example:

- 5 kWh: 11.6 h (DC)/18.6 h (AC)
- 7.5 kWh: 14.4 h (DC)/23 h (AC)
- 10 kWh: 17.2 h (DC)/27.5 h (AC)
- 12.5 kWh: 20 h (DC)/32 h (AC)
- 15 kWh: 22.8 h (DC)/36.5 h (AC)

We assume that DC-coupled batteries are installed to new builds, and AC-coupled batteries to retrofits per industry practice (see e.g. Ecoflow, 2025).

Learning improvements

Technological choices and learning can significantly affect installation speed. NREL’s time-and-motion study, for example, found that roof-integrated solar options are 7 percent faster to install than standard retrofit approaches (Cook et al., 2023). Learning rates thus far suggest that most input costs, including labour, decrease by around 10–20 percent with each doubling of solar capacity as efficiencies are discovered (Rubin et al., 2015; Louwen et al., 2018).

We assume that the time taken to install solar PV will decrease by 1 percent annually in countries of destination, and by 2 percent annually in countries of origin, where markets are currently less developed and greater efficiency improvements are anticipated.

We assume that battery installation speeds will follow similar trends. We assume a 1 percent annual decrease in installation times in countries of destination, and 2 percent annual decrease in countries of origin.

Labour utilisation rates

As is the case in the heat pump installation market, not all of an electrician's time, even if a solar PV specialist, will be spent installing solar panels: a significant part will be used travelling, installing other technologies, conducting maintenance, performing business administration, etc.

No studies of electricians' utilisation rates could be found. In their absence, we use the HPA (2024a)'s calculation of heat pump installers' utilisation rates, adjusting their baseline to take account of varying levels of maturity of solar PV markets in the countries under study. We assume that in countries of origin, where solar PV markets are more fragmented, utilisation rates are currently lower, rising to 2032 as market density increases, reducing travel times, and administrative processes become streamlined and digitised. As with heat pump installer utilisation rates, we project increases to rates over the period.

- **UK:** 60 percent, rising to 70 percent
- **Germany:** 65 percent, rising to 75 percent
- **Italy:** 65 percent, rising to 75 percent
- **India:** 50 percent, rising to 65 percent
- **Philippines:** 45 percent, rising to 65 percent
- **Kenya:** 50 percent, rising to 65 percent

Decarbonisation contribution

Solar panels' embodied emissions

We annualise the IEA-PVPS' (Stucki et al., 2024) estimate of PV system life-cycle emissions intensity (35.8 gCO_2e/kWh) and assumed yield (976 kWh/kWp/year) to assume that the embodied carbon intensity of solar panel systems comes to approximately 35 $kgCO_2$/kWp/year. This assumes that the solar panels used are monofacial monocrystalline silicon, in line with the IEA-PVPS's assessment (Masson et al., 2024) that mono-Si now entirely dominates markets. It assumes that residential solar panels have an average lifespan of 30 years and inverters of 15 years.

As grids in solar PV manufacturing countries decarbonise over the time period, their embodied emissions should decrease considerably. As of 2023, China produced 92 percent of polysilicon, 98 percent of PV wafers, 91.8 percent of PV cells, and 84.6 percent of PV modules (Masson et al., 2024). Over the period of study, China's grid is expected to continue to decarbonise (Yang et al., 2025). In a scenario of high decarbonisation in China, increased PV module recycling in countries of installation, and innovations in PV film technology, the embodied carbon of solar PV is projected to fall by in excess of 50 percent by 2030 (Chen et al., 2023). Moreover, even before China's decarbonisation, changing the location of solar panels' manufacture from current areas with coal-intensive grids to areas with gas- or renewable-intensive grids can reduce their embodied emissions by a factor of two or three (Wikoff et al., 2022): as green industrial policies onshore manufacturing into Europe, embodied emissions are likely to fall. We adopt a conservative assumption of a 15 percent fall in embodied carbon by 2032.

Note that higher-yield bifacial PV is becoming more prevalent (Keiner et al., 2025), but is not modelled in this paper. Bifacial PV modules are bulkier than monofacial modules, and are likely to have higher absolute embodied emissions (Zhang et al., 2023). Their higher yield, however, would mean that on a per-kWh basis their embodied emissions are lower.

Solar panel operations

We focus on residential rooftop solar. We assume varying initial sizes of the average installed rooftop solar array across countries under consideration:

- **UK:** 4.8 kWp (MCS, 2025a)
- **Germany:** 8 kWp (following Wirth, 2025 noting that 66 percent of new installations are below 10 kWp, and Galvin, 2022's observation that 8 kWp is the point at which optimal economic benefits are currently achieved)
- **Italy:** 5.2 kWp (Tilli et al., 2024)
- **India:** 4 kWp (Sharma et al., 2024)
- **Philippines:** 4 kWp (PSSEA, 2024's recommendation for a medium-cost house).
- **Kenya:** 3.3 kWp (Khan, 2025)

We assume that policy interventions and continued decreases in the cost of solar PV will see the size of installations rise during the period of study. Solar PV module costs historically fall by roughly 20 percent with each doubling in global installed capacity (Ritchie, 2024); global solar capacity is expected to increase by 150 percent between 2024 and 2030 (IEA, 2024b). Module costs are therefore expected to fall by 30 percent. Unit costs, however, only account for part of total installation costs alongside labour and other factors—in Germany, for example, they account for less than one third of costs (Wirth, 2025). Factoring this in alongside policy directions, we assume the following increases. These are indicative, and subject to many different factors:

- **UK:** rise to 6.5 kWp by 2032. Reforms introducing net metering and widening price spreads will incentivise larger systems (Jackman, 2025), as will increasing electrification and falling costs.

