Mallard
Pass
Solar Farm

Mallard Pass Solar Farm

Appendices to Response to Rule 17 Request for further information

Deadline 9 (10th November 2023)

EN010127
EN010127/APP/9.52
Revision 0

Planning Act 2008

Infrastructure Planning (Examination Procedure) Rules 2010

Mallard Pass Solar Farm

9.52 Appendices to Response to Rule 17 Request for further information

Regulation Reference:	N/A
Planning Inspectorate Scheme Reference	EN010127
Application Document Reference	EN010127/APP/9.52
Author	Mallard Pass Project Team

Version	**Date**	**Status of Version**
Rev 00	10 November 2023	Deadline 9 Version

Table of Contents

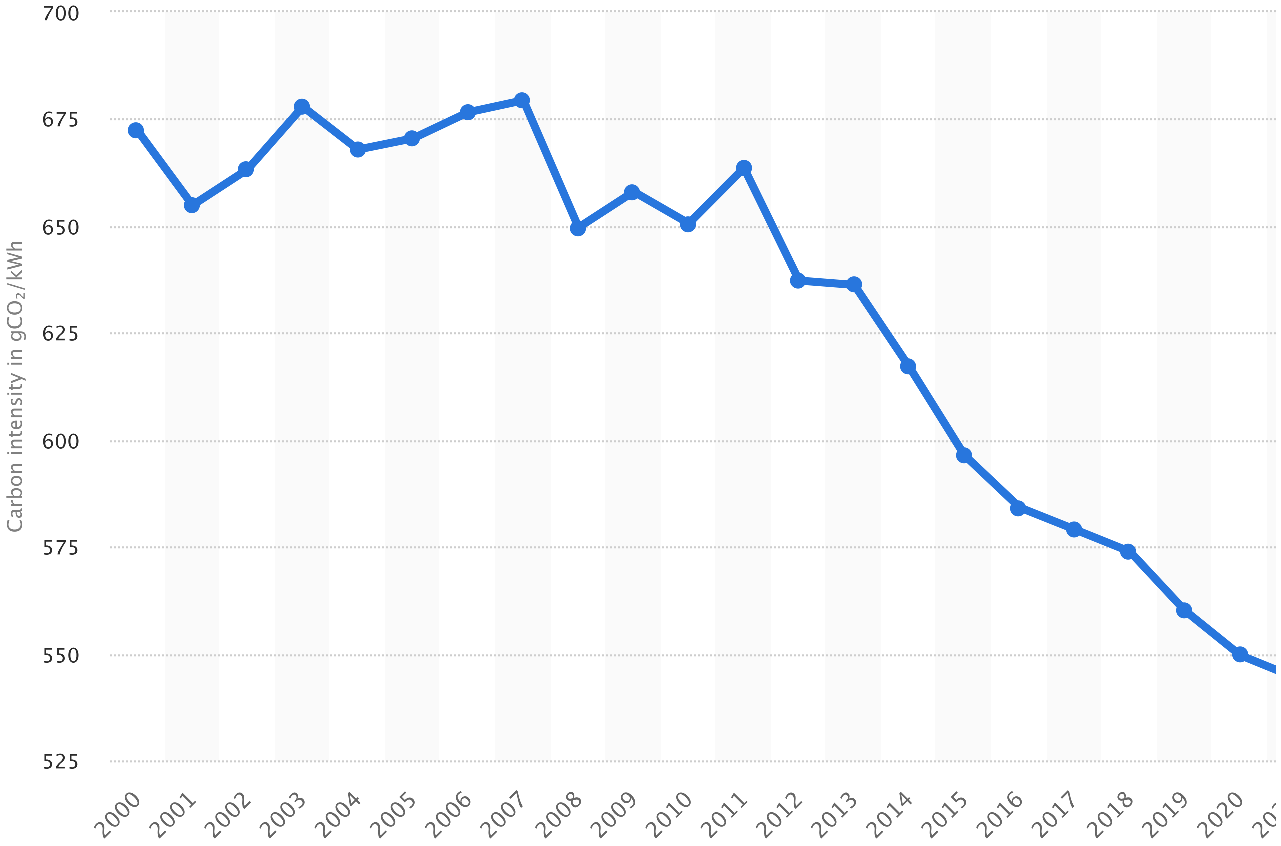
Appendices

Appendix A China

Source: https://www.statista.com/statistics/1300419/power-generation-emission-intensity-china/

Carbon intensity of the power sector in China from 2000 to 2022

(in grams of CO_2 per kilowatt-hour)



Additional Information

Show source

Source

- Show sources information
- Show publisher information
- Use Ask Statista Research Service

In cooperation with

EMBER

Release date

June 2023

Region

China

Survey time period

2000 to 2022

Supplementary notes

Figures aim to include full lifecycle emissions including upstream methane, supply-chain and manufacturing emissions, and include all gases, converted into CO_2 equivalent over a 100 year timescale.

Citation formats

➞ View options

Power sector carbon intensity in China 2000-2022

Published by Ian Tiseo, Jul 4, 2023

The carbon intensity of electricity generation in China was 531.15 grams of carbon dioxide per kilowatt-hour (gCO_2/kWh) in 2022. Although China's emission intensity has fallen over the past two decades, it remains high. This is mainly due to the country's dependence on coal power generation.

Appendix B Taiwan

You are here: Home > Policies > Electricity > 2021 Electricity Carbon Emissi

2021 Electricity Carbon Emission Factor

$$\frac{\text{Electricity carbon emissions from the sales of electricity of the Electricity Retailing Utility Enterprise by the Electricity Generating Enterprise and the Self-Usage Power Generation Equipment - Electricity carbon emissions from line loss}}{\text{Total electricity sold by the Electricity Retailing Utility Enterprise}} = 0.509 \text{ kg } CO_2e/kWh$$

Explanation:

1.Scope of application: In response to the greenhouse gas inventory quantification operation, electricity carbon emission factor serves as the basis for calculating the greenhouse gas emissions from indirect fuel combustion required for the purchase and use of the Electricity Retailing Utility Enterprise’s electricity.

2.The above calculation results are handled in accordance with the "Standard Operating Procedures for the Calculation of Electricity Carbon Emission Factor of the Electricity Retailing Utility Enterprise" and are used as reference only. The results of electricity carbon emission factors over the years are summarized as follows:

Unit: kg CO_2e/kWh

Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Electricity Carbon Emission Factor	0.555	0.562	0.558	0.555	0.543	0.534	0.534	0.529	0.519	0.518	0.525	0.530	0.554	0.533	0.509	0.502	0.509

Update: 2023-05-29

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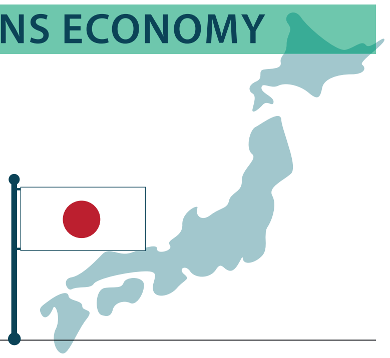
Appendix C Japan

Climate Transparency

BROWN TO GREEN: 2019

THE G20 TRANSITION TOWARDS A NET-ZERO EMISSIONS ECONOMY

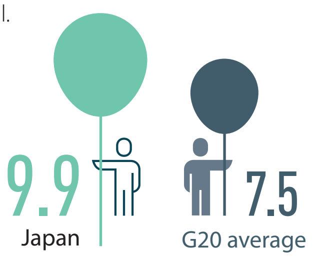


JAPAN

Japan's greenhouse gas (GHG) emissions are – per capita – well above the G20 average.

Japan's total GHG emissions (excl. land use) have decreased recently but not enough to be less than the country's 1990 level.

Greenhouse gas (GHG) emissions (incl. land use) per capita[1]
(tCO_2e/capita)



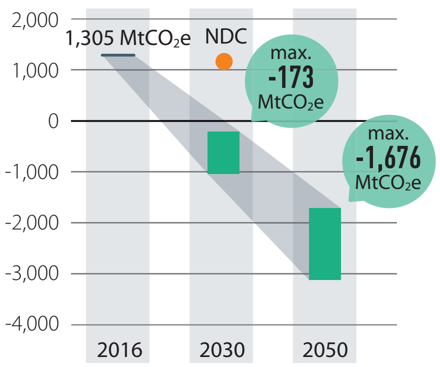
Data for 2016
Source: CAT 2019; PRIMAP 2018; World Bank 2019

Trend (2011-2016) 👍 -4% 👍 -1%

Japan is not on track for a 1.5°C world. Japan's 2030 NDC proposes to limit its emissions to 1,078 $MtCO_2e$.

According to the Climate Action Tracker, a fair-share range compatible with global 1.5°C IPCC scenarios could be achieved via strong domestic emissions reductions and could be supplemented with contributions to global emissions-reduction efforts. Japan's fair-share range is below -173 $MtCO_2e$ by 2030 and below -1,676 $MtCO_2e$ by 2050. Under current policies, Japan's emissions are projected to be between 1,082 and 1,144 $MtCO_2e$ in 2030. All figures exclude land use.

1.5°C compatible pathway[2]
($MtCO_2e$/year)



Source: CAT 2019

Recent developments[3]

👍 Japan published a long-term strategy in 2019 that aims to reduce GHG emissions by 80% by 2050 and to become carbon-neutral as early as possible in the second half of this century.

👎 The 2030 Strategic Energy Plan envisages the construction of new coal and nuclear plants.

👎 Japan has reduced the unit price for its feed-in-tariff as it aims to reduce the economic costs of its renewable energy support scheme.

Key opportunities for enhancing climate ambition[3]

32% of Japan's electricity supply comes from coal

→ **Japan needs to include the phasing out of coal in its next strategic energy plan.**

#1

Japan spent US$1.8 billion on fossil fuel subsidies in 2017

→ **The country needs to phase out fossil fuel subsidies by 2030 and introduce higher carbon pricing.**

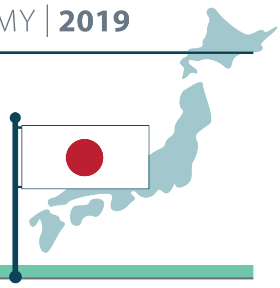
#2

Japan remains one of the largest providers of public finance for coal overseas (US$5.2 bn per year)

→ **The country needs to phase out international finance for coal to keep global warming below 1.5°C and reduce the risk of stranded assets.**

#3

This country profile is part of the **Brown to Green 2019** report. The full report and other G20 country profiles can be downloaded at: *http://www.climate-transparency.org/g20-climate-performance/g20report2019*



JAPAN – SOCIO-ECONOMIC CONTEXT

Human Development Index

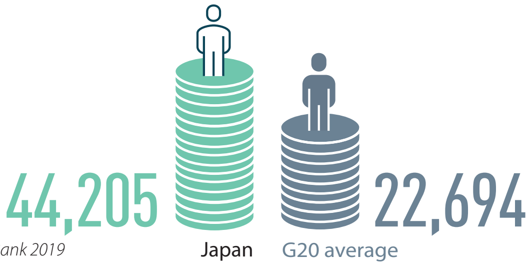
0.909

The Human Development Index reflects life expectancy, level of education, and per capita income. Japan ranks among the highest countries.

Data for 2017 | Source: UNDP 2018

Gross Domestic Product (GDP) per capita

(PPP US$ const. 2018, international)

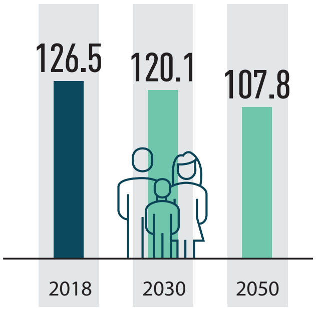


Data for 2018 | Source: World Bank 2019

Population projections

(millions)

Japan's population is expected to decrease by around 15% by 2050.



Source: World Bank 2019

Death through ambient air pollution

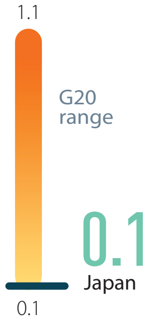
(total ambient air pollution attributable deaths)

Almost 55,000 people die in Japan every year as a result of outdoor air pollution, due to stroke, heart disease, lung cancer and chronic respiratory diseases. Compared to total population, this is one of the lowest levels in the G20.

54,780

attributable deaths

Data for 2016
Source: World Health Organization 2018



Ambient air pollution attributable death rate per 1,000 population per year, age standardised

JUST TRANSITION[3]

Prior to the Fukushima Daiichi nuclear disaster in March 2011, Japan was on course to reduce its reliance on coal and gas power generation (both imported), and was aiming at increasing the role of nuclear power.

But since the disaster, and the requirement for safety upgrades at all nuclear plants, the resulting absence of nuclear power has meant that Japan has increased its reliance on coal and gas (32% and 35% respectively in the electricity mix in 2017).

Japan submitted its first NDC in 2015 and intends to reduce reliance on coal and gas (to 26% and 27% each in electricity mix in 2030).

Japan mentioned 'just transition' in its long-term strategy, noting that "the Government, local authorities and companies will work together to provide vocational training to the workforce, support for diversification and shifts in business operations, inviting new business and support for placement of the labour force, in order to achieve the transition of the workforce to a decarbonized society smoothly and without delay". However, there is as yet no concrete plan.

Legend for all country profiles

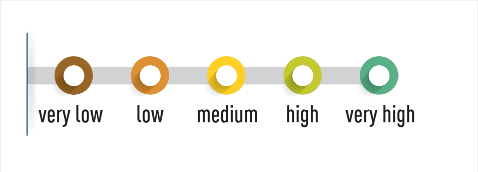
Trends

👍 👎 The trends show developments over the past five years for which data are available.

The thumbs indicate assessment from a climate protection perspective.

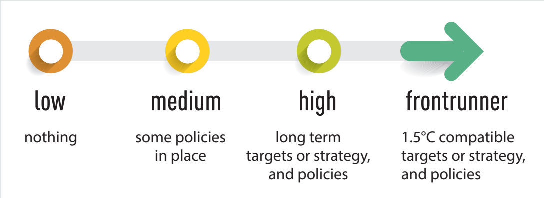
Decarbonisation Ratings[4]

These ratings assess a country's performance compared to other G20 countries. A high scoring reflects a relatively good effort from a climate protection perspective but is not necessarily 1.5°C compatible.



Policy Ratings[5]

The policy ratings evaluate a selection of policies that are essential pre-conditions for the longer-term transformation required to meet the 1.5°C limit.



For more information see the Annex and Technical Note

MITIGATION BIG PICTURE

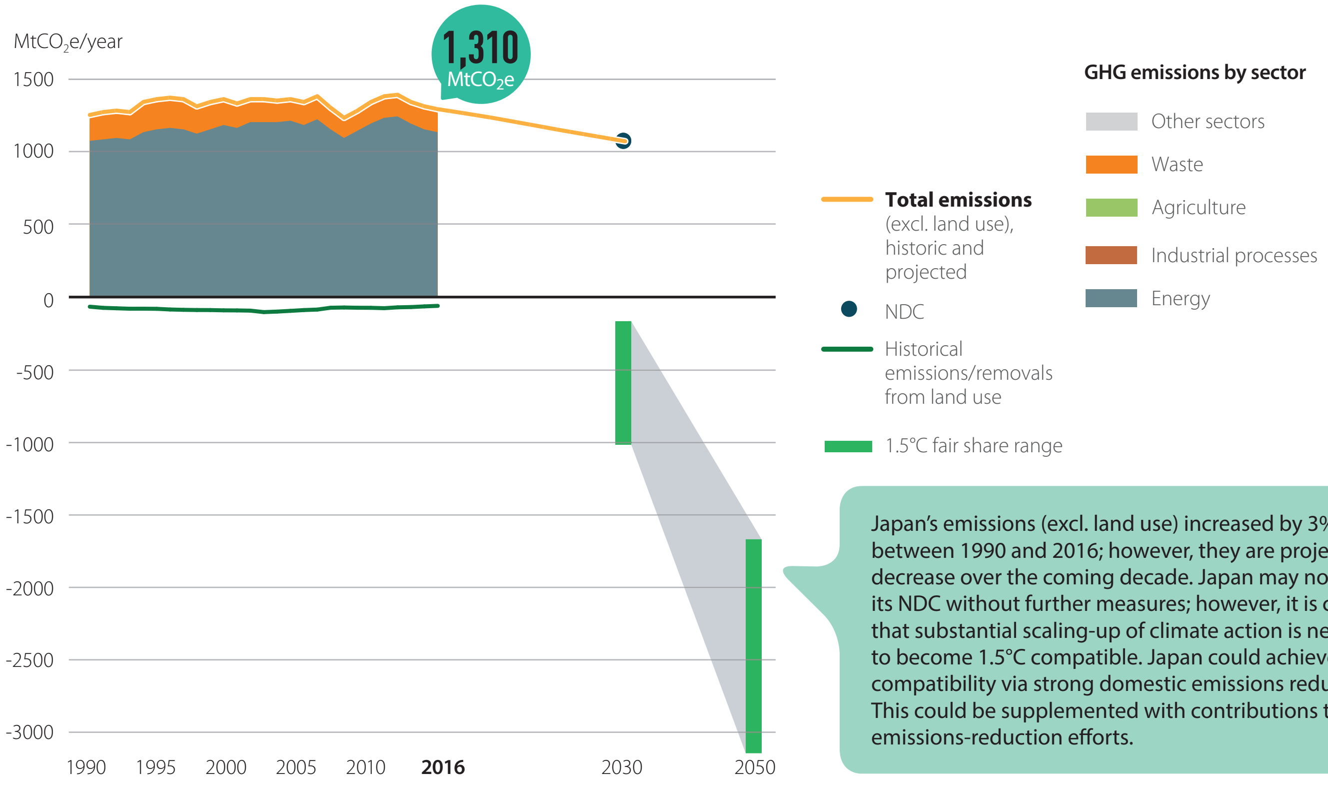
Japan's GHG emissions have increased by 3% (1990-2015) and the government's climate targets for 2030 (-26% compared to 2013) are not in line with a 1.5°C pathway.

In 2030, global GHG emissions need to be 45% below 2010 levels and reach net zero by 2070.

