# Quantifying the $CO_2$ Reduction Contribution of the Marginal “Green” (Migrant) Worker: 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 $y$.
- $\phi_y$: 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 ($\theta_y^{bat}$), battery round-trip efficiency ($\eta^{rt}$), curtailment ($\gamma$), rebound ($\rho$), share of a system's generation routed via battery ($f_y^{bat}$).

### *Installation time per system*

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

- 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 CO₂ abatement*

*Countries with grid-tied/hybrid PV installations:*

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

*Kenya (off-grid PV installations):*

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

- $A_y$: Net $CO_2$ abatement (tonnes) by year $y$.
- $\alpha_k$: Grid carbon intensity in cohort $k$ ($gCO_2$/kWh).
- $J_y^{cum}$: Cumulative installation-years.
- $\epsilon_y$: 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 |
| $\theta_y^{bat}$ | Share of installations with batteries |
| $\eta^{rt}$ | Battery round-trip efficiency |
| $\gamma$ | Export curtailment rate |
| $\rho$ | Rebound rate |
| $\phi_y$ | 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 |
| $\alpha_k$ | Grid carbon intensity in cohort year $k$ ($gCO_2$/kWh) |
| $J_y^{cum}$ | Cumulative installation-years |
| $\epsilon_y$ | 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 $\tau$ as the amount of time taken to complete an apprenticeship and be able to install solar PV, and impose a $\tau$-year cap on the abatement contribution and embodied carbon amortisation of each installation cohort

Note that our assumption of a fixed $\tau$ -year ‘head-start’ window for accelerated installations abstracts from learning: in practice learning rates would mean that a ‘catch-up worker’ entering in year $\tau$ would be slightly more productive than a year-1 worker, so full catch-up would occur in a little under $\tau$ 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 $\tau$ post-installation years (for $y \leq i + (\tau - 1)$), the two scenarios yield identical annual results. Differences only arise when the earliest cohorts become older than $\tau$ years:

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

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

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 $\tau$ -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 $\tau$ -year windows for final ‘accelerated’ cohorts, annual net abatement would converge towards zero as the baseline catches up.

### *Cohort activity window ($\tau$ -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* |
|---|---|
| $\tau$ | 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 $i$) |
| $1_{i,y}^{(\tau)}$ | $\tau$ -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 5kW solar PV system via retrofit, and 6.3 hours (0.8 working days) to install a 5kW 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 12.5kWh 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 – 10kWh), 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 6h as a floor (due to commissioning, connection, software set-up, etc. required regardless of battery capacity), and add 1.12h 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:

- 5kWh: 11.6h (DC) / 18.6h (AC)
- 7.5kWh: 14.4h (DC) / 23h (AC)
- 10kWh: 17.2h (DC) / 27.5h (AC)
- 12.5kWh: 20h (DC) / 32h (AC)
- 15kWh: 22.8h (DC) / 36.5h (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**: 4.8kWp (MCS, 2025a)

- **Germany**: 8kWp (following Wirth, 2025 noting that 66 percent of new installations are below 10kWp, and Galvin, 2022's observation that 8kWp is the point at which optimal economic benefits are currently achieved)
- **Italy**: 5.2kWp (Tilli et al., 2024)
- **India**: 4kWp (Sharma et al., 2024)
- **Philippines**: 4kWp (PSSEA, 2024's recommendation for a medium-cost house).
- **Kenya**: 3.3kWp (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 6.5kWp 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 10kWp by 2032. Germany offers 0 percent VAT for solar PV systems up to 30kWp (Enders, 2023); we assume that policy incentives and falling prices will lead to a drift upwards in size.
- **Italy**: rise to 6kWp 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 4.5kWp 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 3kWp installed (Sunboost Energy, 2025), so we assume only a small uplift in average installation size.
- **Philippines**: rise to 4.5kWp 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 4kWp 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**: 960kWh/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**: 8.6kWh (derived from installation numbers and reported totals (DESNZ, 2025c)), rising to 10kWh by 2032
- **Germany**: 8.5kWh (Sternerg, 2025), rising to 10kWh by 2032
- **Italy**: 12.8kWh (Matalucci, 2024), rising to 14.7kWh by 2032
- **India**: 5kWh (Nagaraj, 2025), rising to 5.8kWh by 2032
- **Philippines**: 5kWh (per market sources, e.g. Solarius Energy, 2025), rising to 5.8kWh by 2032
- **Kenya**: 5kWh (per market sources, e.g. Seghers, 2024), rising to 5.8kWh 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 241kg$CO_2$e/kWh capacity, conservatively including one replacement inverter. We use their lower-bound lifespan estimate of 15 years. We therefore assume annualised embodied emissions of 16.1kg$CO_2$e/kWh-cap·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 $CO_2$e/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 (kg$CO_2$/yr) | Household heat demand (kWh/yr) | Labour utilisation rate |
| Gas boiler embodied carbon (kg$CO_2$/yr) | Heat pump rebound effect | Learning rate |
|  | Heat pump seasonal performance factor |  |
|  | Grid electricity g$CO_2$/kWh: decarbonisation goals achieved and 75 percent achieved |  |
|  | Gas g$CO_2$/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)
- $\eta_b$: Boiler efficiency
- $\delta_y$: 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*

$$\Delta CO2_y = \left(C_y \cdot H_{y.} \cdot f_b\right) - (C_y \cdot E_{HP,y} \cdot f_{el,y}) - (C_y \cdot (EC_{HP} - EC_B))$$