- **Germany:** rise to 10 kWp by 2032. Germany offers 0 percent VAT for solar PV systems up to 30 kWp (Enders, 2023); we assume that policy incentives and falling prices will lead to a drift upwards in size.
- **Italy:** rise to 6 kWp by 2032. Italy's new net-metering system incentivises self-consumption, and with battery installation growth is assumed to see average kWp rise slightly (GSE, 2025).
- **India:** rise to 4.5 kWp by 2032. Installations are rising fast as costs fall (although data on kWp is not available) (Feldman et al., 2025). The introduction of new Time-of-Day tariffs should widen price spreads and incentivise households to export self-generated electricity to the grid at times of peak demand (Shah, 2025), incentivising larger solar PV installations. The PM Surya Ghar Yojana scheme is assumed to further increase PV installations, allowing costs to reduce with scale (Sharma et al., 2024). However, subsidies are currently capped at the first 3 kWp installed (Sunboost Energy, 2025), so we assume only a small uplift in average installation size.
- **Philippines:** rise to 4.5 kWp by 2032. We assume that increased air conditioning demand (Mobility Foresights, 2025) will drive energy consumption and average solar PV kWp, but that the current net-metering policy will disincentivise significant growth in average size (Philergy German Solar, 2025).
- **Kenya:** rise to 4 kWp by 2032. Module costs are likely to be a significant component of total installation costs in Kenya, and so price decreases could increase demand for larger arrays. However, current net-metering regulations cap single-phase input at 4kW (Kenya Gazette, 2024); we therefore assume that average size will not climb significantly above this, and that grid-tied solar remains nascent during the period of study.

We follow country-specific sun and incline estimates to assume the following levels of kWh/kWp·yr. We assume that they remain static during the time period: this is likely to give conservative estimates for later years in the period given that technologies are improving. In particular, the growing prevalence of bifacial PV modules in rooftop installations, whose kWh/kWp yields can be around 15 percent higher than monofacial, is likely to see efficiency increase (Ernst et al., 2024; Masson, 2024; Pirouz et al., 2025).

- **UK:** 960 kWh/kWp·yr, when weighted by the distribution of installed generating capacity (Mason, 2016).
- **Germany:** 1,000 kWh/kWp·yr, following Galvin (2022).
- **Italy:** 1,122 kWh/kWp·yr (Tilli et al., 2024).
- **India:** 1,500 kWh/kWp·yr (Dondariya et al., 2018).
- **Philippines:** 1,350 kWh/kWp·yr (Philippines Department of Energy, 2013).
- **Kenya:** 1,225 kWh/kWp·yr (adjusted from Ayora et al., 2023).

Solar panels degrade over time in use. Degradation rates are variously estimated at 0.1 percent–1.2 percent per year depending on environmental conditions (Olczak, 2023; Atia et al., 2023). We assume an annual degradation rate of 0.5 percent, following the IEA-PVPS (Stucki et al., 2024).

Electricity usage from solar PV

In the absence of reliable studies of household self-consumption of PV generation, we assume that for grid-tied systems all electricity routed via batteries is self-consumed, while all remaining (non-battery) PV generation is exported to the grid. Exported electricity is then subject to curtailment according to the assumed curtailment rate. This implies that essentially all PV generation either displaces grid electricity directly at the household or indirectly elsewhere in the system. Our treatment of curtailment is therefore conservative: by assuming zero non-battery self-consumption, we expose the entire non-battery stream to curtailment.

In the absence of reliable curtailment estimates and projections for rooftop solar PV for almost all countries, we assume an average curtailment rate of 2.75 percent, the midpoint in the IEA (2023)'s estimate for current curtailment in 'most large renewable energy markets'. This assumes that as variable renewable energy generation grows, infrastructure buildout—especially of batteries—occurs alongside installation of generation capacity. It does not assume perfect buildout, but may understate outlier curtailment rates where poor infrastructure policy means buildout does not keep pace with installations; equally, countries with adequate buildout may experience average curtailment of less than 2.75 percent. (Curtailment is not factored in for Kenya, for which almost all solar PV installations are off-grid.)

Batteries

Usage patterns vary where batteries are involved. Batteries introduce small energy losses due to heat inefficiencies. As noted subsequently, we assume the use of lithium iron phosphate batteries. We follow NREL (2024)'s assumption of a round-trip efficiency of 90 percent, i.e. the energy loss of a 'round trip' into and out of the battery is assumed to be 10 percent. We assume that this remains static; this is conservative given likely advances in efficiency.

We assume, on the basis of the most recent studies available, that the following proportions of generated electricity are routed through batteries before use across countries. We assume that round trip rates will rise in proportion to assumed increases in battery size.

- **UK:** 25 percent (Luthander et al., 2015)
- **Germany:** 28 percent (Verbraucherzentrale Rheinland-Pfalz, 2025)
- **Italy:** 40 percent (Lage et al., 2024)
- **India:** 30 percent (Luthander et al., 2015)
- **Philippines:** 30 percent (Luthander et al., 2015)
- **Kenya:** 30 percent (only relevant for grid-tied) (Luthander et al., 2015)

We assume that battery prevalence and size will change over the period of interest due to decreasing costs or changes to net-metering regulations. We assume the following initial battery storage prevalence rates:

- **UK:** 9 percent (derived from Rippin, 2023, and Ross, 2025)
- **Germany:** 77 percent (Wedepohl, 2023)
- **Italy:** 38 percent (GSE, 2024)
- **India:** 23 percent of residential solar PV installations have battery energy storage (Sharma et al., 2024)
- **Philippines:** 3 percent (estimate: almost all residential solar PV installations in the Philippines are on-grid, i.e. use the grid as a battery, per the Philippines Department of Energy (2022); per industry sources, e.g. Solar Install PH (2025), some install hybrid systems against brownouts)
- **Kenya:** 98 percent (conservative estimate, derived from: GOGLA reporting (Reynolds and Paixão, 2025) that 6.6 million new off-grid (battery-equipped) residential solar installations occurred in East Africa 2024; the IEA (2025b)'s reporting that Kenya accounts for almost 74 percent of off-grid solar home system sales in East Africa in 2023, with 20 percent of Kenyan households using solar-powered mini-grids or standalone systems; and the fact that net-metering was only made possible in June 2024 (Kenya Gazette, 2024), disincentivising grid-tied rooftop solar PV until very recently).

Between 2022–2023, global battery storage additions increased by 136 percent (Altieri et al., 2024); the IEA (2024a) projects that global battery storage will increase by fourteen times from 2023 to 2030. Residential battery pack prices fell 20 percent from 2023-2024 to US$115/kWh (BNEF, 2024), and are likely to continue falling during the period of study: the IEA (2024a) projects that their cost will fall by approximately 40 percent by 2030.