1.5°C[6]

Source: IPCC SR1.5 2018

Total GHG emissions across sectors[2]



Source: PRIMAP 2018; CAT 2019

Japan's emissions (excl. land use) increased by 3% between 1990 and 2016; however, they are projected to decrease over the coming decade. Japan may not achieve its NDC without further measures; however, it is clear that substantial scaling-up of climate action is needed to become 1.5°C compatible. Japan could achieve 1.5°C compatibility via strong domestic emissions reductions. This could be supplemented with contributions to global emissions-reduction efforts.

Nationally-determined contribution (NDC): Mitigation

Targets	26.0% of emission reductions by fiscal year 2030 compared to fiscal year 2013 (25.4% reduction compared to fiscal year 2005)
Actions	Actions specified (sectors: industry, transport, energy, waste, agriculture, land use and forestry)

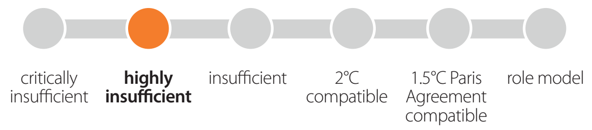
Source: UNFCCC, NDC of respective country

Long-term strategy (LTS) to be submitted to the UNFCCC by 2020

Status	Submitted to UNFCCC in 2019
2050 target	80% reduction by 2050 (no base year provided), 'decarbonised society' as early as possible in the second half of this century
Interim steps	–
Sectoral targets	–

Source: UNFCCC, LTS of respective country

Climate action tracker (CAT) evaluation of NDC[2]



Source: CAT 2019

MITIGATION ENERGY

JAPAN

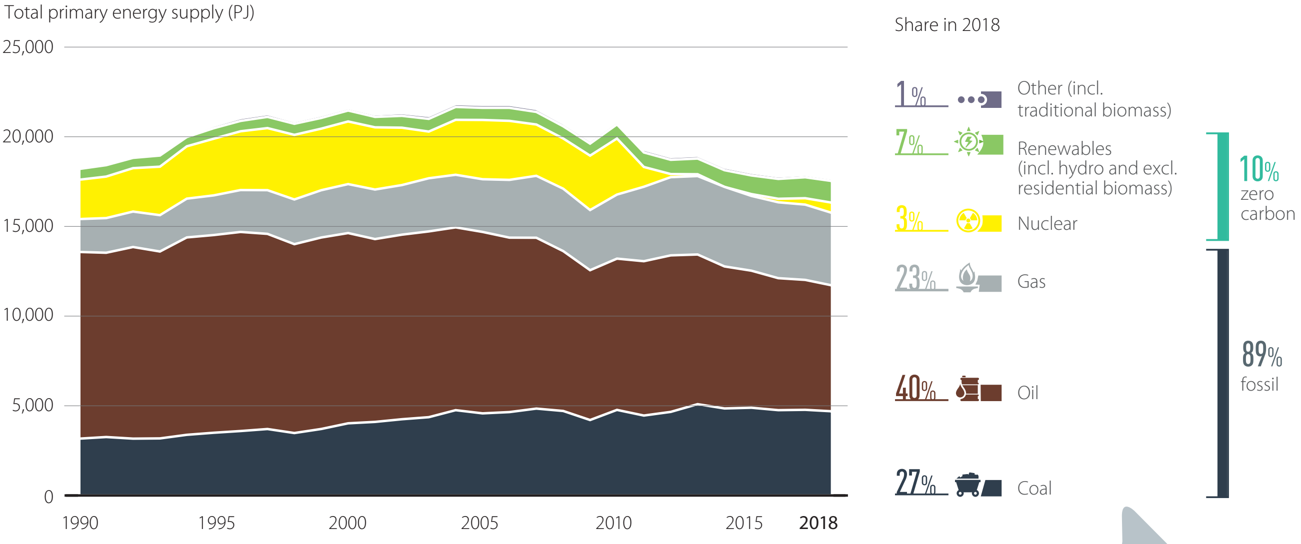
Fossil fuels still make up 89% of Japan's energy mix (including power, heat, transport fuels, etc). Renewables have increased only marginally over the last few decades.

The share of fossil fuels globally needs to fall to 67% of global total primary energy by 2030 and to 33% by 2050 and to substantially lower levels without Carbon Capture and Storage.

1.5°C[6]

Source: IPCC SR1.5 2018

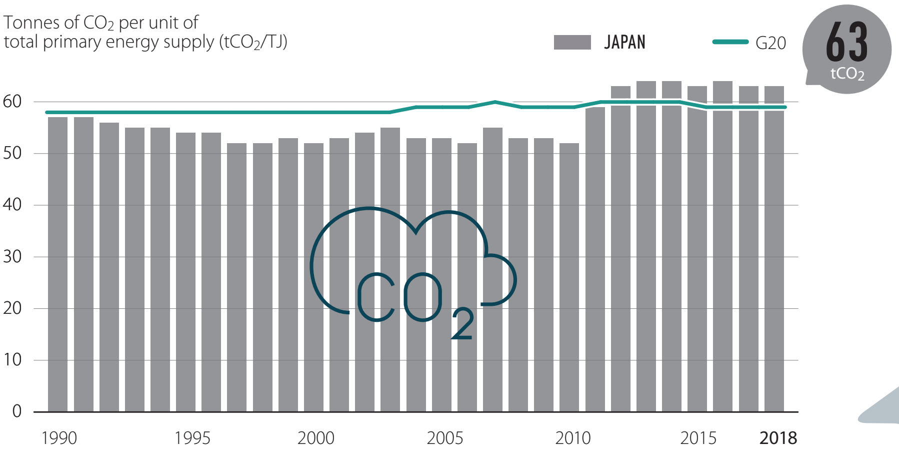
Energy mix[7]



Source: Enerdata 2019

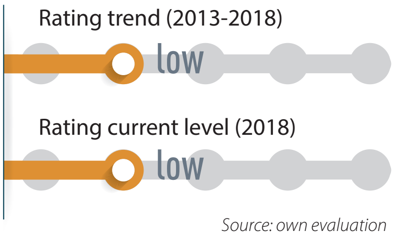
This graph shows the fuel mix for all energy supply, including energy used for electricity generation, heating, cooking, and transport fuels. Fossil fuels (oil, coal and gas) still make up 89% of the Japanese energy mix. This is above the G20 average of 82%.

Carbon intensity of the energy sector



Source: Enerdata 2019

Rating of carbon intensity compared to other G20 countries[4]



Source: own evaluation

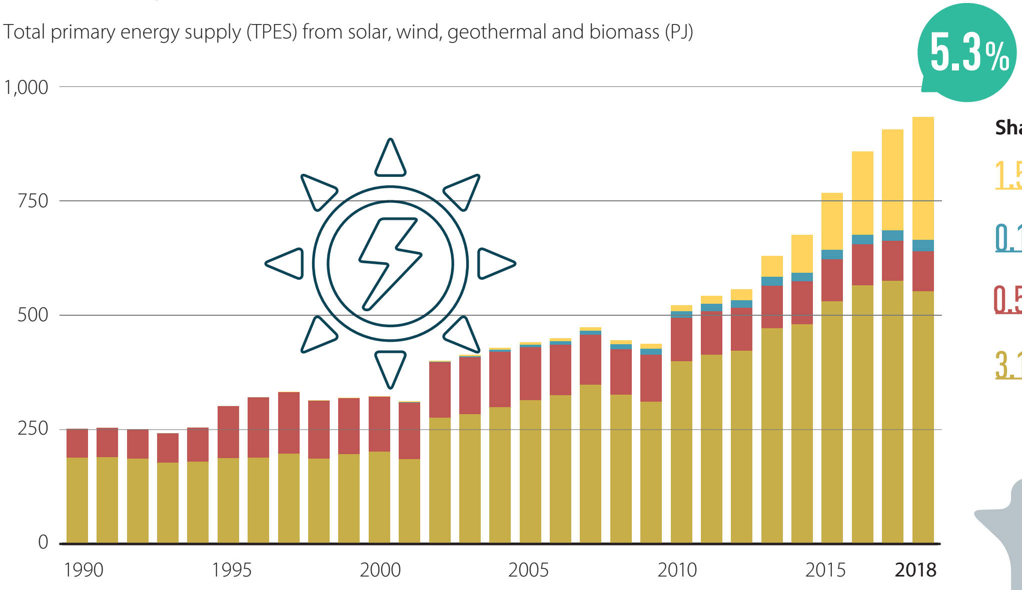
Carbon intensity shows how much CO_2 is emitted per unit of energy supply. In Japan, carbon intensity has remained almost constant at around 63 tCO_2/TJ over the last six years and is slightly above the G20 average (59tCO_2/TJ). This high level reflects the consistent high share of fossil fuels in the energy mix.

MITIGATION ENERGY

JAPAN

Solar, wind, geothermal and biomass development[8]

Total primary energy supply (TPES) from solar, wind, geothermal and biomass (PJ)



Source: Enerdata 2019

Share of TPES in 2018

1.52 %	Solar
0.14 %	Wind
0.50 %	Geothermal
3.13 %	Biomass, excl. traditional biomass

Solar, wind, geothermal and biomass account for 5% of Japan's energy supply – the G20 average is 6%. In the last five years, the share of these sources in total energy supply has increased by around 61%, much more than the G20 average (+29% 2013-2018). Bioenergy (for electricity, biofuels for transportation and heat) makes up the largest share.

Rating of share in TPES compared to other G20 countries[4]

Rating trend (2013-2018): high

Rating current level (2018): low

Source: own evaluation

Energy supply per capita

Total primary energy supply per capita (GJ/capita)

140	98
Japan	G20 average

The level of energy supply per capita is closely related to economic development, climatic conditions and the price of energy.

At 140 GJ/capita, energy supply per capita in Japan is well above the G20 average (98 GJ/capita), but is decreasing (-5%, 2013-2018) in contrast to the increasing G20 average (+1%).

Trend (2013-2018) -5% +1%

Data for 2018 | Source: Enerdata 2019; World Bank 2019

Rating of energy supply per capita compared to other G20 countries[4]

Rating trend (2013-2018): medium

Rating current level (2018): low

Source: own evaluation

MITIGATION ENERGY

! While Japan's economy remains less energy intensive than the G20 average, energy supply per capita is still comparatively high and energy-related CO_2 emissions are only decreasing slightly.

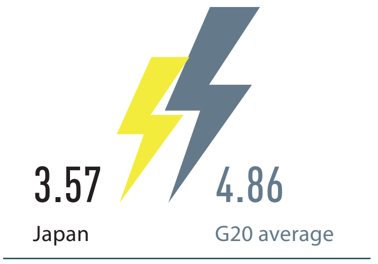
Global energy and process-related CO_2 emissions must be cut by 40% below 2010 levels by 2030 and reach net zero by 2060.

1.5°C[6]

Source: IPCC SR1.5 2018

Energy intensity of the economy

(TJ/PPP US$2015 million)

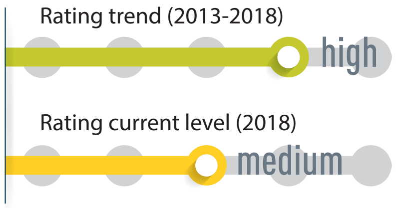


This indicator quantifies how much energy is used for each unit of GDP. This is closely related to the level of industrialisation, efficiency achievements, climatic conditions or geography. Japan's energy intensity is below the G20 average and has decreased by an amount (-11%, 2013-2018) similar to the G20 average.

Trend (2013-2018) 👍 -11% 👍 -12%

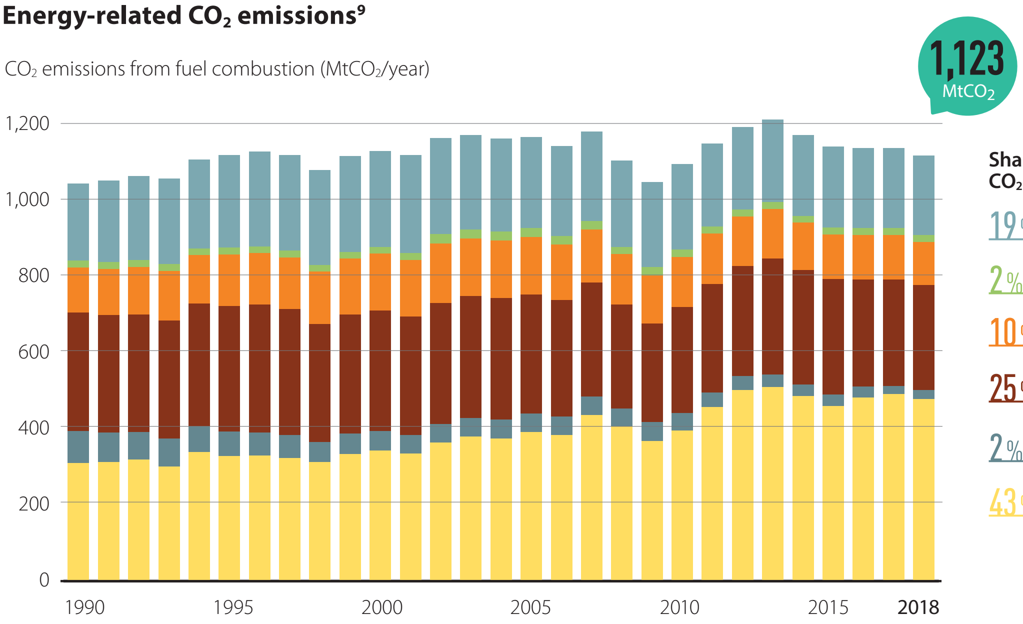
Data for 2018 | Source: Enerdata 2019; World Bank 2019

Rating of energy intensity compared to other G20 countries[4]



Source: own evaluation

Energy-related CO_2 emissions[9]



Source: Enerdata 2019

Share of total energy-related CO_2 emissions in 2018

19 %	Transport
2 %	Agriculture
10 %	Buildings
25 %	Industries (incl. autoproducers)
2 %	Other energy sector
43 %	Electricity and heat

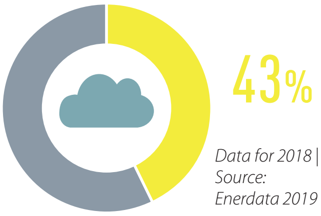
The largest driver of overall GHG emissions are CO_2 emissions from fuel combustion. In Japan, they have recently started to decrease again. At 43%, the electricity sector is the largest contributor, followed by industries at 25% and transport at 19%.

MITIGATION POWER SECTOR

JAPAN

! Japan still produces 32% of its electricity from coal and plans to add a further 6.6 GW of coal capacity. This is not compatible with a 1.5°C pathway, as coal will have to be phased out soon.

Share in energy-related CO_2 emissions



Data for 2018 | Source: Enerdata 2019

Coal must be phased out in the EU/OECD no later than 2030, in the rest of the world no later than 2040. Electricity generation needs to be decarbonised before 2050, with renewable energy the most promising option.[5]

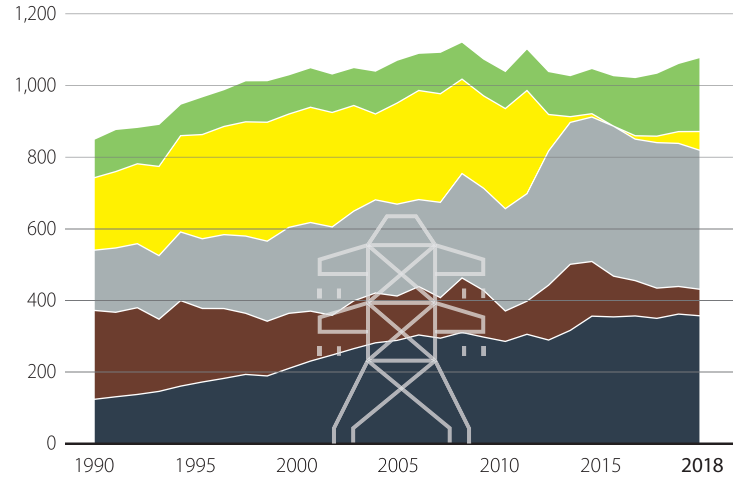
1.5°C[6]

Source: IPCC SR1.5 2018; Climate Analytics 2016; Climate Analytics 2019

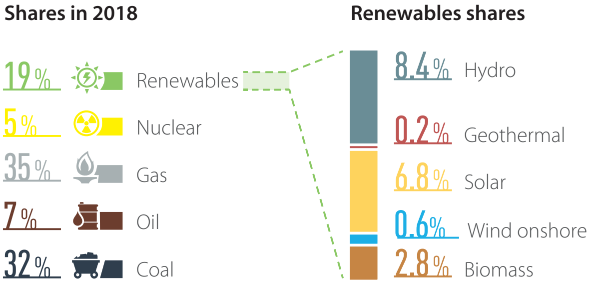
STATUS OF DECARBONISATION

Power mix

Gross power generation (TWh)

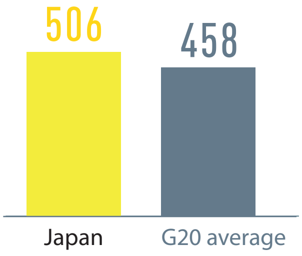


Source: Enerdata 2019



Japan is increasingly producing energy from renewable sources, which now make up 19% of the electricity mix – the G20 average is 25%. The main renewable sources are hydro and solar power. They have mostly replaced nuclear power. Power generation from fossil fuels has increased considerably (now 74%).

Emissions intensity of the power sector
(gCO_2/kWh)

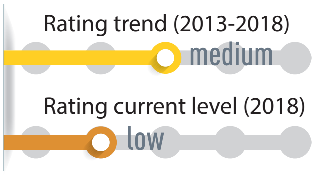


Data for 2018 | Source: Enerdata 2019

Trend (2013-2018)

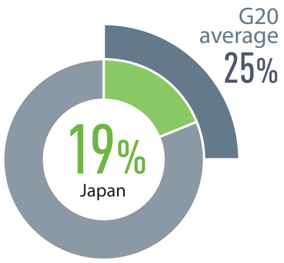
-8%	-11%
Japan	G20 average

Rating of emissions intensity compared to other G20 countries[4]



Source: own evaluation

Share of renewables in power generation
(incl. large hydro)

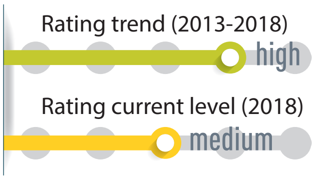


Data for 2018 | Source: Enerdata 2019

Trend (2013-2018)

+54%	+20%
Japan	G20 average

Rating of share of renewables compared to other G20 countries[4]



Source: own evaluation

For each kilowatt hour of electricity, $506gCO_2$ are emitted in Japan. This is above the G20 average. Emission intensity has dropped by 8% in the past five years, reflecting the increasing share of renewables.