- $\Delta CO2_y$: Annual emissions abated in year $y$ (tonnes)
- $f_b$: Carbon intensity of gas combustion (g$CO_2$/kWh)
- $EC_{HP}$: Annual embodied emissions of a heat pump (kg$CO_2$/yr)
- $EC_B$: Annual embodied emissions of a boiler (kg$CO_2$/yr)

### *Cumulative emissions displaced*

$$\Delta CO2_y^{cum} = \sum_{t=1}^{y} \Delta CO2_t$$

- $\Delta CO2_y^{cum}$: 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) |
| $\eta_b$ | Boiler efficiency |
| $\delta_y$ | 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 $y$ |
| $\Delta CO2_y$ | Annual emissions abated in year $y$ (tonnes) |
| $f_b$ | Carbon intensity of gas combustion (g$CO_2$/kWh) |
| $f_{el,y}$ | Carbon intensity of electricity grid in year $y$ (g$CO_2$/kWh) |
| $EC_{HP}$ | Annual embodied emissions of a heat pump (kg$CO_2$/yr) |
| $EC_B$ | Annual embodied emissions of a boiler (kg$CO_2$/yr) |
| $\Delta CO2_y^{cum}$ | 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 $\tau$ 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 $\tau$ post-installation years, and diverge after $\tau$ 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 ($\tau$-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*

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

- $E_y^{HP}$: 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 CO₂ and HP CO₂ (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 CO₂2 (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 (gCO₂e) in year y*

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

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

### *Annual net abated CO₂ (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 CO₂
- $r_y$: Rebound factor in year $y$
- $B_y$: Embodied grams CO₂ (active cohorts)

### *Cumulative net abated CO₂ (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 |
|---|---|
| $\tau$ | 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) |
| $\Delta e_i$ | Embodied carbon delta per installation cohort, $e_i^{HP} - e_i^{boil}$ |
| $1_{i,y}^{(\tau)}$ | $\tau$-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 7kW 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**: 9.3kW (Volt et al., 2024), leading to total embodied carbon of 0.73 $kgCO_2eq./m^2/year$

- **Italy**: 10.5kW (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 20kW 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**: 9,558kWh
- **Germany**: 10,994kWh
- **Italy**: 9,975kWh

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

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**: 202g$CO_2$/kWh (converted from 0.183kg$CO_2$/kWh per DESNZ, 2023)
- **Germany**: 202g$CO_2$/kWh (European Commission, 2020)
- **Italy**: 202g$CO_2$/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 g$CO_2$/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*

| | **UK** | | **Germany** | | **Italy** | | **India** | | **Kenya** | | **Philippines** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **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**: 4.44t$CO_2$/yr
- **Germany**: 7.05t$CO_2$/yr
- **Italy**: 5.27t$CO_2$/yr
- **India**: 2.13t$CO_2$/yr
- **Philippines**: 1.35t$CO_2$/yr
- **Kenya**: 0.39t$CO_2$/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**: 2.56t$CO_2$/yr
- **Germany**: 1.92t$CO_2$/yr
- **Italy**: 1.68t$CO_2$/yr
- **India**: -0.19t$CO_2$/yr
- **Philippines**: 0.37t$CO_2$/yr
- **Kenya**: 0.19t$CO_2$/yr

This gives the following total per-person annual emissions:

- **UK**: 7t$CO_2$/yr
- **Germany**: 8.97t$CO_2$/yr
- **Italy**: 6.95t$CO_2$/yr
- **India**: 1.94t$CO_2$/yr
- **Philippines**: 1.72t$CO_2$/yr
- **Kenya**: 0.58t$CO_2$/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 CO2 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 ($CO_2$t) | India ($CO_2$e, tonnes) | Kenya ($CO_2$t) | Kenya ($CO_2$e, tonnes) | Philippines ($CO_2$t) | Philippines ($CO_2$e, 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 – 400t$CO_2$e 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 350t$CO_2$e over 50 years and be planted with 1,800 trees. This gives 194kg $CO_2$e per tree, or 3.9kg $CO_2$e 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$190/$tCO_2e$ 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$417/$tCO_2e$ 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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