In addition, policy changes in several countries are likely to make batteries more attractive. We assume the following rates of battery prevalence increase as prices fall: these are relatively arbitrary estimates, and outcomes will be affected by many factors, including tariffs. We place intermediary years on a glidepath.

- **UK:** rise to 35 percent by 2032. The UK has assigned zero VAT to batteries from February 2024–March 2027 (HMRC, 2024) and will introduce more dynamic tariffs and sharper spreads between peak and off-peak energy prices from July 2027, incentivising retention of solar-generated electricity to peak evening hours (Ofgem, 2025). With rapidly decreasing costs and increased need for batteries due to rising electrification, including of mobility, we assume a significant rise in battery prevalence.
- **Germany:** rise to 90 percent by 2032. Battery storage in Germany is already approaching ubiquity in solar PV installations (Grostern, 2025); we assume a continued rise towards a plateau.

- **Italy:** rise to 65 percent by 2032. Under the extremely generous 'Superbonus' subsidy scheme, running from 2020–2023, battery prevalence in Italy rose to 77 percent of new rooftop solar installations before falling after its end (BNEF and Pylontech, 2023). Recent policy shifts incentivise self-use of generated electricity against export, incentivising battery installations (QualEnergia, 2025). With price declines, we assume a rise remaining below the 'Superbonus' peak.
- **India:** rise to 35 percent by 2032. The introduction of new Time-of-Day tariffs should widen price spreads and incentivise households to export self-generated electricity to the grid at times of peak demand (Shah, 2025), incentivising battery installations. The PM Surya Ghar Yojana scheme is assumed to further increase PV installations, allowing costs to reduce with scale (Sharma et al., 2024). We assume a moderate rise.
- **Philippines:** rise to 10 percent by 2032. The residential solar PV market, currently fairly small, is assumed to grow following policy assistance (Philippines Department of Energy, 2023). At the same time, current net-metering credit approaches, which pay at sub-retail blended generation rates, reduce price spreads and disincentivise battery use (SunPhilSolar, 2025). We assume a slight rise in battery use due to cheaper batteries allowing mitigation against brownouts.
- **Kenya:** remain at ~98 percent due to the domination of the solar market by off-grid installations.

We also assume that the size of batteries will grow progressively each year as prices fall. We assume that they start at the following sizes, and grow towards a plateau, noting that household demand for battery installations is constrained by space and energy need. We assume simplistically that with a 40 percent reduction in cost, we will also see a roughly 15 percent increase in average installed size. We assume that unit costs account for roughly 50 percent of total costs, and that there is otherwise a 0.75 elasticity of size to price.

- **UK:** 8.6 kWh (derived from installation numbers and reported totals (DESNZ, 2025c)), rising to 10 kWh by 2032
- **Germany:** 8.5 kWh (Sternerg, 2025), rising to 10 kWh by 2032
- **Italy:** 12.8 kWh (Matalucci, 2024), rising to 14.7 kWh by 2032
- **India:** 5 kWh (Nagaraj, 2025), rising to 5.8 kWh by 2032
- **Philippines:** 5 kWh (per market sources, e.g. Solarius Energy, 2025), rising to 5.8 kWh by 2032
- **Kenya:** 5 kWh (per market sources, e.g. Seghers, 2024), rising to 5.8 kWh by 2032

Embodied carbon in batteries

Lithium-ion batteries dominate battery storage sales globally. We assume that all batteries installed are lithium iron phosphate (LFP), rather than the main rival technology, nickel manganese cobalt (NMC). LFP batteries have been recommended by the US National Renewable Energy Laboratory as the primary chemistry for stationary storage from 2021 (NREL, 2024). They are approximately

30 percent cheaper than NMC batteries (Lombardo et al., 2025), and are safer, and are more durable, but have lower peak electricity output (Evro et al., 2024).

We follow Fett et al. (2022)'s estimate that a residential LFP battery storage system has total embodied carbon emissions of 241 $kgCO_2e/kWh$ capacity, conservatively including one replacement inverter. We use their lower-bound lifespan estimate of 15 years. We therefore assume annualised embodied emissions of 16.1 $kgCO_2e/kWh\text{-}cap{\cdot}yr$.

As of 2025, over 75 percent of batteries are produced in China (Lombardo et al., 2025). China's grid is currently decarbonising (Myllyvirta, 2025): over the period of study, the carbon intensity of constructing battery systems will fall, potentially considerably (Xu et al., 2022; Llamas-Orozco et al., 2023). We assume a 10 percent decrease in embodied carbon between 2024–2032; this may be somewhat conservative.

Rebound rates in the use of solar PV

Solar PV provides reliable electricity with zero marginal cost. With the reduction in electricity costs, households often do not reduce their purchase of grid-drawn electricity by an amount corresponding to their solar PV system's generation: instead, their total electricity consumption can affordably increase. This is a great benefit of solar PV installation, but means that the estimated level of CO_2 displacement must be tempered by the 'solar rebound effect'.

We follow a range of studies—Aydın et al. (2023) (estimating a 7.7 percent rebound rate in the Netherlands), Bigler (2025) (estimating an 8–11 percent rebound rate in Switzerland), McKenna et al. (2018) (estimating rebound rates at 18 percent in the UK), Deng and Newton (2017) (estimating an 18 percent rebound rate in Australia), and Qiu et al. (2019) (estimating an 18 percent rebound effect in the US)—to assume that the solar rebound effect for high-income countries of destination is approximately 15 percent, meaning that only 85 percent of the used electricity generated by solar PV installations is taken to displace grid-drawn energy.

There is a dearth of studies calculating the solar rebound effect in lower-income countries. We follow studies of potential latent demand after other supply increases (e.g. Gupta et al., 2025) to assume higher latent energy demand in India and the Philippines, and allocate them a solar rebound effect of 20 percent. For Kenya, the use of GOGLA's off-grid solar abatement estimate obviates the need for an estimate of the rebound effect.

Carbon emissions reduction in the case of Kenya's off-grid solar

The primary vector for carbon emissions reduction in the installation of residential solar PV systems is in the displacement of high CO_2-intensity electricity from the grid. In the case of Kenya, where off-grid solar dominates the market, further analysis is needed. New solar installations will not displace electricity drawn from the grid; instead, it will be displacing other off-grid electricity sources, typically generators or biofuels (e.g. charcoal stoves).