MITIGATION POWER SECTOR

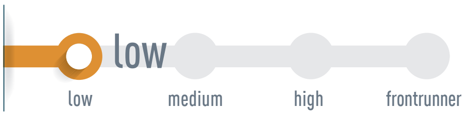
POLICIES[5]

Renewable energy in the power sector

Japan aims to increase the share of renewables in the electricity mix to 22-24% by 2030 (from 15% in 2016). According to Japan's new long-term strategy, renewables will become "a stable main power source", although the government has not set a 2050 target.

Source: own evaluation

Coal phase-out in the power sector



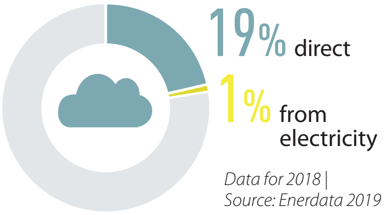
In 2015, Japan set a goal of reducing its share of coal power in the electricity mix to 26% (from 32% in 2016) and to phase out inefficient coal power plants. However, 8.7 GW of coal capacity is currently under construction and Japan has plans to add a further 6.6 GW.

Source: own evaluation

MITIGATION TRANSPORT SECTOR

In Japan, 63% of passenger transport is by private car, and 87% of freight transport is by road. The sector is still dominated by fossil fuels, and electric vehicles make up only 1% of car sales. While some policies have been implemented for reducing fossil fuel use, modal shift policies are generally non-existent.

Share in energy-related CO_2 emissions



Data for 2018 | Source: Enerdata 2019

The proportion of low-carbon fuels in the transport fuel mix must increase to about 60% by 2050.

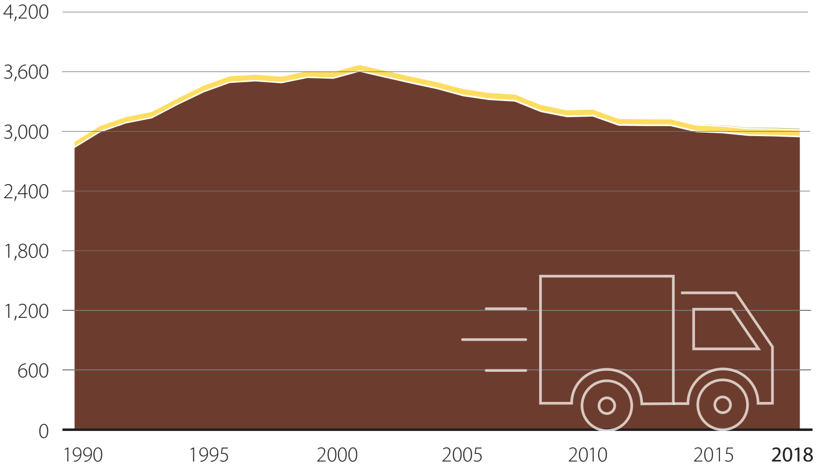
1.5°C[6]

Source: IPCC SR1.5 2018

STATUS OF DECARBONISATION

Transport energy mix

Final energy consumption of transport by source (PJ/year)



Share in 2018

0.6%	Biofuels
2.2%	Electricity
0.1%	Gas
97.1%	Oil
0.0%	Coal

Electricity and biofuels make up only 3% of the energy mix in transport.

Source: Enerdata 2019

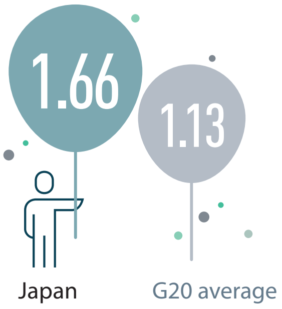
MITIGATION TRANSPORT SECTOR

JAPAN

STATUS OF DECARBONISATION (continued)

Transport emissions per capita[10]

(tCO₂/capita,
excl. aviation emissions)



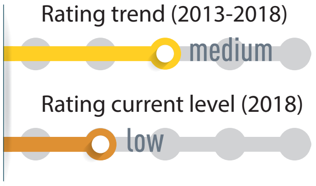
Data for 2018
Source: Enerdata 2019; World Bank 2019

Trend (2013-2018)

👍 -3% Japan

👎 +5% G20 average

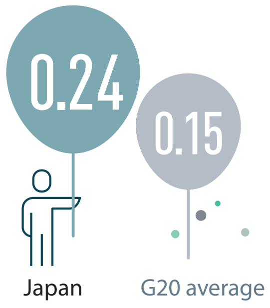
Rating of transport emissions compared to other G20 countries[4]



Source: own evaluation

Aviation emissions per capita[11]

(tCO₂/capita)



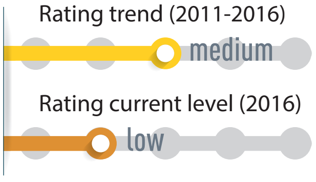
Data for 2016
Source: Enerdata 2019; IEA 2018

Trend (2011-2016)

👎 +4% Japan

👎 +10% G20 average

Rating of aviation emissions compared to other G20 countries[4]



Source: own evaluation

Motorisation rate

(vehicles per 1,000 inhabitants)

719

Data for 2016 | Source: Agora 2018

Market share of electric vehicles in new car sales

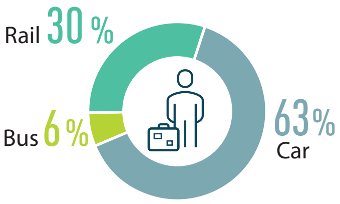
(%)

1.1%

Data for 2018 | Source: IEA 2019

Passenger transport

(modal split in % of passenger km)



Data for 2009 | Source: Agora 2018

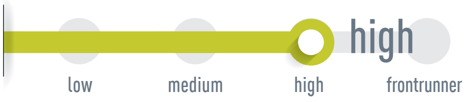
Freight transport

(modal split in % of tonne-km)

Data for 2015 | Source: Agora 2018

POLICIES[5]

Phase out fossil fuel cars



In 2018, the Japanese government announced that by 2050 all cars sold would be electrified (no fossil fuel cars by 2035 would be 1.5°C compatible). The country aims to have electric vehicles account for 20-30% of car sales by 2030. Japan has a fuel efficiency labelling system, and tax breaks and subsidies for low-carbon vehicles.

Source: own evaluation

Phase out fossil fuel heavy-duty vehicles

Japan has no strategy for reducing absolute emissions from freight transport. In March 2019, the government tightened the fuel efficiency standards, requiring manufacturers to enhance efficiency by approximately 13.4% for heavy duty vehicles and 14.3% for buses, compared to the 2015 standards, by 2025.

Source: own evaluation

Modal shift in (ground) transport

Japan states in its long-term strategy that it will facilitate the modal shift from car transport to coastal shipping or rail transport in order to reduce CO_2 emissions and countermeasure labour shortages in the logistics.

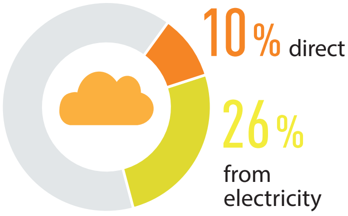
Source: own evaluation

JAPAN

MITIGATION BUILDINGS SECTOR

Japan's building emissions –including heating, cooking and electricity use – make up over a third of total CO_2 emissions. Per capita, building-related emissions are more than double the G20 average. To get on a 1.5°C track, all new buildings need to be near-zero energy, and renovation rates need to increase.

Share in energy-related CO_2 emissions



Data for 2018 | Source: Enerdata 2019

Global emissions from buildings need to be halved by 2030, and be about 80% below 2010 levels by 2050, achieved mostly through increased efficiency, reduced energy demand and electrification in conjunction with complete decarbonisation of the power sector.

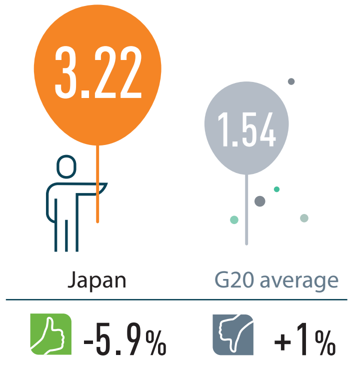
1.5°C[6]

Source: IEA ETP B2DS scenario assessed in IPCC SR1.5 2018

STATUS OF DECARBONISATION

Building emissions per capita

(incl. indirect emissions)
(tCO_2/capita)

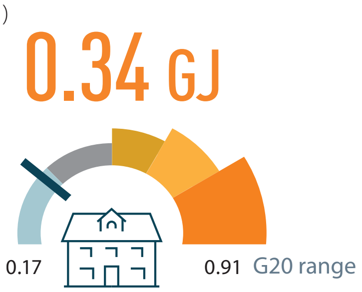


Trend (2013-2018)

Data for 2018 | Source: Enerdata 2019; World Bank 2019

Residential buildings: energy use per m²

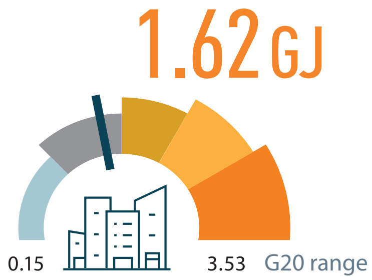
(GJ)



Data: year different per country | Source: ACEEE 2018

Commercial and public buildings: energy use per m²

(GJ)

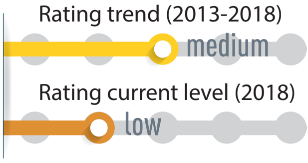


Data: year different per country | Source: ACEEE 2018

Building-related emissions per capita are more than double the G20 average, reflecting the large floor space per person. In contrast to the G20 average, Japan has reduced this level by 6% (2013-2018).

Building emissions are largely driven by how much energy is used in heating, cooling, lighting, household appliances, etc. In Japan, energy use per m² is in the lower range of the G20 countries for residential building and in the middle one for commercial and public ones.

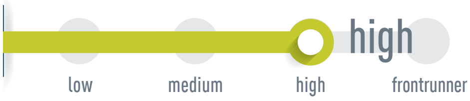
Rating of building emissions compared to other G20 countries[4]



Source: own evaluation

POLICIES[5]

Near-zero energy new buildings



Japan's 2014 Strategic Energy Plan aims to achieve net-zero energy buildings by 2020 for new non-residential buildings and by 2030 for new public buildings nationwide. For residential buildings, Japan aims to achieve net-zero energy houses for all newly constructed houses on average by 2030 (2020 for all new buildings would be 1.5°C compatible). Grants and subsidies support implementation.

Source: own evaluation

Renovation of existing buildings

Japan's long-term strategy states that existing buildings will be renovated and rebuilt to improve energy efficiency. However, the government has not set quantitative targets. Low-interest loans and rebates are available for construction and retrofit costs for buildings.

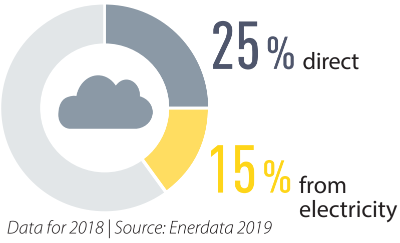
Source: own evaluation

MITIGATION INDUSTRY SECTOR

JAPAN

Industry-related emissions make up 40% of CO_2 emissions in Japan. Although the Japanese industry sector is already comparatively energy efficient, emissions need to be significantly reduced to stay within the 1.5°C limit.

Share in energy-related CO_2 emissions (not including process emissions)



Data for 2018 | Source: Enerdata 2019

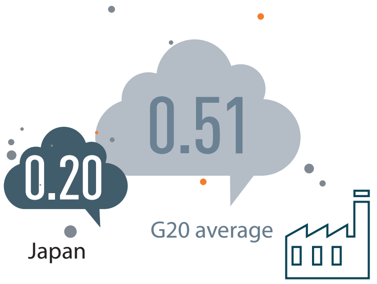
Global industrial CO_2 emissions need to be reduced by 65–90% from 2010 levels by 2050.

1.5°C[6]

Source: IPCC SR1.5 2018

STATUS OF DECARBONISATION

Industry emissions intensity[12]
(tCO_2e/US$2015 GVA)

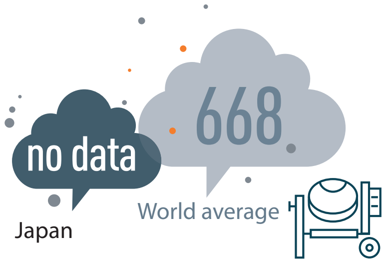


Data for 2016 | Source: Enerdata 2019; PRIMAP 2018; World Bank 2019

👍 -5.3% 👍 -10.2%

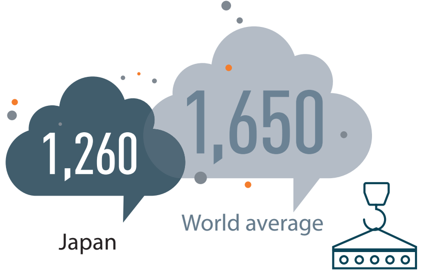
Trend (2011-2016)

Carbon intensity of cement production[13]
($kgCO_2$/tonne product)



Data for 2015 | Source: CAT 2019

Carbon intensity of steel production[13]
($kgCO_2$/tonne product)

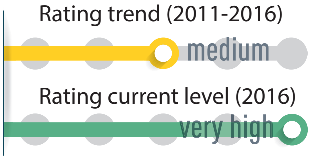


Data for 2015 | Source: CAT 2019

When comparing industrial emissions with the gross value added (GVA) from the industry sector, Japan performs comparatively well within the G20.

Steel production and steelmaking are significant GHG emission sources, and are challenging to decarbonise. Japan's steel industry is less emission intensive than the world average.

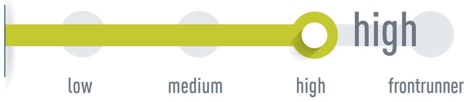
Rating of emissions intensity compared to other G20 countries[4]



Source: own evaluation

POLICIES[5]

Energy efficiency



According to the International Energy Agency (IEA), Japan's mandatory energy efficiency policies covered 26-50% of industrial energy use in 2017. However, the Act on the Rational Use of Energy (revised in 2018) covers 90% of industrial use of energy. The Act established energy efficiency benchmarks for industry for sub-sectors such as iron and steel, cement, and electricity supply. Companies covered by the scheme must take measures for energy efficiency and report their energy use annually.

Source: own evaluation

JAPAN

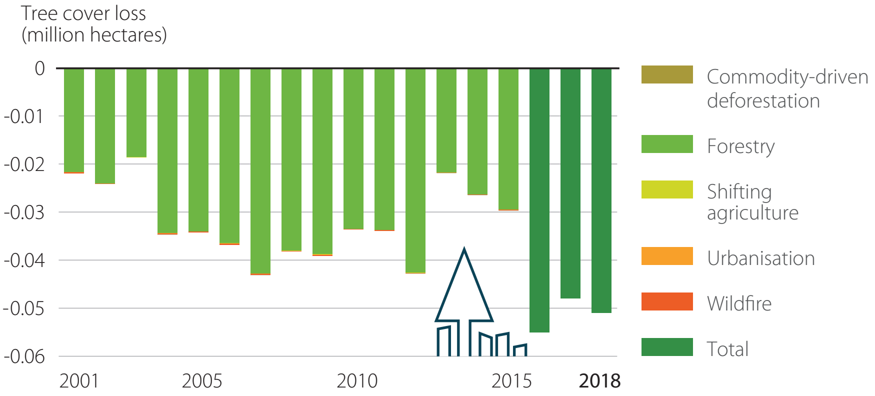
MITIGATION LAND USE

! **In order to stay within the 1.5°C limit, Japan needs to make the land use and forest sector a net sink of emissions.**

Global deforestation needs to be halted and changed to net CO_2 removals by around 2030. 1.5°C[6]

Source: IPCC SR1.5 2018

Gross tree cover loss by dominant driver[14]



Source: Global Forest Watch 2019

Note: 2000 tree cover extent | >30% tree canopy | these estimates do not take tree cover gain into account

From 2001 to 2018, Japan lost 663kha of tree cover, equivalent to a **2.5% reduction since 2000**. This does not take tree-cover gain into account.

POLICIES[5]

(Net) zero deforestation

Japan has a mandatory reporting system of reforestation after harvesting. It has announced that a Forest Environmental Tax will be introduced from 2024. The tax revenue will be used for forest management to help achieve Japan's NDC. The NDC aims at removals by forest carbon sinks of approximately 27.8 million t-CO_2 by 2030.

Source: own evaluation

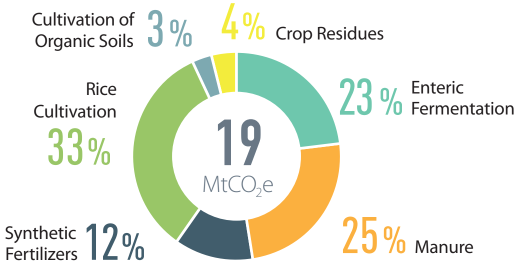
MITIGATION AGRICULTURE

! **Japan's agricultural emissions are mainly from rice cultivation, digestive processes in animals, and livestock manure. A 1.5°C pathway requires carbon storage in cropland soil as well as the application of organic matter such as compost and green manure on to the soil.**

Global methane emissions (mainly enteric fermentation) need to decline by 10% by 2030 and by 35% by 2050 (from 2010 levels). Nitrous oxide emissions (mainly from fertilzers and manure) need to be reduced by 10% by 2030 and by 20% by 2050. 1.5°C[6]

Source: IPCC SR1.5 2018

GHG emissions from agriculture (not including energy)



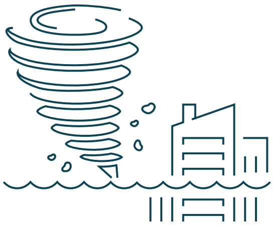
Data for 2016 | Source: FAOSTAT 2019

In Japan, the largest sources of GHG emissions in the agricultural sector are rice cultivation, digestive processes in animals (enteric fermentation), and livestock manure. A shift to organic farming, more efficient use of fertilizers, and diet changes could help reduce emissions.

JAPAN

ADAPTATION

- → **Japan is vulnerable to climate change and adaptation actions are needed.**
- → **On average, 79 fatalities and losses amounting to US$2.7 billion occur yearly due to extreme weather events.**
- → **With global warming, society and its supporting sectors are increasingly exposed to severe climate events, such as a reduction in crop duration for rice.**



ADAPTATION POLICIES

Nationally-determined contribution: Adaptation

Targets	Not mentioned
Actions	Not mentioned

Source: UNFCCC, NDC of respective country

National adaptation strategies

Document name	**Publication year**	**Fields of action (sectors)**													**M&E process (reporting frequency)**
		Agriculture	Biodiversity	Coastal areas & fishing	Education & research	Energy & industry	Finance & insurance	Forestry	Health	Infrastructure	Tourism	Transport	Urbanism	Water	
National Plan for Adaptation to the Impacts of Climate Change	2015	x		x	x	x	x	x	x	x	x	x	x	x	Revision planned every 5 years

Source: own research

JAPAN

ADAPTATION NEEDS

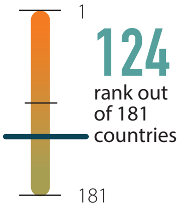
Climate Risk Index for 1998-2017

Impacts of extreme weather events in terms of fatalities and economic losses that occured

Global Climate Risk Index 2019 | All numbers are averages (1998-2017)

Weather-related fatalities	Per 100,000 inhabitants
79	0.1

Annual average losses (PPP US$ mn)	Per unit GDP (%)
2,738	0.1



Source: Germanwatch 2018

Japan has already been struck by extreme weather events such as storms, floods, landslides, heat waves, typhoons and droughts. In July 2018, Japan was hit by torrential rains unleashing floods and landslides, killing around 200 people. As highlighted by the numbers from the Climate Risk Index, such extreme weather events result in fatalities and economic losses. Climate change is expected to worsen the intensity, frequency and impacts of such events.

Exposure to future impacts at 1.5°C, 2°C and 3°C

		1.5°C	2°C	3°C
Water	% of area with increase in water scarcity	⬜	⬜	⬜
	% of time in drought conditions	🟨	🟨	🟧
Heat & Health	Heatwave frequency	⬜	🟨	🟥
	Days above 35°C	⬜	🟨	🟨

Source: own research

Agriculture	Rice	Reduction in crop duration	🟨	🟥	🟫
		Reduction in rainfall	🟥	🟧	🟧

Source: Based on Arnell et al 2019

Overall, with rising temperatures, all sectors are adversely affected. In the water sector, water scarcity slightly increases and time spent in drought conditions increases. Heat wave frequency increases significantly, together with an increase in the number of days when temperatures reach higher than 35°C.

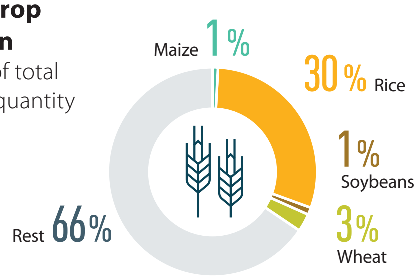
Impact ranking scale

⬜ Very low
🟨 Low
🟧 Medium
🟥 High
🟫 Very high

Blank cells signify that there is no data available

National crop production

(share in % of total production quantity in tonnes)



Data for 2017 | Source: FAOSTAT 2019

Rice represents the largest proportion of crop production out of the four crops analysed (maize, rice, soybeans, wheat). Rice is affected by a drastic reduction in crop duration and a reduction in rainfall.

FINANCE

JAPAN

! Japan spent US$1.8 billion on fossil fuel subsidies in 2017, mainly on petroleum and natural gas, but has generated over US$2 billion revenues through explicit carbon pricing.

Investment into green energy and infrastructure needs to outweigh fossil fuel investments by 2025.

1.5°C[6]

Source: IPCC SR1.5 2018

Nationally-determined contribution: Finance

Conditionality	Not applicable
Investment needs	Not specified
Actions	Not mentioned
International market mechanisms	Accumulated emission reductions or removals by 2030 through markets to be undertaken within the government's annual budget are estimated to be ranging from 50 to 100 million t-CO_2

Source: UNFCCC, NDC of respective country

Financial policy and regulation supporting a brown to green transition

Through policy and regulation governments can overcome challenges to mobilising green finance, including: real and perceived risks, insufficient returns on investment, capacity and information gaps.

Category	Instruments	Objective	Under discussion/ implementation	Not identified
Green Financial Principles	N/A	This indicates political will and awareness of climate change impacts, showing where there is a general discussion about the need for aligning prudential and climate change objectives in the national financial architecture.	x	

			Mandatory	Voluntary	Under discussion	Not identified
Enhanced supervisory review, risk disclosure and market discipline	Climate risk disclosure requirements	Disclose the climate-related risks to which financial institutions are exposed			x	
	Climate-related risk assessment and climate stress-test	Evaluate the resilience of the financial sector to climate shocks				x
Enhanced capital and liquidity requirements	Liquidity instruments	Mitigate and prevent market illiquidity and maturity mismatch		x		
	Lending limits	Limit the concentration of carbon-intensive exposures				x
		Incentivise low carbon-intensive exposures				x
	Differentiated Reserve Requirements	Limit misaligned incentives and canalise credit to green sectors				x

Source: own research

Japan has no overarching national framework for green finance. However, in 2017 a study group on long-term investment evaluating environmental, social and governance (ESG) factors and intangible assets in sustainable growth, produced guidance for companies and investors aimed at driving corporate disclosure. In 2004 an Environmental Rating Loan programme was established by the Development Bank of Japan providing preferential interest rates by evaluating a company's environmental management, while in 2007 Japan began subsidising interest payments on environmental-rating loans. In 2010 sectors and requirements for liquidity support were identified, including those relating to green sectors. In December 2018, the Japanese Ministry of Economy, Trade and Industry (METI) declared its support for the TCFD recommendations, although the timeline for implementing them is not yet clear.

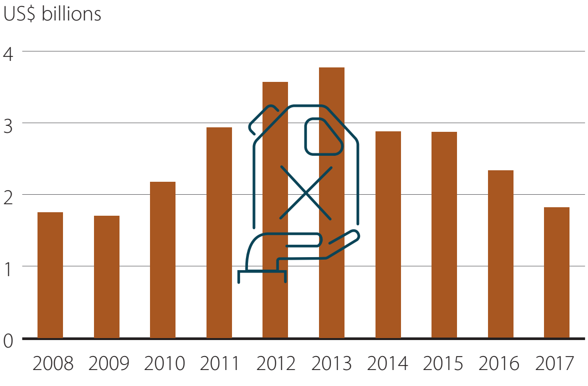
FINANCE

JAPAN

Fiscal policy levers

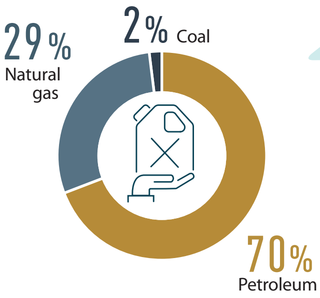
Fiscal policy levers raise public revenues and direct public resources. Critically, they can shift investment decisions and consumer behaviour towards low-carbon, climate-resilient activities by reflecting externalities in prices.

Fossil fuel subsidies



Source: OECD-IEA 2019

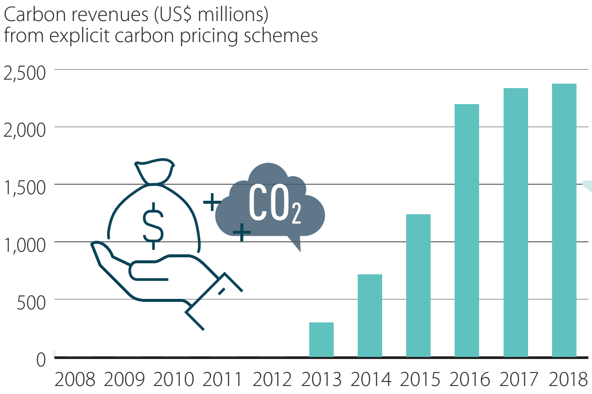
Subsidies by fuel type



Data for 2017 | Source: OECD-IEA 2019

In 2017, Japan's fossil fuel subsidies totalled US$1.8bn (compared to US$1.8bn in 2008, and the last decade's peak of US$3.8bn in 2013). Of the subsidies quantified, 99% were for consumption of fossil fuels. The highest amount of subsidies were for petroleum, at US$1.3bn, followed by natural gas at US$0.5bn. The largest subsidy was for oil stockpiling by the government in case of a major oil supply disruption (US$3.8bn).

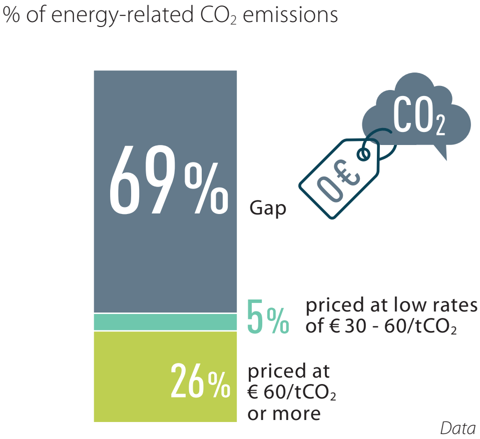
Carbon revenues



Source: I4CE 2019

Japan's 2012 national carbon tax covered 68% of domestic emissions and generated US$2.4bn in 2018. Japan's 2010-11 subnational emissions trading schemes (it is considering a national scheme) do not have complete revenue estimates. Emissions for these schemes are priced at US$6/tCO$_2$ (in 2019).

Carbon pricing gap[15]



Data for 2015 | Source: OECD 2018

Only 31% of Japan's CO$_2$ emissions are priced at EUR30 or higher (the low-end benchmark), creating a carbon pricing gap of 69%. This gap is slightly smaller than the G20 average of 71%. The price covers not only explicit carbon taxes but also specific taxes on energy use and the price of tradable emission permits.

FINANCE

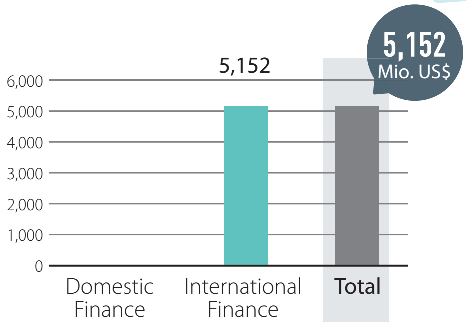
JAPAN

Public finance

Governments steer investments through their public finance institutions including via development banks, both at home and overseas, and green investment banks. Developed G20 countries also have an obligation to provide finance to developing countries and public sources are a key aspect of these obligations under the UNFCCC.

Public finance for coal[16]

(million US$)



Between 2016 and 2017, Japan's public finance institutions provided $5.2 billion per year for coal and coal-fired power production internationally. The projects that received the largest amount of finance were coal-fired power plants in Bangladesh, Indonesia and Viet Nam.

● Domestic Finance

● International Finance

Data year: 2016-2017 average
Source: Oil Change International 2019

Commitments to restrict public finance to coal and coal-fired power[17]

MDB level	National development agencies and banks	Domestic export credit agencies	Export credit restriction in OECD	Comment
–	–	–	X	Japan is part of the OECD Agreement for export credit agencies to restrict coal financing.

X yes – no ▨ not applicable

Source: own research

Provision of international public support[18]

Japan's total climate finance contribution was the largest among the G20 countries in absolute value. It is also the highest contributor of bilateral climate finance relative to GDP. Compared to the 2013/14 period, its bilateral and multilateral climate flows increased in 2015/16, while core and general contributions to the multilateral development banks decreased slightly. Most funding is delivered through bilateral channels, including the Japanese Bank for International Cooperation (JBIC) and JICA, which is heavily concentrated towards mitigation. At the Green Climate Fund pledging meeting for its replenishment in 2019, Japan announced it will match its previous contribution of US$1.5 billion.

Obligation to provide climate finance under UNFCCC [✓ YES] NO

United Nations Framework Convention on Climate Change

Bilateral climate finance contributions

Annual average contribution (mn US$, 2015-2016)	Theme of support			
	Mitigation	Adaptation	Cross-cutting	Other
9,767.9	89%	8%	3%	0%

Source: Country reporting to UNFCCC

Multilateral climate finance contributions

See Technical Note for multilateral climate funds included and method to attribute amounts to countries

Annual average contribution (mn US$, 2015-2016)	Theme of support			
	Mitigation	Adaptation	Cross-cutting	Other
155.3	14%	1%	85%	0%

Source: Country reporting to UNFCCC

Core/General Contributions

Annual average contribution (mn US$, 2015-2016)
2,165.3

Source: Country reporting to UNFCCC

ENDNOTES

1) 'Land use' emissions is used here to refer to land-use, land use change and forestry (LULUCF). The Climate Action Tracker (CAT) derives historical LULUCF emissions from the UNFCCC Common Reporting Format (CRF) reporting tables data converted to the categories from the IPCC 1996 guidelines, in particular separating Agriculture from Land use, land-use change and forestry (LULUCF), which under the new IPCC 2006 Guidelines is integrated into Agriculture, Forestry, and Other Land Use (AFOLU).
2) The 1.5°C fair share ranges for 2030 and 2050 are drawn from the CAT, which compiles a wide range of perspectives on what is considered fair, including considerations such as responsibility, capability, and equality. Countries with 1.5°C fair-share ranges reaching below zero, particularly between 2030 and 2050, are expected to achieve such strong reductions by domestic emissions reductions, supplemented by contributions to global emissions-reduction efforts via, for example, international finance. On a global scale, negative emission technologies are expected to play a role from the 2030s onwards, compensating for remaining positive emissions.

   The CAT's evaluation of NDCs shows the resulting temperature outcomes if all other governments were to put forward emissions reduction commitments with the same relative ambition level.

   The 2030 projections of GHG emissions are from the CAT's June 2019 update and are based on implemented policies, expected economic growth or trends in activity and energy consumption.

   The CAT methodology does not consider GHG emissions from LULUCF due to the large degree of uncertainty inherent in this type of data, and alsoto ensure consistency and comparability across countries.
3) See the Brown to Green 2019 Technical Note for the sources used for this assessment.
4) The Decarbonisation Ratings assess the relative performance across the G20. A high scoring reflects a relatively good efforts from a climate protection perspective but is not necessarily 1.5°C compatible. The ratings assess both the 'current level' and 'recent developments' to take account of the different starting points of different G20 countries. The 'recent developments' ratings compare developments over the last five available years (often 2013 to 2018).
5) The selection of policies rated and the assessment of 1.5°C compatibility are informed by the Paris Agreement, the Special Report on 1.5°C of the International Panel on Climate Change (2018), and the Climate Action Tracker (2016): 'The ten most important short-term steps to limit warming to 1.5°C'. The table below displays the criteria used to assess a country's policy performance. See the Brown to Green Report 2019 Technical Note for the sources used for this assessment.

On endnote 5)	low	medium	high	frontrunner
Renewable energy in power sector	No policy to increase the share of renewables	Some policies	Policies and longer-term strategy/ target to significantly increase the share of renewables	Short-term policies + long-term strategy for 100% renewables in the power sector by 2050 in place
Coal phase-out in power sector	No target or policy in place for reducing coal	Some policies	Policies + coal phase-out decided	Policies + coal phase-out date before 2030 (OECD and EU28) or 2040 (rest of the world)
Phase out fossil fuel cars	No policy for reducing emissions from light-duty vehicles	Some policies (e.g. energy/ emissions performance standards or bonus/malus support)	Policies + national target to phase out fossil fuel light-duty vehicles	Policies + ban on new fossil-based light-duty vehicles by 2035 worldwide
Phase out fossil fuel heavy-duty vehicles	No policy	Some policies (e.g. energy/ emissions performance standards or support)	Policies + strategy to reduce absolute emissions from freight transport	Policies + innovation strategy to phase out emissions from freight transport by 2050
Modal shift in (ground) transport	No policies	Some policies (e.g. support programmes to shift to rail or non-motorised transport)	Policies+ longer-term strategy	Policies + longer-term strategy consistent with 1.5°C pathway
Near zero-energy new buildings	No policies	Some policies (e.g. building codes, standards or fiscal/ financial incentives for low-emissions options)	Policies + national strategy for near zero-energy new buildings	Policies + national strategy for all new buildings to be near zero-energy by 2020 (OECD countries) or 2025 (non-OECD countries)
Retrofitting existing buildings	No policies	Some policies (e.g. building codes, standards or fiscal/ financial incentives for low-emissions options)	Policies + retrofitting strategy	Policies + strategy to achieve deep renovation rates of 5% annually (OECD) or 3% (non-OECD) by 2020
Energy efficiency in industry	No policies	Mandatory energy efficiency policies cover more than 26-50% of industrial energy use	Mandatory energy efficiency policies cover 51–100% of industrial energy use	Policies + strategy to reduce industrial emissions by 75%–90% from 2010 levels by 2050
(Net) zero deforestation	No policy or incentive to reduce deforestation in place	Some policies (e.g. incentives to reduce deforestation or support schemes for afforestation /reforestation in place)	Policies + national target for reaching net zero deforestation	Policies + national target for reaching zero deforestation by 2020s or for increasing forest coverage

ENDNOTES (continued)

6) The 1.5°C benchmarks are based on the Special Report on 1.5°C of the International Panel on Climate Change (2018). See the Brown to Green 2019 Technical Note for the specific sources used for this assessment.

7) Total primary energy supply data displayed in this Country Profile does not include non-energy use values. Solid fuel biomass in residential use has negative environmental and social impacts and is shown in the category 'other'.

8) Large hydropower and solid fuel biomass in residential use are not reflected due to their negative environmental and social impacts.

9) The category 'electricity and heat' covers CO_2 emissions from power generation and from waste heat generated in the power sector. The category 'other energy use' covers energy-related CO_2 emissions from extracting and processing fossil fuels (e.g. drying lignite).

10) This indicator shows transport emissions per capita, not including aviation emissions.

11) This indicator adds up emissions from domestic aviation and emissions from international aviation bunkers in the respective country. Emissions by aircrafts in the higher atmosphere lead to a contribution to climate change greater than emissions from burning fossil fuels. In this Country Profile, however, only a radiative forcing factor of 1 is assumed.

12) This indicator includes only direct energy-related emissions and process emissions (Scope 1) but not indirect emissions from electricity.

13) This indicator includes emissions from electricity (Scope 2) as well as direct energy-related emissions and process emissions (Scope 1).