We follow the carbon emissions reduction estimate for off-grid solar used by GOGLA (2020), which assesses the contribution of each residential solar system at 431kg CO_2e/yr prior to the deduction of embodied emissions. (This calculation assumes that solar panels are displacing carbon emissions from cooking using black carbon and lighting using kerosene-wick lamps.)

This is primarily relevant to Kenya. Only 4 percent of solar PV installations in India (Indian Ministry of New and Renewable Energy, 2025) are off-grid. Less than 1 percent of installations in the Philippines are off-grid: around 14.3MW of installed off-grid solar is reported (Philippines Department of Energy, 2024), versus total installed capacity of over 1.8GW (Jowett, 2025). Our analysis assumes that the marginal worker installs off-grid solar in Kenya and grid-tied or hybrid solar everywhere else.

Methodology: Heat pump installation abatement

Our primary scenario is of a worker installing residential heat pumps, whose presence in the country of destination labour market is again wholly additional throughout the period of study: they are performing work that would otherwise not have been done. The range of factors considered is shown in Table 2.

TABLE 4. Modelling factors in heat pump installations

Embodied Emissions Factors	Operational Decarbonisation Factors	Installation Factors
Floor area	Gas input (kWh/yr)	Working days per year
Heated area share	Boiler efficiency factor	Days per heat pump installation
Heat pump embodied carbon (kgCO_2/yr)	Household heat demand (kWh/yr)	Labour utilisation rate
Gas boiler embodied carbon (kgCO_2/yr)	Heat pump rebound effect	Learning rate
	Heat pump seasonal performance factor	
	Grid electricity gCO_2/kWh: decarbonisation goals achieved and 75 percent achieved	
	Gas gCO_2/kWh	

Formulae: 'Additional worker' scenario

We use the following formulae to calculate abated emissions, with values following the assumptions set out in the subsequent sections.

Per-home heat demand

$$H_y = (G \cdot \eta_b) \cdot (1 - \delta_y)$$

- H_y: Annual heat demand in year y (kWh)
- G: Annual household gas input for heating (kWh)
- h_b: Boiler efficiency
- d_y: Heat demand reduction factor due to insulation in year y

Heat pump electricity use

$$E_{HP,y} = \frac{H_y \cdot (1+r)}{SPF_y}$$

- $E_{HP,y}$: Annual electricity used by heat pump per household (kWh)
- r: Rebound rate
- SPF_y: Seasonal performance factor of heat pumps in year y

Installations per worker and cumulative stock

$$N_y = \frac{D \cdot U_y}{d_y}$$

$$C_y = \sum_{t=1}^{y} N_t$$

- N_y: New installations per worker in year y
- D: Available days per worker per year
- U_y: Worker utilisation rate in year y
- d: Days required per installation in year y
- C_y: Cumulative number of installations by year y

Annual emissions displaced

$$\Delta CO_{2y} = (C_y \cdot H_y \cdot f_b) - (C_y \cdot E_{HP,y} \cdot f_{el,y}) - (C_y \cdot (EC_{HP} - EC_B))$$

- ΔCO_{2y}: Annual emissions abated in year y (tonnes)
- f_b: Carbon intensity of gas combustion (gCO_2/kWh)
- EC_{HP}: Annual embodied emissions of a heat pump ($kgCO_2$/yr)
- EC_B: Annual embodied emissions of a boiler ($kgCO_2$/yr)

Cumulative emissions displaced

$$\Delta CO_{2y}^{cum} = \sum_{t=1}^{y} \Delta CO_{2t}$$

- ΔCO_{2y}^{cum}: Cumulative emissions abated to year y (tonnes)

TABLE 5. Symbols: 'Additional worker' scenario for heat pump modelling

Symbols	Meaning
H_y	Annual heat demand in year y (kWh)
G	Annual household gas input for heating (kWh)
η_b	Boiler efficiency
δ_y	Heat demand reduction factor due to insulation in year y
$E_{HP,y}$	Annual electricity used by heat pump per household (kWh)
r	Rebound rate
SPF_y	Seasonal performance factor of heat pumps in year y
N_y	New installations per worker in year y
D	Available working days per worker per year
U_y	Worker utilisation rate in year y
d_y	Days required per installation in year y
C_y	Cumulative number of installations by year y
ΔCO_{2y}	Annual emissions abated in year y (tonnes)
f_b	Carbon intensity of gas combustion (gCO$_2$/kWh)
$f_{el,y}$	Carbon intensity of electricity grid in year y (gCO$_2$/kWh)
EC_{HP}	Annual embodied emissions of a heat pump (kgCO$_2$/yr)
EC_B	Annual embodied emissions of a boiler (kgCO$_2$/yr)
ΔCO_{2y}^{cum}	Cumulative emissions abated to year y (tonnes)

Formulae: 'Acceleratory worker' scenario

As in the solar PV installation modelling, we also model a scenario in which the domestic labour supply catches up to demand during the period of study. As for the solar PV installer, we assume perfect catch-up after the length of a complete apprenticeship, varying across countries:

- **UK:** a refrigeration, air conditioning, and heat pump engineering technician apprenticeship typically takes 3 years, with a further 6 months for end-point assessment (Skills England, 2025c). An alternative apprenticeship in plumbing and domestic heating takes 4 years with a 6-month end-point assessment (Skills England, 2025b). Both subsequently require very short additional modules. We assume an average length of 4 years.
- **Germany:** a heating and plumbing apprenticeship dual typically takes 3.5 years, with very short additional training modules (a few days to a week) required for technology-specific installations (Bundesagentur für Arbeit, 2025a).

- **Italy:** an apprenticeship to become a plumbing and heating engineer typically takes 3 years, with an optional fourth year (Unico, 2025). We assume a 4-year course.

We again designate τ as the amount of time taken to complete an apprenticeship and be able to install heat pumps. As for the PV modelling, the scenarios are identical for the first τ post-installation years, and diverge after τ years, when the earliest cohorts age beyond the cap, with the same methodological notes regarding modelling time horizons and simplification of learning rate effects.