14) This indicator covers only gross tree-cover loss and does not take tree-cover gain into account. It is thus not possible to deduce from this indicator the climate impact of the forest sector. The definition of 'forest' used for this indicator is also not identical with the definition used for the indicator on page 3.

15) 'Effective carbon rates' are the total price that applies to CO_2 emissions, and are made up of carbon taxes, specific taxes on energy use and the price of tradable emission permits. The carbon pricing gap is based on 2015 energy taxes and is therefore likely to be an underestimate, as taxation has tended to increase in countries over time.

16) The database used to estimate public finance for coal is a bottom-up database, based on information that is accessible through various online sources, and is therefore incomplete. For more information, see to the Brown to Green 2019 Technical Note.

17) See the Brown to Green 2019 Technical Note for the sources used for this assessment.

18) Climate finance contributions are sourced from Biennial Party reporting to the UNFCCC. Refer to the Brown to Green Report 2019 Technical Note for more detail.

For more detail on the sources and methodologies behind the calculation of the indicators displayed, please download the Technical Note at: http://www.climate-transparency.org/g20-climate-performance/g20report2019

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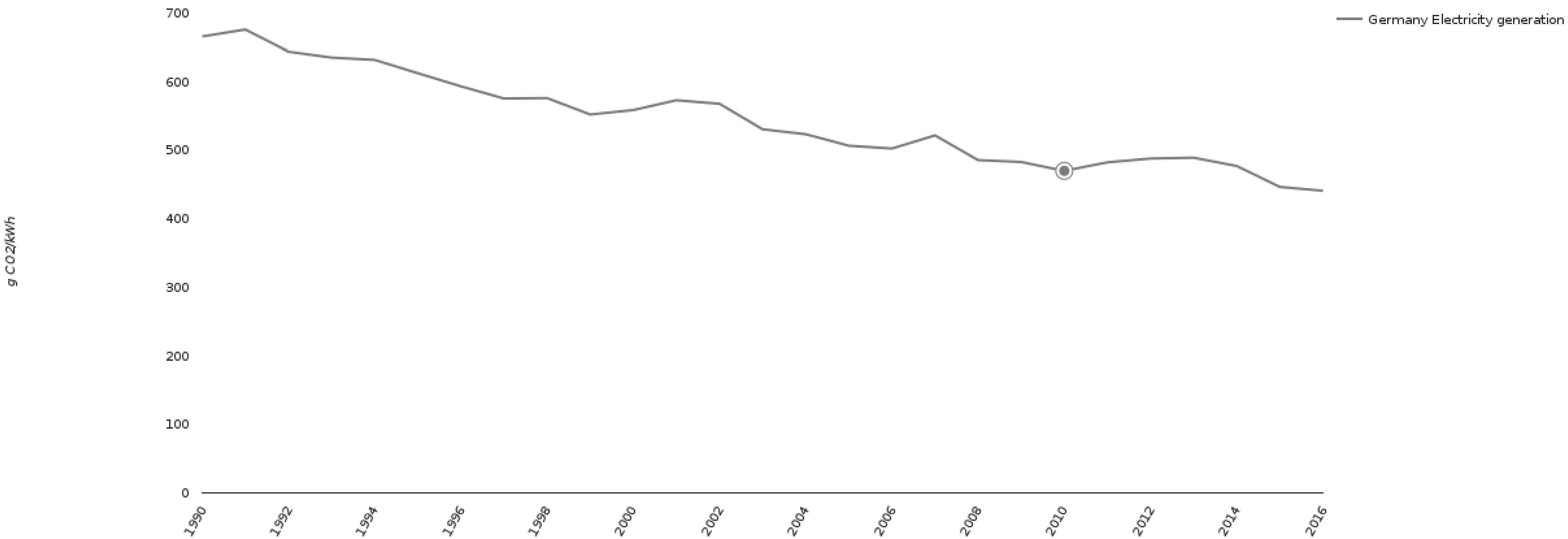
Appendix D Germany

Electricity generation — CO2 emission intensity



Note: The CO_2 emission intensity (g CO_2/kWh) is calculated as the ratio of CO_2 emissions from public electricity production (as a share of CO_2 emissions from public electricity and heat production related to electricity production), and gross electricity production.

Data sources:

National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism provided by European Environment Agency (EEA)

Supply, transformation, consumption - all products - annual data provided by Statistical Office of the European Union (Eurostat)

Appendix E Malaysia

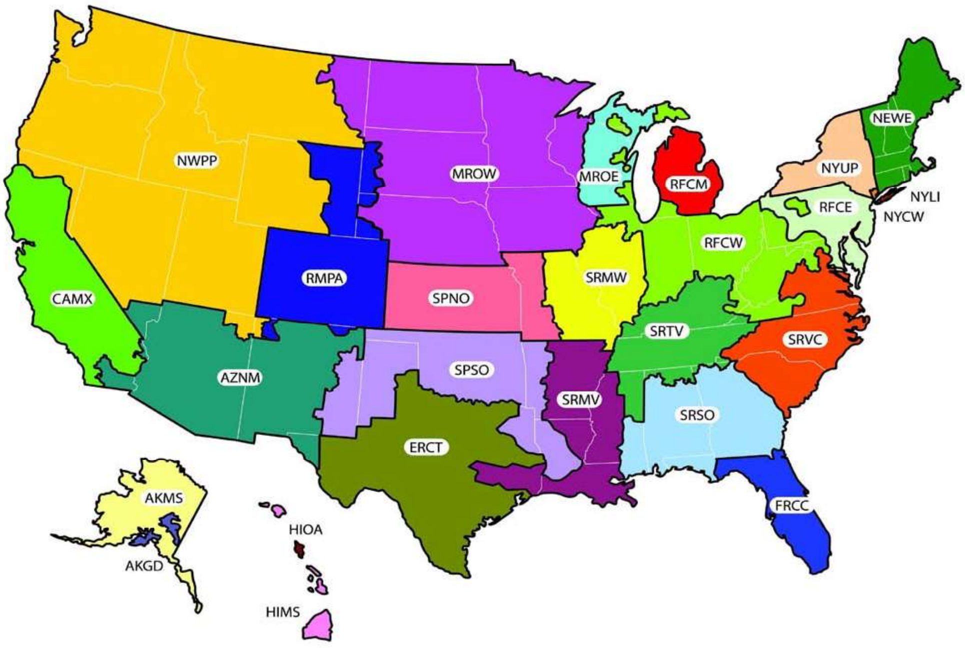
Grid Emissions Factors (GEF) Published by Country Government or Adopted as CDM Standardized Baseline

Country	For Region/Grid	Latest GEF published/ adopted by	Data vintage	Method													
Malaysia	Malaysia	Government		OM	0.6448			0.653	0.681	0.713	0.689	0.657	0.626	0.603	0.611	0.613	0.592
				BM	0.5257			0.735	0.803	0.769	0.804	0.864	0.748	0.741	0.757	0.710	0.636
				CM	0.5850			0.694	0.742	0.741	0.747	0.76	0.683	0.672	0.684	0.661	0.614
	Sarawak			OM	0.9667			0.472	0.617	0.878	0.868	0.85	0.877	0.813	0.863	0.959	0.966
				BM	0.1179			0.925	0.831	0.866	0.814	0.843	0.779	0.837	0.882	0.897	0.945
				CM	0.3300			0.699	0.724	0.872	0.841	0.847	0.805	0.825	0.873	0.928	0.96
	Sabah			OM	0.5637			0.566	0.567	0.578	0.547	0.591	0.623	0.705	0.828	0.818	0.59
				BM	0.4867			0.515	0.500	0.514	0.515	0.556	0.554	0.597	0.787	0.783	0.9
				CM	0.5250			0.536	0.533	0.546	0.531	0.574	0.612	0.651			
	West Sabah														0.807	0.801	0.745
	East Sabah														0.800	0.800	0.800
	Year				**2017**	**2016**	**2015**	**2014**	**2013**	**2012**	**2011**	**2010**	**2009**	**2008**	**2007**	**2006**	**2005**

Appendix F USA

Year 2010 eGRID Subregion Emissions - Greenhouse Gases

eGRID subregion acronym	eGRID subregion name	Carbon dioxide (CO_2) Emissions (tons)	Carbon dioxide (CO_2) Total output emission rate (lb/MWh)	Methane (CH_4) Emissions (lbs)	Methane (CH_4) Total output emission rate (lb/GWh)	Nitrous oxide (N_2O) Emissions (lbs)	Nitrous oxide (N_2O) Total output emission rate (lb/GWh)	Carbon dioxide equivalent (CO_2e) Emissions (tons)	Carbon dioxide equivalent (CO_2e) Total output emission rate (lb/MWh)
AKGD	ASCC Alaska Grid	3,350,817.0	1,256.87	139,035.5	26.08	38,279.9	7.18	3,358,210.3	1,259.64
AKMS	ASCC Miscellaneous	317,398.6	448.57	26,527.0	18.74	5,208.6	3.68	318,484.5	450.10
AZNM	WECC Southwest	104,967,483.8	1,177.61	3,424,005.1	19.21	2,802,975.8	15.72	105,437,897.1	1,182.89
CAMX	WECC California	64,799,260.4	610.82	6,044,809.1	28.49	1,278,773.3	6.03	65,060,940.8	613.28
ERCT	ERCOT All	210,366,837.2	1,218.17	5,820,108.3	16.85	4,859,884.0	14.07	211,181,230.4	1,222.88
FRCC	FRCC All	130,376,587.7	1,196.71	8,478,102.7	38.91	2,995,217.6	13.75	130,929,866.5	1,201.79
HIMS	HICC Miscellaneous	1,963,642.7	1,330.16	218,438.7	73.98	40,985.9	13.88	1,972,289.1	1,336.02
HIOA	HICC Oahu	6,393,027.4	1,621.86	782,825.4	99.30	176,679.8	22.41	6,428,632.4	1,630.90
MROE	MRO East	26,009,237.7	1,610.80	784,331.9	24.29	888,770.5	27.52	26,155,232.6	1,619.84
MROW	MRO West	156,444,752.4	1,536.36	5,809,874.5	28.53	5,354,351.3	26.29	157,335,680.5	1,545.11
NEWE	NPCC New England	46,905,984.7	722.07	9,322,707.0	71.76	1,685,853.4	12.98	47,265,180.4	727.60
NWPP	WECC Northwest	112,891,853.5	842.58	4,300,901.6	16.05	3,502,980.9	13.07	113,479,975.1	846.97
NYCW	NPCC NYC/Westchester	12,733,660.7	622.42	974,161.1	23.81	114,582.6	2.80	12,761,649.6	623.78
NYLI	NPCC Long Island	8,115,858.7	1,336.11	989,929.6	81.49	124,943.6	10.28	8,145,619.2	1,341.01
NYUP	NPCC Upstate NY	24,165,154.6	545.79	1,443,157.6	16.30	641,283.5	7.24	24,279,706.7	548.37
RFCE	RFC East	137,558,868.7	1,001.72	7,434,984.1	27.07	4,210,267.5	15.33	138,289,527.5	1,007.04
RFCM	RFC Michigan	74,602,328.8	1,629.38	2,789,651.5	30.46	2,457,844.2	26.84	75,012,586.0	1,638.34
RFCW	RFC West	449,994,271.4	1,503.47	10,897,168.6	18.20	14,813,680.5	24.75	452,404,812.2	1,511.52
RMPA	WECC Rockies	61,839,528.9	1,896.74	1,477,560.7	22.66	1,904,448.4	29.21	62,150,232.8	1,906.27
SPNO	SPP North	62,457,258.2	1,799.45	1,444,401.4	20.81	1,986,994.1	28.62	62,780,408.5	1,808.76
SPSO	SPP South	117,325,297.0	1,580.60	3,444,187.9	23.20	3,095,469.5	20.85	117,841,258.7	1,587.55
SRMV	SERC Mississippi Valley	90,967,299.2	1,029.82	3,650,522.7	20.66	1,900,187.0	10.76	91,300,158.7	1,033.58
SRMW	SERC Midwest	123,042,911.4	1,810.83	2,783,643.6	20.48	4,019,051.2	29.57	123,695,092.6	1,820.43
SRSO	SERC South	183,236,856.9	1,354.09	6,176,437.4	22.82	5,653,138.2	20.89	184,177,945.9	1,361.05
SRTV	SERC Tennessee Valley	163,960,526.8	1,389.20	4,177,202.5	17.70	5,290,412.2	22.41	164,824,401.3	1,396.52
SRVC	SERC Virginia/Carolina	167,452,188.6	1,073.65	6,766,296.6	21.69	5,502,582.8	17.64	168,376,135.0	1,079.57
U.S.		**2,542,238,893.0**	**1,232.35**	**99,600,972.2**	**24.14**	**75,344,845.9**	**18.26**	**2,554,963,154.4**	**1,238.52**



This is a representational map; many of the boundaries shown on this map are approximate because they are based on companies, not on strictly geographical boundaries.

Appendix G Reuters - Chinas Solar Capacity Expected to hit 1000GW by 2026

A worker operates a machinery to clean solar panels at a photovoltaic industrial park in Hami, Xinjiang Uighur Autonomous Region, China October 22, 2018. REUTERS/Stringer/File photo *Acquire Licensing Rights*

Sept 12 (Reuters) - China's installed solar capacity will double to 1,000 gigawatts (GW) by the end of 2026 as the world's second-largest economy continues to ramp up investment in renewables, energy research firm Rystad Energy wrote in a note published on Monday.

Beijing had set a goal of boosting the country's installed capacity of wind and solar power to more than 1,200 GW by 2030.

China had installed 365 GW of wind power capacity and 392 GW of solar capacity by the end of last year - about a third of the world's total. The country's installed capacity is expected to top 500 GW by the end of 2023, the note added.

"China's national program to build out solar capacity, launched in June 2021, has led to a significant boost in large-scale projects," said Yicong Zhu, senior renewables and power analyst at Rystad.

The note added China's investment in solar photovoltaic (PV) capacity was 3.4 times higher than its investment on thermal power during the first half of 2023.

owever, utility-scale solar PV development, that produce 10 megawatts (MW) or more of energy, has been concentrated in its less populous northwestern parts due to geographical advantages.

"There is limited land availability and costs are high in coastal regions, so large-scale utility solar PV developments are not feasible," the note added.

The challenges have paved the way for more investment in rooftop solar and provinces such as Henan, Shandong and Hubei have seen a surge in installations, Rystad said.

Despite the growth, some provinces are lagging behind in meeting their province-specific goals for installed capacity, the note added.

"Overall, all provinces will need to bring at least 250 GW of solar PV capacity online by the end of 2025 to achieve their respective targets," Rystad noted.

Reporting by Sourasis Bose in Bengaluru; Editing by Krishna Chandra Eluri

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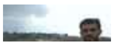

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World · November 3, 2023 · 1:16 PM GMT

Russian President Vladimir Putin said on Friday that some Western weapons supplied to Ukraine were finding their way to the Middle East through the illegal arms market and being sold to the Taliban.

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Appendix H Rapid falls in solar embodied carbon - Chris Worboys

The rapid fall of solar's embodied carbon

Chris Worboys
Energy & Passivhaus Consultant
Published Jul 15, 2021

Some excellent papers have been published over the past few years that investigate how the embodied carbon of solar photovoltaic technology is changing over time. The message is clear: the embodied carbon of solar has fallen rapidly, solar offers very low carbon electricity (even in the UK), and the embodied carbon is expected to continue to fall in the future.

By comparing the figures from these papers to a range of blog posts and articles doing the rounds, it appears that embodied carbon calculations are using figures that are about a decade out of date. The resulting embodied carbon estimates are typically **three to five times** higher than expected, based on more recent research.

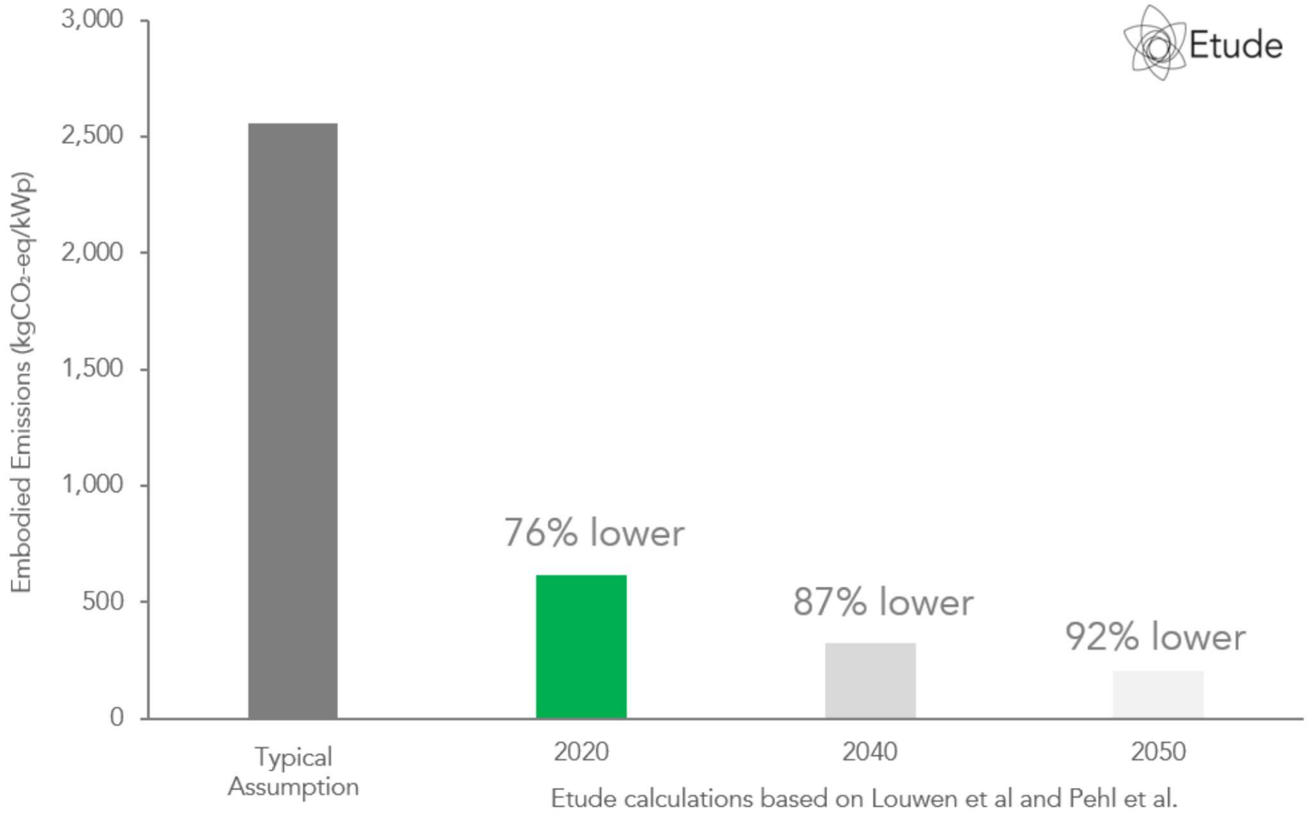

Figure 1 - The embodied carbon of solar is already much lower than commonly assumed.

The main sources for Figure 1 were papers written by Louwen et al and Pehl et al, and also data from Tier 1 manufacturers such as Trina Solar. Our calculations* indicate that the embodied carbon of solar in 2020 was around 615 kgCO2/kWp of installed capacity. This is **76% lower** than the 2,560 kgCO2/kWp that is commonly referenced. First Solar's Global Sustainability Director also recently reported a typical value of 500-600 kgCO2/kWp for monocrystalline silicon.

The fall appears to be mainly driven by improvements in manufacturing process and the ongoing global decarbonisation of electricity, based on both the academic papers and sustainability reporting by manufacturers. Looking forward to 2040, Louwen et al project a drop to 325 kgCO2/kWp and by 2050 Pehl et al project just 205 kgCO2/kWp, a **92% reduction** compared to currently assumed values.

Charting the fall of solar's embodied carbon

Louwen et al have undertaken a comprehensive review of dozens of papers, going back over forty years to chart the fall of solar's embodied carbon. Based on this, they have also projected figures for 2040. Their projections show good alignment with Pehl et al, who have modelled the embodied carbon of solar that is expected in 2050.

Figure 2 - Per unit of electricity, the embodied carbon of solar has fallen for decades. Data points represent individual papers/sources referenced by Louwen et al. The embodied carbon for 2040 is projected by Louwen et al. and the 2050 figure is projected by Pehl et al.

Both studies calculated emissions per unit energy generated based on generic locations. These have been adjusted by Etude in Figure 2 to represent a typical reference system in London**.

In 2020, embodied carbon for the reference system was calculated at just **27 gCO2/kWh**, with an expected range of **20-34 gCO2/kWh** for systems in the UK. The lower end of the range represents a South facing system located in Penzance with 0.5% annual degradation and microinverters. The upper end of the range represents an East/West facing system in Aberdeen with a 0.54% annual degradation and a central inverter.

In addition to the improvements in manufacturing efficiency and grid decarbonisation highlighted previously, embodied emissions per unit of solar energy produced are are also falling due to increasing module efficiencies and better power output warranties, which increase lifetime energy generation per unit of material used.

Solar powered solar

These figures are likely conservative as four of the world's largest solar manufacturers (Longi, Jinko, First Solar, and Hanwha Q-Cells) have signed up to RE100, committing to

100% renewable electricity supplies for their operations. Of these, Jinko were already using 51% renewable electricity in 2022, and are aiming for 100% by 2025.

These and other manufacturers already have extensive solar generation capacity at their facilities. The contribution of solar energy in terms of local grid decarbonisation is unlikely to be reflected in lifecycle analyses that are based on national electricity grid mixes in the country of manufacture.

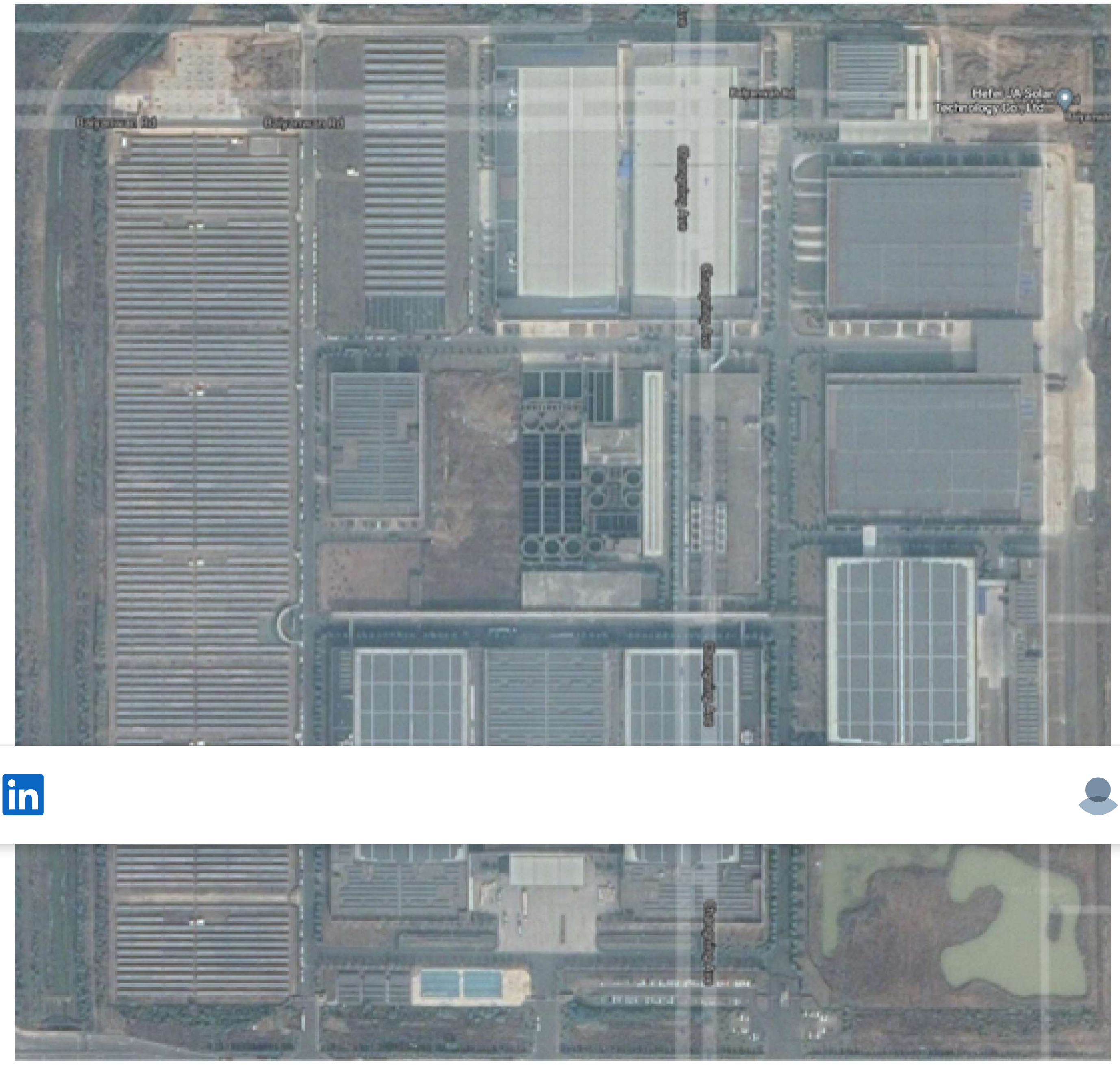

Figure 3 - JA Solar facility in Hefei, Anhui Province, China. A combination of ground and building mounted solar is installed across the site of one of the world's top three solar manufacturers, based on module capacity. (Image courtesy of Google Maps)

Figure 4 - Schletter Solar facility in Kirchdorf, Germany. Example of a leading mounting

While there are plenty of other examples of solar manufacturing sites that have less solar, or no solar at all, there does appear to be a promising trend of leadership from large manufacturers committing to decarbonise their energy supplies, well before the rest of the grid.

Does it still make sense to install solar photovoltaics?

Yes, yes, yes. Solar offers one of the lowest carbon forms of electricity generation available, and it is getting better all the time. The embodied emissions per kWh are currently about **five to eight times lower** than the average grid carbon intensity, and about **eleven to eighteen times lower** than electricity generated by a combined cycle gas turbine.

According to the Climate Change Committee, the UK's solar capacity needs to increase by around **six times** to achieve net zero. At current build rates this will take 60 years, so build rates need to significantly accelerate, and then stay there.

Figure 5 - Historical build rates for solar photovoltaics in the UK, reported by BEIS and Solar Energy UK, compared to the 85GW required to achieve the Climate Change Committee's Balanced Net Zero pathway. Build rates must accelerate significantly.

What about the carbon payback?

Calculating a 'carbon payback' time by comparing solar's embodied carbon against operational emissions from the UK's electricity grid can suggest that long periods are required before solar achieves a carbon break-even point. There appear to be several issues with this approach that indicate it may not be a sensible way of establishing the environmental performance of solar:

1. **Technical accuracy:** It is not equitable to compare embodied emissions of solar to operational emissions for the electricity grid. This approach ignores the embodied emissions associated with fossil fuel extraction and construction of power plants, (including other sources of renewable energy). A full lifecycle emissions comparison would be fairer.

2. **Catch 22:** The carbon payback time of any renewable generator trends toward infinity as the grid decarbonises. This means if we base our decisions on carbon payback, we will never install enough renewable energy to decarbonise the electricity grid. Also note that the carbon intensity of grid electricity falls below zero in all of the National Grid's net zero compliant scenarios.

3. **Decarbonising other sectors:** Once the grid has fully decarbonised, we still need new renewable energy generation to decarbonise heating and transport, and to meet any increase in demand for electricity. If we base our decisions on carbon payback time, calculated within the power sector alone, deployment of this essential new renewable generation will never take place.

4. **Outdated figures:** Existing analyses appear to compare embodied (solar) and operational (grid) carbon emissions from two different points in time. This is producing misleading results. As the embodied carbon of solar has changed significantly over the past decade, it is important that up-to-date figures are used (though for the reasons outlined above, we might want to think about better ways to evaluate the performance of solar).

Moving beyond carbon payback

If we accept that carbon payback is no longer a sensible measure of solar's environmental performance, then what next? For a start, we could acknowledge the

Climate Change Committee's advice that a six fold increase in solar capacity is required; this is already reflected in the National Grid's Future Energy Scenarios.

The role of solar in achieving net zero should then become clear to architects, engineers, consultants, local authorities, and others. Hopefully this would translate into an increased sense of urgency, and the importance of good solar design would follow. This doesn't mean we should forget about embodied carbon, but focus could shift toward how to minimise it. Here are a few ideas to get started:

- Specify solar panels produced by Jinko, Longi, First Solar or Hanwha Q-Cells, who have all committed to 100% renewable electricity to supply their facilities.

- Specify high efficiency panels to reduce the amount of mounting structure required per unit of energy produced. Manufacturers are already phasing out less efficient polycrystalline technology and are increasingly competing on efficiency as a way to deliver array level cost reductions. Typical power ratings for a standardised 1722mm x 1134mm 54 cell panel are now 380W - 400W, with up to 450W available, and even higher powers anticipated.

- Specify panels with a 30 year power output warranty to increase system lifetime, and select a linear power output warranty to increase lifetime system energy generation. Both reduce embodied carbon per unit of energy generated.

- Specify microinverters or DC Optimisers to increase lifetime energy yield per panel. Some microinverters have 25 year warranties, so can be expected to last two to three times as long as a central inverter on a standard warranty.

- Specify an extended warranty if using central inverters. Standard 5-12 year warranties can typically be increased to 10, 15, 20 or even 25 years for a modest additional cost.

- Building mounted solar is often a great way to reduce embodied carbon. In many cases, existing structure can support panels with less material than would be required for a ground mount system. Facade and roof materials can be substituted for solar panels. Roof designs can be optimised to create unshaded monopitch solar arrays, increasing energy generation, which reduces embodied carbon per unit of energy produced.

- Timber can be used in mounting systems to reduce embodied carbon, as demonstrated at one of the UK's largest solar farms:

- Avoid specifying small battery systems. Substantial amounts of embodied carbon are associated with their inverters, charge controllers and physical casings. Cells typically degrade over time, so batteries may reach their calendar life before their cycle life has been fully utilised, at which point the whole system may need replacing. Energy storage is generally more resource efficient at larger scales thanks to the benefits of diversity, scale, professional maintenance and repair, and careful operation to maximise useful cycle life.

- Prioritise smart controls over batteries to make use of existing thermal storage capacity of buildings. The embodied carbon associated with smart thermostats, smart heat pump controls, and hot water tank solar diverters, is likely to be far lower than for a building scale battery storage system.

- While there seems to be little chance of UK consumers influencing the big solar manufacturers (whose annual production capacity is now greater than the UK's entire installed capacity), wider use of requirements for low carbon modules such as those established by France's ADEME could be a sensible first step. Establishing current good practice levels of embodied carbon, and asking installers to provide embodied carbon data, for example through Environmental Product Declarations, could travel up the supply chain to motivate manufacturers to take action.

What other ways can you think of to accelerate deployment and reduce the embodied carbon of solar?

Notes

*As these studies provided figures in gCO2/kWh, we have calculated the emissions per kWp of installed capacity based on the assumed solar energy generation used in each study. It was also necessary to interpolate using the most recently available embodied carbon data, and projected future levels of embodied carbon to establish the current value.

**The typical reference system is assumed to have a 10 degree tilt, East/West orientation, 80% performance ratio, 30 year lifetime, and 2% first year degradation followed by a 0.54% linear annual degradation. We have assumed use of monocrystalline silicon panels as these now dominate the market.

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Acknowledgements

Thanks to everyone in the Etude team who has helped with this research. In particular Leon for reviewing the calculations and Tom for assisting with research on embodied carbon, also Amber, Ed and Will for their helpful suggestions.

Siu-Cheung M. 1y

Electronic engineer, entrepreneur, inventor, innovation strategist.

Chris Worboys thank you so much for your Detailed presentation on the embodied energy of solar PV systems. Also important is your highlight that the embodied energy dropped several times in the last decade alone with solar panel suppliers usingfar lower emissionelectricitythan grid average, such that many discussions are based on outdated data which are off by almost an order of magnitude.

In light of this, we should greatly accelerate solar systems deployment to speed up our energy system decarbonisation.

Like · Reply | 1 Reaction

Neil Evans 2y

Managing Director at Caplor Energy - B-Corp certified

Very useful article Chris. Thank you.

Like · Reply | 1 Reaction

Elrond Burrell 2y

Architect + Passive House & Low Carbon Expert | Born at 331.36 ppm CO2

Jonathan Holmes did you see this? Now just need the EPDs as Tim Martel MCIAT commented.

Like · Reply | 1 Reaction

James Robb 2y

CEnv MCIAT | Whole Life Carbon | Circular Economy

Interesting stuff Chris, though I agree with Tim that we need more manufacturers to provide current EPD's. I've had a few projects now where the embodied carbon to operational carbon avoidance ratio has not balanced out over the life of the installation (one reason being inefficient PV location/orientation) so if the embodied has actually come down this is helpful.

Like · Reply | 1 Reaction

Tim Martel 2y

AECB Certification and Standards, Embodied CO_2 Specialist, Software Developer

Thanks Chris, great article. It would make sense for PV manufacturers to be producing EPDs to show this improvement, as it stands there are hardly any! I'd gladly include updated figures in PHribbon if there were EPDs for it. The info you have here isn't quite enough for me to do that as I dont know what stages you have included. Are your figures A1-A3? We also have to be careful as these figures are for very specific manufacturers who are leading the way by decarbonising their manufacturing process too.

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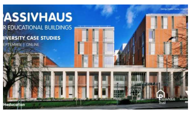

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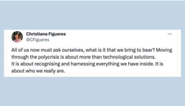

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Appendix I Science Direct Extract

ScienceDirect

Solar Energy Materials and Solar Cells
Volume 230, 15 September 2021, 111277

A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory

Amelie Müller, Lorenz Friedrich, Christian Reichel, Sina Herceg, Max Mittag, Dirk Holger Neuhaus

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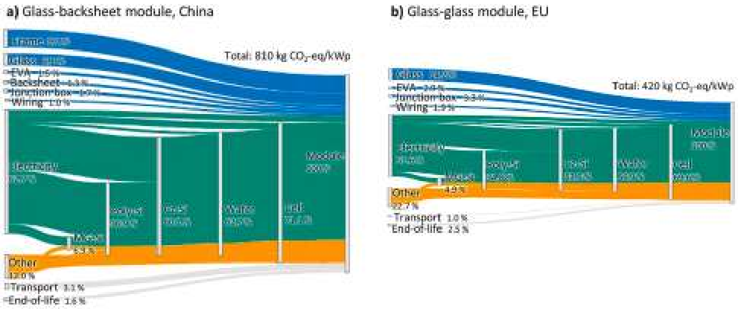
Highlights

- Single-Si glass-glass modules show lower impacts than glass-backsheet modules.
- Most impacts lowest for module production in EU, followed by Germany and China.
- Comparison of influence of different life cycle inventory datasets on results.
- Proposal of warranty-based yield calculation method for more exact impacts per kWh.
- Call for differentiated LCA guidelines to support sustainable panel designs.

Abstract

Life Cycle Assessments (LCA) of single-crystalline silicon (sc-Si) photovoltaic (PV) systems often disregard novel module designs (e.g. glass-glass modules) and the fast pace of improvements in production. This study closes this research gap by comparing the environmental impacts of sc-Si glass-backsheet and glass-glass modules produced in China, Germany and the European Union (EU), using current inventory data. Results show lower potential environmental impacts for glass-glass compared to glass-backsheet modules and lower impacts for production in the EU and Germany compared to China for most impact categories. Concerning climate change, glass-backsheet (glass-glass) modules produced in China, Germany or the EU are linked to emissions of 810 (750), 580 (520) and 480 (420) kg CO_2-eq/kW_p, respectively. This corresponds to CO_2-eq emission reductions of 30% for German and 40% for European production compared to Chinese production, and 8–12.5% reduction in glass-glass compared to glass-backsheet modules. Carbon intensity of produced electricity, excluding balance of system (BOS), amounts to 13–30 g CO_2-eq/kWh, depending on production location and electricity yield calculation method. A warranty-based yield calculation method shows the influence of different lifetime electricity yields of glass-glass and glass-backsheet modules on the potential environmental impacts. This study identifies module efficiency, energy requirements, silicon consumption and carbon-intensity of electricity during production as significant levers for future reductions of environmental impacts. It emphasizes the importance of up-to-date inventories and current modelling of electricity mixes for representative LCA results of PV modules. Lastly, this paper argues that more differentiated methodological guidelines are needed to incentivize the development of sustainable module designs.