Cohort activity window (τ-year cap)

$$1_{i,y}^{(\tau)} = \begin{cases} 1, if\ i \le y \le i + (\tau - 1) \\ 0, otherwise \end{cases}$$

The number of active installations in year *y* is:

$$A_y^{inst} = \sum_{i \le y} N_i \cdot 1_{i,y}^{(\tau)}$$

- *i*,*y*: Cohort year, current year

Annual HP electricity use (kWh) in year y

$$E_y^{HP} = \sum_{i \le y} \left(N_i \cdot \frac{H_y}{S_i} \cdot 1_{i,y}^{(\tau)} \right)$$

- E_y^{HP}: HP electricity, year *y*
- N_i: Installations completed in cohort *i*
- H_i: Heat demand per dwelling in year *y*
- S_i: SPF of cohort *i*

Annual boiler CO$_2$ and HP CO$_2$ (operational)

$$Boiler\ CO_2 : C_y^{boil} = A_y^{inst} \cdot G_y \cdot b_y$$

$$HP\ CO_2 : C_y^{HP} = E_y^{HP} \cdot I_y^{goals,75\ percent}$$

- $C_y^{boil,HP}$: Boiler, heat pump CO$_2$2 (operational)
- I_y^{el}: Grid electricity carbon intensity, goals or 75 percent decarbonisation scenarios
- G_y: Gas input per dwelling
- b_y: Boiler emission factor

Annual embodied-carbon flow (gCO_2e) in year y

$$B_y = 1000 \cdot \sum_{i \le y} (N_i \cdot \Delta e_i \cdot 1^{(\tau)}_{i,y}$$

- Δe_i: Embodied carbon delta per installation cohort, $e_i^{HP} - e_i^{boil}$

Annual net abated CO_2 (tonnes) to year y

$$A_y = \frac{(1 - r_y)(C_y^{boil} - C_y^{HP}) - B_y}{10^6}$$

- A_y: Annual net abated CO_2
- r_y: Rebound factor in year *y*
- B_y: Embodied grams CO_2 (active cohorts)

Cumulative net abated CO_2 (tonnes) to year y

$$C_y^{goals,75\ percent} = \sum_{s=2024}^{y} A_y^{goals,75\ percent}$$

TABLE 6. Symbols: 'Acceleratory worker' scenario for heat pump modelling

Symbols	Meaning
τ	Years taken to complete apprenticeship
i, y	Cohort year, current year
N_i	Installations completed in cohort *i*
H_y	Heat demand per dwelling in year *y*
S_i	SPF of cohort *i*
$I_y^{goal}, I_y^{75 percent}$	Grid intensity by decarbonisation scenario (goals/75 percent)
b_y	Boiler emission factor
G_y	Gas input per dwelling
r_y	Rebound fraction
e_i^{HP}, e_i^{boil}	Annualised embodied per installation (HP/boiler)
Δe_i	Embodied carbon delta per installation cohort, $e_i^{HP} - e_i^{boil}$
$1^{(\tau)}_{i,y}$	τ-year activity indicator
A_y^{inst}	Active installations in year *y*
E_y^{HP}	HP electricity, year *y*
C_y^{boil}	Boiler CO_2 (operational)
C_y^{HP}	HP CO_2 (operational)
B_y	Embodied gCO_2 (active cohorts)
A_y	Annual net abated CO_2
C_y	Cumulative net abated CO_2

Installation rates

We assume that each worker will work 230 days per year. This assumes 52 5-day weeks, from which is subtracted 30 days for public holidays and vacations.

Heat pumps in countries of destination

We follow industry sources in estimating the number of days taken to install a heat pump in a residential property. These figures reflect the person-days contribution needed from individuals qualified to install heat pumps; qualified HVAC technicians will typically also be supported by technicians with fewer technology-specific qualifications.

- **UK:** 6 person-days (HPA, 2024a)
- **Germany:** 6 person-days (Altermatt et al., 2023)
- **Italy:** 6 person-days (following UK and Germany estimates, absent country-specific studies)

We follow analysis conducted by the UK's Heat Pump Association (HPA, 2024a) in assuming that, with increased expertise and standardisation, installations will become more efficient. We assume that by 2030 installations will take 10 percent less time. This is potentially very conservative: for comparison the UK's Department for Energy Security and Net Zero (DESNZ, 2025a), in its modelling, assumes a 50 percent reduction in labour intensity by 2035.

We follow the HPA's analysis further in assuming that in the UK, heat pump installers currently have a utilisation rate of 48 percent of available time installing heat pumps, rising to a conservative 72 percent by 2028 and remaining constant thereafter. (Labour utilisation rates below 100 percent are due to time spent installing other technologies, on business administration, travelling between jobs, conducting maintenance, or completing other tasks.) Similar studies are not available in Germany and Italy. We assume, given greater market development in those countries, that utilisation rates are higher outside the UK:

- **UK:** 48 percent rising to 72 percent by 2028
- **Germany:** 60 percent rising to 78 percent by 2032
- **Italy:** 60 percent rising to 78 percent by 2032

Decarbonisation contribution

Embodied emissions in heat pumps

We assume that embodied carbon levels remain flat across the timeframe under consideration, i.e. that a heat pump installed in 2032 has the same embodied carbon as one installed in 2024. This is conservative: energy inputs during manufacture and installation will become less carbon intensive as decarbonisation accelerates, and embodied carbon will therefore decrease over time.

For *heating* in countries of destination, we adapt embodied and operational carbon estimates for heat pumps and gas boilers from Gergely et al. (2025). This tracks alternative heating technologies over 50 years, factoring in rates of replacement, and assumes that 7kW air-to-water units are being used for domestic heating via radiators. We assume that the lower-carbon refrigerant R290 is used (see Crown, 2023), recognising that policy shifts will encourage the heat pump supply chain to reduce leakage emissions. The estimated embodied carbon of 7kW R290 heat pumps is placed at 0.719 $kgCO_2eq./m^2/year$; of this 0.548 $kgCO_2eq./m^2/year$ is for distribution networks, and 0.171 $kgCO_2eq./m^2/year$ for the heat pump itself.

We assume the following average residential floor areas:

- **UK:** 97 m^2 (Hudson, 2024)
- **Germany:** 103.5 m^2 (Eurostat, 2025)
- **Italy:** 100.3 m^2 (Eurostat, 2025)

We assume the following proportions of average residential floor areas are heated:

- **UK:** 90 percent (assumption; no figure is available)
- **Germany:** 99 percent (Marchetti, 2019)
- **Italy:** 80 percent (Marchetti, 2019)

New installations of heat pumps in the countries of destination are currently well above 7 kW on average. We adjust the heat pump embodied carbon estimate according to national sizing averages. We assume that each unit increase in capacity translates to a unit increase in size and embodied carbon of 1:0.8, recognising that mass and materials increase sub-linearly with capacity (James et al., 2022).