Graphical abstract



Previous Next

Keywords

Life cycle assessment; Single-crystalline silicon; Glass-glass module; Life cycle inventory

1. Introduction

To limit global warming below the 2 °C threshold of the Paris agreement, a rapid decarbonisation of the global energy supply by shifting from fossil-based to renewable energies, such as photovoltaic (PV), is needed [1]. Despite PV's “emission-free conversion” of sunlight into electricity [2], PV electricity still causes environmental impacts during the extraction of raw materials, their processing and assembly into PV systems [3]. These embedded impacts need to be accurately quantified to understand the overall environmental profile of PV technologies and to allow for a meaningful comparison with other energy sources [4]. Life cycle assessment (LCA) is a well-established method to evaluate potential environmental impacts caused by a product or a process throughout its entire life cycle [5]. LCA is governed by ISO standards 14040–44 [6,7] and is supported by general guidelines by the EU [[8], [9], [10], [11], [12]] as well as PV-specific guidelines [13,14]. The abundant body of PV LCAs can be studied in various literature reviews [[15], [16], [17], [18], [19], [20]]. A tabular summary of recent LCAs on single-crystalline silicon (sc-Si) PV systems is given in Table 2. This overview shows highly diverging results of existing PV LCAs - even for the same PV technology -, which can be explained by differences in inventory data (e.g. electricity mixes, material consumption and energy requirements), differences in system boundaries (e.g. inclusion or exclusion of balance of system (BOS), transport and end-of-life treatment) and differences in operation parameters (e.g. solar irradiation, lifetime, module efficiency and performance ratio) [15,21].

Existing PV LCAs are often based on outdated life cycle inventory (LCI) data. The two prominently used LCI sources are the Ecoinvent PV datasets [22], which reflect crystalline silicon PV module production in 2005, and the IEA PVPS 2015 datasets [3], which reflect crystalline silicon PV module production in 2011. Given the rapid reductions in energy and material consumption in the PV industry and the significant increase in module efficiencies since then [23], studies based on these old inventories are likely to overestimate the environmental impact of PV systems. Moreover, the recent shift in production to China is not always accounted for in PV LCAs [24], and despite scientific efforts to compile LCIs from Chinese producers [3,[25], [26], [27], [28]], the historic focus on inventory data from European producers prevails [28]. In late 2020, IEA PVPS released an updated LCI for PV systems that contains updates for crystalline silicon PV technology reflecting the year 2018, while some information, such as the amounts of auxiliary materials, are still based on 2011 [29]. Due to the recentness of this publication, it has not yet been widely applied in the scientific community. As described in section 1.2, this study uses a current LCI based on industry data [30] and compares it to other commonly used LCIs [3,22] in the sensitivity analysis.

The existing literature also gives little attention to new developments in module designs of crystalline silicon PV systems. Alternatives to the conventional glass-backsheet (G-BS) layout, such as glass-glass (G-G) design, are rarely studied. The G-G design has emerged as a promising alternative, with 10% market share in 2019 and expected 30% market share by 2030 [23]. Its lower water vapor ingress and reduced mechanical cell stress under load allow for lower degradation rates (DR) and longer lifetimes compared to conventional G-BS modules [31,32]. Although the double-glass layout offers sufficient mechanical stability on its own [31] and the omission of the frame leads to cost reductions, not all G-G modules are produced without a frame [33]. However, in order to contrast the differences between G-G and G-BS module designs, this study focuses on frameless G-G modules, excluding framed G-G modules. Despite their potential, there is a lack of LCAs on glass-glass modules with only one peer-reviewed study assessing this module design and only for multi-crystalline silicon cells [34]. Not only scientific studies but also regulatory literature fails to acknowledge different module designs. By recommending the same degradation rates and lifetimes for all module designs despite proven diverging performances in the field [35,36], the guideline for LCA of PV systems by the IEA PVPS [13] fails to encourage a differentiated comparison of different module designs. However, this guideline permits to use long-term, site-specific data to allow for a differentiation between real-life installations [13]. Yet, long-term installation data is often not available to LCA practitioners.

This study will be useful for future PV LCA practitioners as it comprehensively addresses the potential environmental impact of single-crystalline silicon glass-glass modules compared to glass-backsheet modules, produced in China, Germany and the European Union (EU), using state-of-the-art inventory. It is also helpful for policy makers as it highlights the need for differentiated LCA guidelines for different PV systems and emphasizes the importance of updated inventories.

2. Methodology

2.1. LCA goal & scope

The primary objective of this study is to assess the differences in potential environmental impact between single-crystalline silicon glass-backsheet (G-BS) and glass-glass (G-G) PV systems using the current state of technology for production locations in China, Germany and the EU. Results are given per kW_p nameplate power as well as per kWh of produced electricity. In addition to the recommended calculation methods by the International Energy Agency (IEA) LCA guidelines for PV systems [13], a technology-specific lifetime electricity yield calculation based on average performance warranties by module producers is used for the carbon footprint per kWh of produced electricity, see Table 3. This two-folded approach emphasizes the need for more differentiated assessment guidelines for different PV module technologies.

The secondary objective is to trace the improvements in environmental impacts within the last 10 years by comparing this study to the commonly used life cycle inventories in the field: Ecoinvent v3.7 [22] and IEA PVPS 2015 [3]. This attributional LCA follows ISO 14040–44 [6,7] and PV LCA guideline by the IEA [13]. It uses the software SimaPro Analyst v9.0 [37]. PV foreground processes are based on Friedrich et al. t.b.p. [30], while background processes are based on Ecoinvent v3.7 [22].

2.1.1. PV system description

This study analyses two monofacial, single-crystalline silicon module designs: framed glass-backsheet (G-BS) and frameless glass-glass (G-G) design (layout given in Fig. 1), produced in China, Germany or the EU. Monofaciality is chosen for both designs to allow for a fair comparison, e.g. no additional rear-side electricity gain for G-G modules through bifaciality. Single-crystalline silicon was chosen over multi-crystalline silicon as it is the leading polysilicon feedstock with a market share of 65% in 2019 and expected market share of 80% by 2030 [23]. The production location China has been selected, representing the majority of PV production [38], while the EU and Germany have been selected to investigate the implications for a potential European and Germany production location.

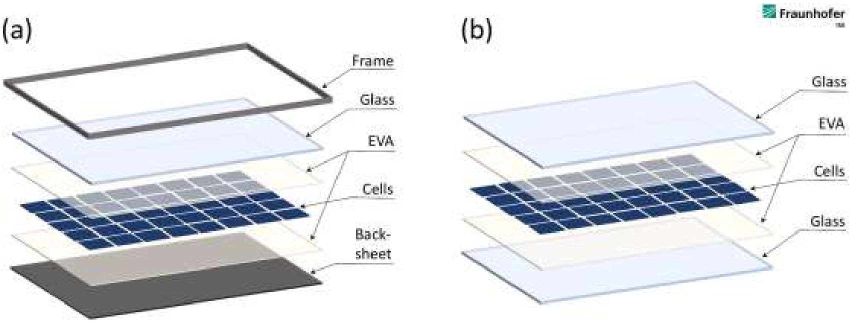


Fig. 1. Structure of glass-backsheet (G-BS) module (a) and glass-glass (G–G) module (b).

The main difference between the two designs is that G-G modules are frameless and use two thin (2 mm) glass layers as front and rear encapsulants, whereas the G-BS module is framed and uses a thick (3.2 mm) glass as front encapsulant and a polymer backsheet as rear encapsulant. The technical details of the two designs are listed in Table 1. The power rating of G-BS modules is higher than of G-G modules (366 vs. 359 W_p) as the G-BS design has a higher cell-to-module (CTM) ratio because of optical gains by reflection of sunlight at the encapsulant-backsheet interface in the cell gap region, which is missing in the G-G design [34].

Table 1. Technical details of modules under review.

Parameter	Unit	Glass-backsheet module	Glass-glass module	Source
Module				
Reference flow	m^2/kW_p	5.052	5.156	Own calc.
Rated Power	W_p	366	359	Own calc.
Module size	m^2	1.85	1.85	Own calc.
Number of cells	pcs.	60	60	[23]
CTM	%	99	97	[39]
Module efficiency	%	19.79	19.40	Own calc.
Glass thickness	mm	3.2	2x 2.0	[23]
Backsheet	µm	25 PVT, 250 PET, 60 Polyolefin	no	[30]
Aluminum frame	kg	2.80	no	[30]
Cell				
Cell type		full-cell M6 psq sc-Si Cz PERC p-type[a]		[30]
Cell efficiency	%	22.5		[23]
Cell area	cm^2	274.15		[30]
Wafer thickness	µm	170		[30]
Kerfloss	µm	80		[30]
Poly-Si consumption	g/wafer	18.0		[30]

[a] This study uses full-cell format whereas Friedrich et al., t.b.p [30]. uses half-cell format.

The lifetime electricity E_{total} generated by a PV system can be calculated using equation (1):

$$E_{total} = \sum_{y=1}^{T} ((1 - DR)^{y} \times I \times A \times \eta \times PR_i) \tag{1}$$

where T is the lifetime of the PV modules (years), DR is the mean annual degradation rate, I is the global tilted location-specific average annual solar irradiation (kWh/(m^{2}yr)), A is the surface area of the PV modules (m^2), η is the module efficiency (%) under standard test conditions (STC) and PR_i is the initial performance ratio. If different degradation rates for the first and consecutive years are given, as it is commonly the case for power warranties of PV modules, equation (1) is adjusted to equation (2):

$$E_{total} = \sum_{y=2}^{T} \left((1 - DR_2)^{y-1} \times (1 - DR_1) \times I \times A \times \eta \times PR_i\right) + (1 - DR_1) \times I \times A \times \eta \times PR_i \tag{2}$$

where DR_1 is the degradation rate in year 1 and DR_2 the degradation rate in year 2 to end of lifetime.

As the total environmental impact per kWh of electricity is inversely proportional to the lifetime electricity generation of PV systems, the correct calculation of the lifetime electricity yield is vital. Apart from technological parameters (e.g. cell efficiency, CTM, module efficiency), operational factors (e.g. solar irradiance, lifetime, performance ratio, degradation rate) strongly influence the yield of the PV system over its lifetime [19,21,24,40]. These factors vary significantly in the literature (see Table 2), rendering comparison of results difficult. To facilitate comparison, the LCA guideline for PV systems by the IEA lists recommendations for these parameters (see Table 3, left) [13]. Unfortunately, these guidelines do not differentiate between different module designs for crystalline PV technologies, and, thus, disregard the differences in field performance and lifetime electricity yields of different module designs [35,36].

Table 2. Tabular overview of LCAs of PV systems with focus on single-crystalline silicon (sc-Si) technologies, PERC cells or glass-glass module design. Publications are listed chronologically, and key parameters are compared. Results are only listed for sc-Si PV technologies if multiple PV technologies were assessed. Unless specified otherwise, all results refer to glass-backsheet module designs.

Authors & Reference	**Year**	**Location**	**Methodological choices**			**Technical parameters**				**Results**	
			Technology reviewed	**LCI source**	**System boundaries**	**Module eff. [%]**	**Irradiation [kWh/(m²*yr)]**	**LT [yr]**	**PR**	**GWP of rated power [kg CO₂/kWₚ]**	**GWP of electricity [g CO₂/kWh]**
Alsema & Wild-Scholten [41]	2005	Europe	sc-, mc-, ribbon Si	European & US PV company data	Cradle-to-gate, including BOS	14	1700	30	0.75	N/A	45 Future: 13
Wild-Scholten [42]	2013	Europe, China	sc- and various other PV technologies	(partly unpubl.) industry and company data	Cradle-to-gate, including BOS	14.8	1700	30	0.75	1220 (EU, only panel), 1408^a (EU, PV sys.), 2810 (CN, only panel), 2998^a (CN, PV sys.)	33 (EU, only panel), 38.1 (PV sys.) 76.1 (CN onl panel), 81.2 (CN, PV sys.)
Yue et al. [43]	2014	Europe, China	sc-, mc-Si and ribbon	Ecoinvent v2.2, CLCD	Cradle-to-grave,	14	1700	30	0.75	1430 (EU),	37.3 (EU), 72. (CN)

Authors & Reference	Year	Location	Methodological choices			Technical parameters				Results	
			Technology reviewed	LCI source	System boundaries	Module eff. [%]	Irradiation [kWh/(m^2*yr)]	LT [yr]	PR	GWP of rated power [kg CO$_2$/kW$_p$]	GWP of electricity [g CO$_2$/kWh]
			Si	v0.8	excluding BOS and transport from CN to EU					2760 (CN)	
Kim et al. [44]	2014	Korea	sc- and mc-Si	Literature, company data	Cradle-to-grave, including BOS	15.96	1310	30	0.80	N/A	41.9 (incl. BO
Louwen et al. [45]	2015	Europe	sc- and SHJ-Si	Ecoinvent v2.1, literature, equipment data	Raw material to operation, including BOS, excluding EoL	16.1, 19.5 (2020 scenario)	1700	30	0.75	N/A	38 (incl BOS, 2015), 25 (in BOS, 2020 scenario)
Leccisi et al. [46]	2016	Europe, US, China	sc-, mc-Si, CdTe, CIGS	IEA PVPS 2015	Panel and BOS, excluding EoL	17	1000–2300	30	0.80	1200 (sc-Si, excl. BOS, Europe), 1700 (sc-Si, excl. BOS, China)	28 (Europe, 2300 kWh/m irrad.) to 83 (China, 1000 kWh/m irrad.)
Chen et al. [27]	2016	China	sc-Si	Chin. cell producer data, Ecoinvent v3.1	Cradle-to-gate, excluding BOS and EoL	15.7	1139–2453	25	–	285	5.6 (excl. BO 2453 kWh/m irrad.) to 12.1 (excl. BOS, 1139 kWh/m
Hong et al. [28]	2016	China	mc-Si	Chin. cell producer data, Ecoinvent v2.2	Cradle-to-gate, excluding BOS and EoL	12.7	1300	25	–	1840 (mc-Si, excl. BOS China)	No sc-Si covered 56.15 (mc-Si, excl. BOS, China)

Authors & Reference	Year	Location	Methodological choices			Technical parameters				Results	
			Technology reviewed	**LCI source**	**System boundaries**	**Module eff. [%]**	**Irradiation [kWh/(m^2*yr)]**	**LT [yr]**	**PR**	**GWP of rated power [kg CO$_2$/kW$_p$]**	**GWP of electricity [g CO$_2$/kWh]**
Stamford et al. [47]	2018	Germany or China. Install. in Spain or UK	sc- and mc-Si	IEA PVPS 2015, technology roadmaps	Cradle-to-grave, including BOS, excluding EoL	16.4	873 kWh/kW$_p$ (UK) 1500 kWh/kW$_p$ (Spain)	30	–	N/A	49 (DE-UK), 59.4 (CN-UK 28.5 (DE-Spa 34.6 (CN-Spa
Wambach et al. [48]	2018	Europe	sc- and mc-Si	IEA PVPS 2015, project partners	Cradle-to-grave, including BOS and EoL	–	–	–	–	1333 (sc-Si), 830 (mc-Si)	–
Luo et al. [34]	2018	Singapore	mc-Si: Al-BSF vs. PERC, G-G and G-BS module design	Ecoinvent v3.3, IEA PVPS 2015, research institute data, literature	Cradle-to-grave, including BOS, excluding transport, EoL	16.7 (mc-Si, G-BS), 16.2 (mc-Si, G-G)	1580	25 (G-BS), 30 (GG)	0.785	821^{b} (mc-Si, PERC, G-BS), 767^{b} (mc-Si, PERC, G-G)	No sc-Si covered, 29.2 (mc-Si, PERC, G-BS, i BOS), 20.9 (n Si, PERC, G-G incl. BOS)
Lunardi et al. [49]	2018	China	sc-Si: Al-BSF and PERC cells from different feedstocks	Ecoinvent, IEA PVPS 2015, literature	Cradle-to-grave, excluding BOS, use and EoL	18.2 (PERC, poly-Si), 17.1 (Al-BSF, poly-Si)	1700	25	0.75	N/A	19.5 (PERC, poly-Si), 21 (BSF, poly-Si)
Friedrich et al., t.b.p [30].	2021	China, EU, Norway, Install: EU	sc-Si, PERC half cells	Industry data, Ecoinvent v3.6	Raw material to operation, including BOS, excluding EoL	20.1	1331	30	0.73	480 (NO) 680 (EU) 1270 (CN)	16.5 (NO), 23 (EU), 45.3 (C all incl. BOS
This study	2021	China, EU, Germany. Install: EU	sc-Si, PERC full cells	Industry data, Ecoinvent v3.7	Cradle-to-grave, excluding BOS and maintenance	19.8 (G-BS), 19.4 (G-G)	1391	30 vs. 25.4 (G-BS) 29.9	0.75 vs 0.85	810 (G-BS, CN), 580 (G-BS, DE), 480 (G-BS, EU),	12.9 (G-G, EU LT 29.9yr, ow yield calc.) to 29.9 (G-BS, C LT 25.4yr, ow

Authors & Reference	Year	Location	Methodological choices			Technical parameters				Results	
			Technology reviewed	LCI source	System boundaries	Module eff. [%]	Irradiation [kWh/(m^2*yr)]	LT [yr]	PR	GWP of rated power [kg CO$_2$/kW$_p$]	GWP of electricity [CO$_2$/kWh]
								(G-G)		750 (G-G, CN), 520 (G-G, DE), 420 (G-G, EU), all excl. BOS	yield calc), al excl. BOS

Table 3. Parameters for the lifetime electricity yield calculation. Approach 1 is based on IEA LCA PV guidelines [13] while approach 2 uses degradation rates as outlined in power warranties of modules from 2015 to 2020 ($n_{glass\text{-}backsheet}$=263, $n_{glass\text{-}glass}$=175). Values for approach 2 are given as mean (±standard deviation). Details of the analysis of power warranties are given in the supplementary information (SI).