- **UK:** 10kW (HPA, 2024b), leading to total embodied carbon of 0.74 $kgCO_2eq./m^2/year$
- **Germany:** 9.3 kW (Volt et al., 2024), leading to total embodied carbon of 0.73 $kgCO_2eq./m^2/year$
- **Italy:** 10.5 kW (drawn from EU average per Lorcan et al., 2022), leading to total embodied carbon of 0.75 $kgCO_2eq./m^2/year$

Over the period of study heat pump sizes are likely to fall due to ‘rightsizing’ improvements. For modelling simplicity we assume that heat pumps maintain their current size: the impact on embodied carbon of a 10 percent decrease in size is negligible.

For the counterfactual, we assume that a gas condensing boiler system of less than 20 kW is being used, also for domestic heating via radiators. The estimated embodied carbon of gas boilers is placed at 0.742 $kgCO_2eq./m^2/year$ (Gergeley et al., 2025).

Heat pump operations

Heat pumps are considerably more operationally efficient than gas boilers. To calculate current energy use and the counterfactual of gas boiler use, we use estimates of average boiler efficiency factors and annual kWh gas use.

We use the most recent estimates for average annual kWh gas inputs for use in residential space heating. For comparability of results, we harmonise the UK's reporting to the international reporting standard, converting its figures from Gross Calorific Value (or Higher Heating Value), to Net Calorific Value (or Lower Heating Value), as used internationally and in Germany and Italy.

- **UK:** 10,620 kWh_{th}/yr (converted from 11,800 kWh_{th}/yr per BEAMA, 2022)
- **Germany:** 12,216 kWh_{th}/yr (DEStatis, 2023)
- **Italy:** 10,500 kWh_{th}/yr (derived from ODYSEE-MURE, 2025 kg-oil equivalent/m^2 estimate and Eurostat, 2025 floor estimate)

We use boiler efficiency figures for *new* boilers, assuming that if a heat pump is installed the counterfactual would be the installation of a new high-efficiency condensing boiler. This is significant and potentially very conservative, given that an alternative could be to assume that the counterfactual is the continued use of an older lower-efficiency boiler.

- **UK:** 0.9 (DESNZ and BEIS, 2024)
- **Germany:** 0.9 (DENA, 2023)
- **Italy:** 0.95 (Schito et al., 2023)

We multiply kWh gas use by boiler efficiency to obtain annual heat demand. We assume that heat demand will decline by 10 percent in each country across the period due to an expected drive in insulation retrofit.

- **UK:** 9,558 kWh
- **Germany:** 10,994 kWh
- **Italy:** 9,975 kWh

To calculate the kWh of electrical energy drawn from the grid to power heat pumps, we obtain estimated of heat demand and of average heat pump seasonal performance factor (SPF) values. (Energy input = total heat demand/SPF). We assume the following SPF values for heat pumps:

- **UK:** 2.91 (Energy Systems Catapult, 2024); this may be conservative given that recent open-source use data suggests that with optimisation real-world SPF may now be approaching 3.86 (Rosenow et al., 2026)
- **Germany:** 3.3 (Wapler et al., 2020)
- **Italy:** 3.3 (Mongelli et al., 2023)

We assume that over the time period a combination of technology improvements, increased insulation, and growing workforce experience will lead to improved SPF values. We assume that in Germany and Italy SPF values improve by 20 percent by 2032, while in the UK, which has a less-developed heat pump market and greater room for improvement, SPF values will improve by 25 percent by 2032. A heat pump's SPF value is assumed to remain stable following installation.

We obtain annual electricity used by heat pumps by dividing heat demand by heat pump SPF. For 2024, this gives the following:

- **UK:** 3,690 kWh
- **Germany:** 3,331 kWh
- **Italy:** 3,022 kWh

To calculate the emissions displacement effect, we compare the CO_2 emissions of burning gas to the emissions of electricity drawn from the grid to power heat pumps.

As noted reporting approaches for gas inputs vary across countries. These variations are reflected in carbon intensity estimates. For more convenient comparability, we again harmonise the UK's CO_2 figures by converting them from Gross Calorific Value (or Higher Heating Value) intensity figures to the Net Calorific Value (or Lower Heating Value) used internationally and by Germany and Italy.

- **UK:** 202 gCO_2/kWh (converted from 0.183 $kgCO_2$/kWh per DESNZ, 2023)
- **Germany:** 202 gCO_2/kWh (European Commission, 2020)
- **Italy:** 202 gCO_2/kWh (European Commission, 2020)

Heat pump rebound rates

It is likely that increased efficiency in heating and transition from gas to grid electricity, with attendant lower prices, will enable households to increase their heating use. Households may increase the resting temperature; expand the space heated; or extend the period for which heating is used (see e.g. Winther and Wilhite, 2015).

In the absence of reliable calculations of rebound effects after heat pump installation, we follow modelling conducted for the UK government (Summerfield et al., 2016) in assuming a rebound of 10 percent in countries of destination.

Approach to grid carbon intensity

We factor anticipated grid decarbonisation into the anticipated abatement impacts of installed technologies. We use adapted current and projected average annual gCO_2/kWh across energy sources to calculate the emissions displaced by clean technology installations.

We use average grid carbon intensity (average emissions factors, AEFs) as a proxy for marginal emissions factors (the emissions from marginal electricity supplies) (see Koebrich et al., 2025). Marginal emissions factors (MEFs) would be more accurate in providing an estimate of the carbon displaced by additional renewable sources, but long-run projections of MEFs are not available for most countries under study.

This methodological choice is conservative: MEFs are generally considerably higher than AEFs, sometimes by multiples (Brander et al., 2025). This is, however, not always the case. The choice to use AEFs as a proxy for MEFs may lead to inaccurate estimates, in both directions, of the emissions reduction effects of installation. For example, if MEFs at the point of electricity use are lower than AEFs, the emissions reduction impact of heat pump installation will be understated and that of installing solar PV will be overstated; if vice versa, the opposite.

Data sources for current and projected grid gCO_2/kWh are set out below. Estimates of the carbon intensity of individual power sources are obtained from Ember's *2024 European Electricity Review* (Ember, 2024), using midpoints in estimate ranges derived from IPCC AR5 WG3 Annex III (Bruckner et al., 2014). These estimates include lifecycle emissions factors, such as embedded carbon in utility generation. They may, however, understate real intensities in India and the Philippines due to lower plant efficiencies, poorer fuel quality, and higher supply chain methane leakage. Our estimates should therefore be considered conservative for origin countries.

- Gas: 450 gCO_2e/kWh
- Hard coal: 980 gCO_2e/kWh
- Lignite: 1,050 gCO_2e/kWh
- Oil/Other fossil: 700 gCO_2e/kWh
- Bioenergy: 230 gCO_2e/kWh
- Hydro: 24 gCO_2e/kWh
- Solar: 48 gCO_2e/kWh
- Wind: 13 gCO_2e/kWh
- Other renewables: 38 gCO_2e/kWh
- Nuclear: 5 gCO_2e/kWh

2024 carbon emissions intensity levels and electricity generation sources are obtained from Ember's Electricity Data Explorer (Ember, 2025). We follow Ember to assume the following starting distribution of electricity generation sources, and allocate them into 'clean' or 'fossil' categories.

TABLE 7. Fuel source use by country

Source	Category	UK	Germany	Italy	India	Kenya	Philippines
Bioenergy	Clean	14.11 percent	9.58 percent	6.03 percent	1.1 percent	2.18 percent	1.02 percent
Hydro	Clean	2.03 percent	4.89 percent	19.21 percent	7.71 percent	28.09 percent	8.64 percent
Nuclear	Clean	14.28 percent	0 percent	0 percent	2.69 percent	0 percent	0 percent
Other renewables	Clean	N/A	0.04 percent	2.12 percent	N/A	43.27 percent	8.17 percent
Solar	Clean	5.2 percent	15.46 percent	13.54 percent	6.74 percent	4.28 percent	2.92 percent
Wind	Clean	29.31 percent	27.85 percent	8.38 percent	4.02 percent	14.09 percent	0.98 percent
Coal	Fossil	0.67 percent	21.78 percent	1.75 percent	74.77 percent	0 percent	62.51 percent
Gas	Fossil	30.37 percent	16.35 percent	44.02 percent	2.78 percent	0 percent	14.1 percent
Oil/other	Fossil	4.03 percent	4.05 percent	4.93 percent	0.2 percent	8.09 percent	1.65 percent

We assume that gCO_2/kWh will shift in accordance with decarbonisation programmes, and use stated targets for renewable electricity generation to estimate how carbon intensity will change over the period of study.

In so doing we assume, for simplicity, that the balance of generation sources within the 'fossil' and 'clean' energy categories will remain constant over the time period. We do not account for efforts to phase, for example, from lignite to gas or from bioenergy to wind. Grid carbon intensity estimates are therefore likely to relatively overstate carbon intensity. This is likely, as in the choice of AEFs over MEFs, to affect per-technology abatement outcomes in different ways: it is likely to overstate the efficacy of solar PV and understate the contribution of heat pumps.

TABLE 8. Carbon intensity of energy sources in 'Clean' and 'Fossil' buckets

Country	Clean Generation, 2024	Clean gCO_2/kWh, 2024	Fossil Generation, 2024	Fossil gCO_2/kWh, 2024	Average Grid gCO_2/kWh, 2024
UK	65 percent	95	35 percent	489	233
Germany	58 percent	59	42 percent	748	350
Italy	49 percent	53	51 percent	493	276
India	22 percent	140	78 percent	960	778
Kenya	92 percent	17	8 percent	700	72
Philippines	22 percent	27	78 percent	879	694

We derive projected grid decarbonisation rates from government policy targets:

- **UK:** The UK's *Clean Power 2030 Action Plan* states a goal for 2030 gCO_2/kWh of "well below 50 gCO_2/kWh" (DESNZ, 2025b). (This number only includes operational emissions, and does not include lifecycle embodied emissions). It aims for 95 percent clean power generation by 2030 (Bolton, 2025).
- **Germany:** aims for 80 percent renewable energy by 2030 (European Commission, 2024b).

- **Italy:** according to Italy's National Energy and Climate Plan (European Commission, 2024a), it will decrease its carbon intensity of power generation to approximately 145.7 gCO_2/kWh by 2030, aiming for 70 percent renewable energy generation.
- **India:** achieved its 2030 goal of 50 percent installed clean energy capacity early, in 2025 (Reuters, 2025). Due to grid connection and other challenges, this translates into sub-capacity generation (Arasu, 2025); estimates suggest non-fossil generation of around 25 percent in 2024/2025 (Pachouri and Sinha, 2025; Ember, 2025). The National Electricity Plan (Ministry of Power, 2023) targets clean power generation contributing around 39 percent in 2026/2027 and 44 percent by 2032, with a further ~4 percent contributed by nuclear to give a total of roughly 48 percent.
- **The Philippines:** aims for 35 percent renewable energy generation by 2030 (Climate Action Tracker, 2023).
- **Kenya:** aims to generate 100 percent of its electricity from clean energy sources by 2030 (CIF, 2024).

We interpolate between 2024 carbon intensity and estimated 2030 carbon intensity for the intervening years, placing decarbonisation on a linear glidepath. We assume that this glidepath continues to 2032. (The exception to this is Kenya, which starts at very low grid carbon intensity and may achieve minimal rates by 2030 under stated targets.) For each country, we use both projections that assume the achievement of stated government targets and a more conservative path, in which only 75 percent of governments' goals are estimated to have been achieved. The table below shows the gradual change in assumed grid carbon intensity (gCO_2) during the period of study.

TABLE 9. Projected grid carbon intensity, stated policies and 75 percent achievement

Year	UK		Germany		Italy		India		Kenya		Philippines	
	Goal	75 Percent	Goal	75 Percent	Goal	75 Percent	Goal	75 Percent	Goal	75 Percent	Goal	75 Percent
2024	233	233	350	350	276	276	778	778	72	72	694	694
2025	213	218	324	331	261	265	747	755	63	65	675	680
2026	194	204	299	311	246	253	686	732	54	58	656	665
2027	174	189	273	292	230	242	640	710	45	52	637	651
2028	154	174	248	273	215	230	626	687	35	45	618	637
2029	135	159	222	254	200	219	611	664	26	38	600	623
2030	115	145	197	235	185	208	596	642	17	31	581	609
2031	115	132	171	219	170	198	581	622	17	25	562	597
2032	115	120	146	203	154	188	567	603	17	19	543	585

Calculating the carbon intensity of migration

Lifestyle and per capita emissions

We use Our World in Data's estimates of CO_2 emissions per capita (OWID, 2024a) as a proxy when calculating the changes in emissions due to lifestyle changes of migrant workers. This is conservative: it divides territorial emissions by population, and will overestimate the impact of the marginal worker, whose presence will not be likely to affect, for example, emissions due to existing heavy industry. We assume the following base CO_2 emissions:

- **UK:** 4.44tCO_2/yr
- **Germany:** 7.05tCO_2/yr
- **Italy:** 5.27tCO_2/yr
- **India:** 2.13tCO_2/yr
- **Philippines:** 1.35tCO_2/yr
- **Kenya:** 0.39tCO_2/yr

We adjust these figures to include embodied emissions from imports and exports (OWID, 2024b), which for several countries is a major component in per capita carbon emissions. Embodied emissions from imports and exports are the following:

- **UK:** 2.56tCO_2/yr
- **Germany:** 1.92tCO_2/yr
- **Italy:** 1.68tCO_2/yr
- **India:** −0.19tCO_2/yr
- **Philippines:** 0.37tCO_2/yr
- **Kenya:** 0.19tCO_2/yr

This gives the following total per-person annual emissions:

- **UK:** 7tCO_2/yr
- **Germany:** 8.97tCO_2/yr
- **Italy:** 6.95tCO_2/yr
- **India:** 1.94tCO_2/yr
- **Philippines:** 1.72tCO_2/yr
- **Kenya:** 0.58tCO_2/yr

We apply a multiplier of 0.9 to our trade-adjusted per capita figures, recognising that migrants to OECD countries typically contribute fewer emissions than country of destination natives (Bollino and Galeotti, 2025).

We assume that decarbonisation will continue in countries of destination (see e.g. Wiatros-Motyka et al., 2024), and that economic growth will see energy use and carbon emissions rise in countries of origin (see e.g. IEA, 2025a). We assume that per capita carbon emissions will fall by 2 percent each year in countries of destination, and will rise by 2 percent each year in countries of origin.

Travel

We use the carbon emissions calculator developed by the International Civil Aviation Organisation (ICAO, 2025) to estimate carbon emissions due to travel between countries of origin and countries of destination. We assume migrants travel economy class. Routes used are representative: where ICAO suggests that a direct flight is not available, we insert a stopover in Doha, a common transfer site for all origin/destination pairings.

ICAO's calculator only include CO_2 emissions; to estimate the full warming impact of travel as CO_2 equivalent we use the 1.9 multiplier used by the UK Government's Department for Transport (DfT, 2024). This captures other elements such as radiative forcing.

We assume the following travel emissions between origin/destination pairs for a single flight. We assume that migrants make one single flight in the first year, and then a return flight to their country of origin each subsequent year.

TABLE 10. Carbon emissions of air travel between country pairs per passenger-flight

	India (CO_2t)	India (CO_2e, tonnes)	Kenya (CO_2t)	Kenya (CO_2e, tonnes)	Philippines (CO_2t)	Philippines (CO_2e, tonnes)
Germany	0.31	0.59	0.49	0.93	0.78	1.48
Italy	0.32	0.60	0.46	0.87	0.74	1.41
UK	0.28	0.52	0.43	0.81	0.86	1.63

Approach to comparators

To anchor the carbon abatement contributions made by marginal workers in their wider context, we compare them to the carbon sequestration achieved by tree planting and to calculations of the social cost of carbon.

Tree-planting

We follow the UK Woodland Carbon Code (UK Forestry Commission, 2025b) to assume that planting of new native woodland will capture 300–400tCO_2e per hectare over a 50-year lifespan (West, 2024)—the lifespan most relevant to decarbonisation timeframes.

Trees are planted at a typical woodland density of at least 400 trees per hectare, or at most five metres between trees (UK Forestry Commission, 2025b), but can hold up to over 4,400 trees per hectare at the densest placement (UK Forestry Commission, 2025); similar programmes typically see between 1,100 and 2,500 trees per hectare (Defra, 2025).

We take the midpoints, and assume that a hectare will capture 350tCO_2e over 50 years and be planted with 1,800 trees. This gives 194 kg CO_2e per tree, or 3.9 kg CO_2e per tree per year: every tonne of CO_2 abated is the equivalent of planting 5.2 trees. This is a simplistic and conservative estimate of gross biological CO_2 sequestration, and does not account for carbon leakage (due to e.g. wood harvesting or fires before the natural end of the trees' lifetime).

Social cost of carbon

The social cost of carbon is defined by the Intergovernmental Panel on Climate Change as "the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change" (Rogelj et al., 2018). Numerous estimates of the monetised value of net damages have been calculated, and vary according to discount rates imposed.

Under the Biden administration, the US Environmental Protection Agency used a central estimate of US$190/t$CO_2$e with a 2 percent discount rate for emissions in 2020, rising to US$230 by 2030 (EPA, 2023), following Rennert et al. (2022).

The OECD, in 2021, suggested a central estimate of the social cost of carbon of EUR 120/tCO_2e by 2030 (OECD, 2021).

The UK uses a 'market-traded carbon value' of £44 (US$60) and a 'net zero strategy-aligned' value of £63 (US$85) for 2025 (DESNZ, 2024).

Academic estimates of the social cost of carbon can be considerably higher. One influential study sets it at US$417/t$CO_2$e in 2018 (Ricke et al., 2018); a synthesis of academic evidence estimates a central calculation of US$283 for a 2020 emissions pulse (Moore et al., 2024).

The social cost of carbon rises over time, reflecting the fact that the marginal tonne of CO_2 emissions will have progressively greater negative consequences as tipping points are exceeded.

We use the US EPA's 2023 update of US$190 in 2020, rising to US$230 in 2030 and to US$270 in 2050. We interpolate the values for intervening years.

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