	Unit	(1.) LCA PV guideline [13]	Source	(2.) Power warranties		Source
		G-BS and G-G		G-BS	G-G	
Lifetime	year	30	[13]	25.44 (±1.42)	29.89 (±1.51)	Own analysis (see SI)
DR (1st year)	%	Included in PR	[13]	−2.67 (±0.54)	−2.55 (±0.46)	Own analysis (see SI)
DR (follow. Years)	%	Included in PR	[13]	−0.64 (±0.10)	−0.45(±0.09)	Own analysis (see SI)
PR		0.75	[13]	0.85	0.85	[51]
Solar irradiation	kWh/(m^{2}yr)	1391[a]	[13]	1391[a]	1391[a]	[13]
Reference flow	cm^2/kWh	1.614 (G-BS), 1.648 (G-G)	Own calc.[b]	1.895	1.591	Own calc.[b]

[a] [13] recommend country-specific irradiation based on [52]. [52] lists 1391 kWh/(m^{2}yr) as the population-weighted average for Europe.

[b] Reference flow is calculated by dividing the module size (see Table 1) by the lifetime electricity yield (E_{total}), which is calculated for (1.) as E_{total}=LT * PR * Solar irradiation and for (2.) based on equation (2).

To highlight the dependence of results on the choice of yield calculation parameters, this study calculates the lifetime electricity yield of the modules following two approaches: (1.) using recommendations of IEA PV LCA guideline [13], (2.) using power warranties from PV companies (average warranties of 438 modules between 2015 and 2020), see Table 3. Power warranties are chosen as a suitable proxy for actual module performance as they indicate the minimum performance of modules, below which consumers can ask for compensation from manufacturers [50].

2.1.2. Functional unit and system boundary

The functional unit (FU) of this study is twofold: (1.) 1 kW$_p$ of nominal module power and (2.) 1 kWh of produced electricity (excluding balance of system (BOS)). The reference flow describes the fraction of the PV module that is required to produce the FU and is listed in Table 1, Table 3. The system boundaries are depicted in Fig. 2. The entire upstream production chain of sc-Si PV panels, transport to installation location and end-of-life treatment is included. BOS is excluded because the focus of this study is on the module components. As BOS is required to deliver electricity to the grid, literature values for the environmental impact of BOS need to be added to the results per kWh of this study, see section 2.2. Use phase is excluded because it is similar for both systems and assumed negligible in literature [25,30].

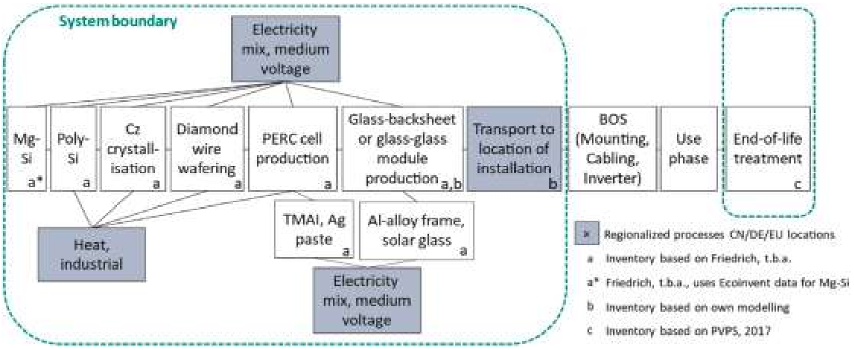


Fig. 2. System boundaries of this study. Adopted from Friedrich et al., t.b.p [30]. Ecoinvent v3.7 [22] is used in this study.

2.1.3. Environmental impact assessment methods

The IEA PV LCA guidelines [13] recommend the 16 impact categories used by the EU product environmental footprint category rules (PEFCR) for PV [14]. All 16 impact categories are assessed in this study. However, in view of the role of PV technologies in the transition to low-carbon energy systems, the focus is on the impact category climate change. Using SimaPro v9.0, the impact category climate change is calculated with the single issue method IPCC 2013, while the other 15 impact categories are calculated with the EF 3.0 (adopted method) as recommended by the PEFCR [14,53,54].

2.2. Life cycle inventory

This study uses the most up-to-date inventory data by Fraunhofer ISE (Friedrich et al., t.b.p [30]). [30] investigates the current material input for the processes polysilicon to module production based on a detailed cost model of PV production facilities. Due to a lack of industry data on process emissions, they base emissions on Ecoinvent. End-of-life treatment is modelled based on [55], which assumes the recycling of glass, frame and cabling while silicon components and polymers are landfilled or incinerated. [55] only assesses recycling of G-BS modules, not of G-G modules. Yet, as no LCI for recycling of G-G modules is available, this study assumes that the recycling process is similar for G-G modules and changes the material composition of [55] to the composition of glass-glass and glass-backsheet modules in this study, see supplementary information (SI). Background data of this study is based on Ecoinvent v3.7 [22]. Full inventory data is given in the SI.

In order to create a regional life cycle inventory, Chinese, German and European medium voltage electricity mixes, based on Ecoinvent v3.7 [22], are used in all PV manufacturing processes and for selected intermediate products (TMAI, silver paste, aluminium alloy and solar glass production). This approach diverges from IEA PVPS Task 12's approach for regional inventories in their 2015 LCI [3], which models European MG-silicon production with Norwegian electricity and European polysilicon purification with a high share of hydropower but applies the average Chinese electricity mix throughout the entire Chinese production chain. This selective choice for low-carbon electricity usage in European production may distort a fair country comparison. Hence, this study ensures a fair comparison by using the respective average grid electricity mix in Ecoinvent v3.7 for the production chains in all production locations. These electricity mixes, although the most up-to-date grid mix inventories available, are based on the year 2012 for China and 2017 for Germany and for the EU, and have a carbon intensity of 1 023, 582 and 405 g CO_2-eq/kWh, respectively, in Ecoinvent v3.7 [22]. The implications of these outdated electricity mix inventories for the results will be discussed in section 3.3. Transport is only modelled for finished modules since the whole PV process chain, including selected intermediate products, are assumed to take place in one single production location in China, Germany or the EU. The finished modules, including packaging, are transported by train, truck and, in the case of China, ship from the production location to an average European installation location (irradiation: 1391 kWh/(m^2yr)). Transport is based on weight of packaged modules (tkm), consistent with the common modelling approach of transportation in Ecoinvent [22] and PV LCA reports [3,29,47,56], and can be viewed in the SI.

2.3. Sensitivity analysis

2.3.1. Impact of module materials

Sensitivity analysis is a key component of LCAs, helping to understand the influence of assumptions and parameters on the outcome of the study [7]. Corresponding to the focus of this study on module design, its sensitivity analysis focuses on module materials as well as selected other factors with potentially large impact. The sensitivity analysis is carried out for both module designs, G-G and G-BS modules, but only for production in Germany, in order to simplify the discussion. Similar sensitivities are expected for production in the EU and China. Each factor (wiring, backsheet, EVA, glass, frame, wafer, module efficiency and total energy requirements) is increased or reduced by 10%.

2.3.2. Impact of life cycle inventory

Existing PV LCA studies mostly use Ecoinvent [22] and IEA PVPS 2015 [3] as LCI sources, see overview in Table 2, while the latest LCI update by IEA PVPS in 2020 [29] has not yet been frequently taken up. Although many studies acknowledge the outdated nature of these inventories in the context of rapidly improving PV technologies and try to compensate this by individually adjusting certain parameters, such as module efficiency or wafer thickness [[45], [46], [47],49], there is no coherence in the adjustment approach, resulting in limited comparability between studies [21]. Moreover, key parameters, such as energy and material consumption in the production chain, are rarely updated although industrial roadmaps show significant savings in production since the years of data acquisition for these LCIs [23,33]. This paper aims to provide some clarity on the influence of using different LCIs by comparing the potential environmental impacts associated with Ecoinvent v3.7 [22], IEA PVPS 2015 [3] and the current, production-based LCI of this study. The most important differences in parameters and assumptions of these inventories are listed in Table 4. Moreover, this sensitivity analysis aims to unveil how module efficiency and source of electricity mix in these commonly used LCIs influence the results, highlighting the significance of modifications to these parameters. To this end, this sensitivity analysis not only compares the (1.) original Ecoinvent and PVPS 2015 LCIs with this study but also these two LCIs adopted for (2.) current module efficiencies, (3.) average electricity mix instead of selective electricity sources as given in Table 4 and (4.) current module efficiencies and average electricity mix. This LCI comparison is carried out for glass-backsheet modules produced in the EU since all three inventories include this module design and production location.

Table 4. Overview of most important parameters and assumptions of the LCIs compared in the sensitivity analysis: Ecoinvent v.3.7 [22], IEA PVPS 2015 [3] and this study for glass-backsheet module production in the EU.

	Unit	**Ecoinvent v3.7 [22]**	**IEA PVPS 2015 [3]**	**This study [30]**
Reference year of LCI		2005	2011	2020[a]
Module power	W_p	224	224	366
Module efficiency	%	14	14	19.8
Wafer thickness	µm	270	270	170
Kerfloss	µm	191	145	80
Wafer sawing method		Slurry based	Slurry based	Diamond wire sawing
Electricity consumption		MG-Si: Norwegian electricity, poly-Si: 60% hydroelectricity, Rest: EU medium voltage grid mix (year 2017)	MG-Si: Norwegian electricity, poly-Si: 60% hydroelectricity, Rest: EU medium voltage grid mix (year 2017)	Only EU medium voltage grid mix (year 2017)
MG-Si	kWh/kg	11	11	11

	Unit	Ecoinvent v3.7 [22]	IEA PVPS 2015 [3]	This study [30]
Poly-Si	kWh/kg	110	110	72
Cz-Si	kWh/kg	85.6	68.2	38.4
Wafering	kWh/m^2	8	25.7	2.35
Cell	kWh/m^2	30.2	14.4	6.24
Module	kWh/m^2	4.71	3.73	3.32
Silicon consumption				
MG-Si	kg Si Sand/kg MG Si	2.7	2.7	2.7
Poly-Si	kg MG Si/kg Poly-Si	1.13	1.13	1.13
Cz-Si	kg Poly-Si/kg Cz Si	1.07	0.781[b]	0.639[b]
Wafering	kg Cz Si/m^2 wafer	1.07	1.58	1.03
Cell	m^2 wafer/m^2 cell	1.06	1.03	1.02
Module	m^2 cell/m^2 module	0.932	0.935	0.898
Poly-Si composition		Mix of electronics grade (14,6%) and solar grade (85,4%) silicon	Mix of electronic grade (14.6%), solar grade (80.2%) and off-grade (5.2%) Si.	Only solar grade silicon
Aluminium	kg/m^2 module	2.63	2.13	1.51
Glass	kg/m^2 module	10.1	8.81	8.00

[a] Reference year for foreground LCI is 2020 [30], while background processes from Ecoinvent have older reference years [22].

[b] Input of recycled Cz-crystal (corners from cutting round ingot in square slabs) not included in Cz-process but in Wafering process.

3. Results

3.1. Environmental impacts per kW$_p$ nominal power

The results of the environmental assessment per kW$_p$ nominal power of glass-backsheet and glass-glass modules produced in China, Germany or the EU are shown in Fig. 3. For all impact categories and for all manufacturing locations, the G-G design shows lower impacts than the G-BS design, despite the slightly higher reference flow due to lower module efficiency. The modules produced in China exhibit lower impacts than those produced in Germany or EU for the impact categories ozone depletion, ionising radiation, freshwater eutrophication, land use and water use. For the other impact categories, module production in Germany has a lower impact than in China, and module production in EU is slightly lower or similar to Germany, with the exception of ionising radiation. The differences in results for each environmental impact category are mainly caused by the different composition of the countries' electricity mixes. For example, the higher results for German production for land use and water use are caused by the high share of biogas and the higher results for German production for freshwater eutrophication are caused by the high share of lignite coal in the German electricity mix. Conversely, the higher results for Chinese production for particulate matter, acidification, terrestrial and marine eutrophication and freshwater ecotoxicity are caused by the high share of hard coal in the Chinese electricity mix. Results for ionising radiation are especially high for the EU because of the high share of nuclear power in the European electricity mix. The indicator resource use (mineral and metals) is identical for all production locations because production and, hence, the absolute amount of minerals and metals contained in the PV modules is modelled identical in each location. It needs to be noted, however, that the results for some impact categories may not be fully representative of current production as the inventory by Ref. [30], which is used in this study, did not obtain current industry data for the emissions along the production chain and, instead, approximated these with the emissions in Ecoinvent, which go back to PV production in 2005 [22].

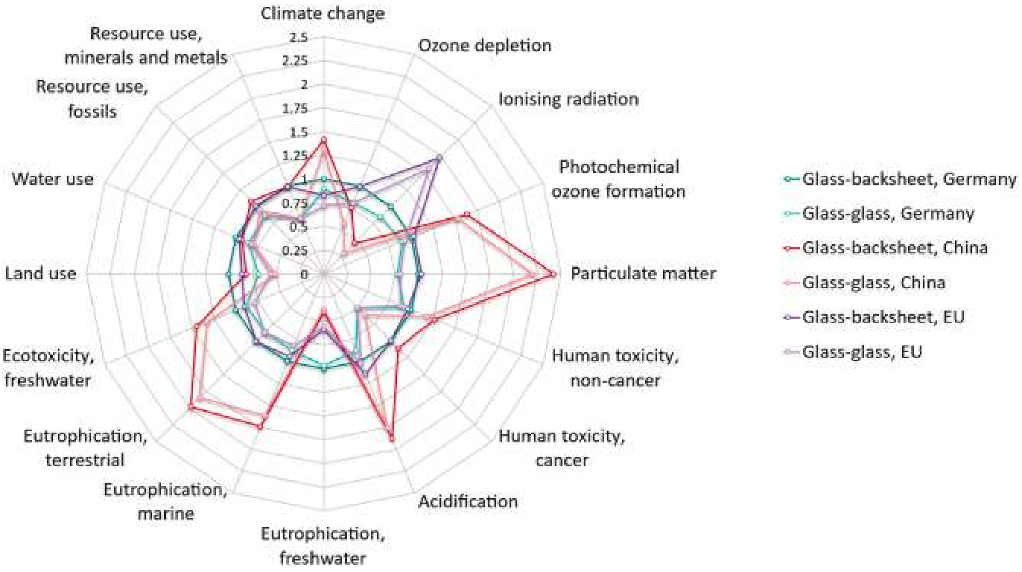


Fig. 3. Results of environmental assessment of 1 kW_p sc-Si glass-backsheet and glass-glass modules produced in China, Germany or the EU for the 16 EF environmental indicators recommended by IEA PVPS and EU PEFCR [13,14]. Glass-backsheet modules: P=366 W_p, η=19.79%. Glass-glass modules: P=359 W_p, η=19.40%. Including production, transport and end-of-life. Excluding BOS, installation and operation. Results of glass-backsheet modules produced in Germany are scaled to 1. Absolute values are given in SI.

Concerning climate change, Fig. 4 shows that glass-backsheet (glass-glass) modules produced in China, Germany or the EU are linked to emissions of 810 (750), 580 (520), and 480 (420) kg CO_2-eq/kW_p, respectively. These results illustrate that production in Germany and the EU causes approximately 30% and 40% less greenhouse gas (GHG) emissions than in China, respectively. Moreover, it shows that G-G design has a smaller carbon footprint than G-BS design (8% less in China, 11% less in Germany and 12.5% less in the EU).

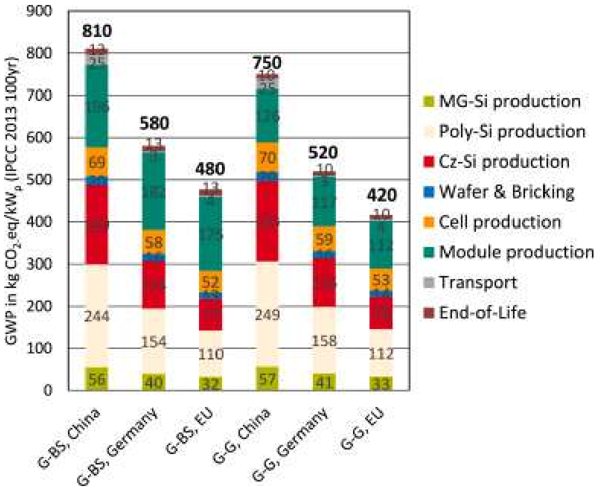


Fig. 4. Climate change: Global Warming Potential (GWP) in kg CO_2-eq/kW$_p$ for sc-Si glass-backsheet (G-BS) and glass-glass (G–G) modules produced in China, Germany or the EU using IPCC 2013 100-year method. Including production, transport and end-of-life. Excluding BOS, installation and operation. Glass-backsheet modules: P=366 W$_p$, η=19.79%. Glass-glass modules: P=359 W$_p$, η=19.40%. LCI listed in SI.

The carbon emissions associated with the different module components, excluding cells, are shown in Fig. 5. Aluminium used for the frame makes up the highest share, followed by glass, while all other components are below 3% of total CO_2-eq emissions. The elimination of the aluminium frame in the G-G design is the main cause for the reduced emissions compared to the G-BS design, while the additional CO_2-eq emissions by the higher glass usage in the G-G design are almost compensated by not requiring a polymer backsheet.

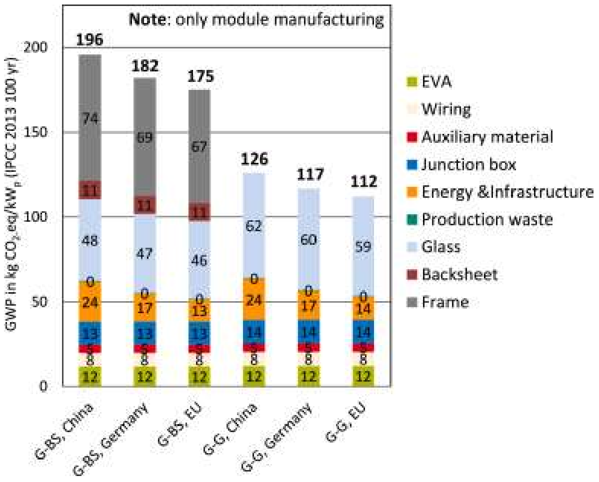


Fig. 5. Climate change: Global Warming Potential (GWP) in kg CO_2-eq/kW$_p$ for module manufacturing for sc-Si glass-backsheet (G-BS) and glass-glass (G–G) modules produced in China, Germany or the EU, respectively, using IPCC 2013 100-year method. Only the impact of module manufacturing are shown, excluding cells. Aluminium and glass are produced using regionalized electricity mixes. Glass-backsheet modules: P=366 W$_p$, η=19.79%. Glass-glass modules: P=359 W$_p$, η=19.40%. LCI listed in SI.

The relative contributions of the processing steps, module components and electricity to the final GHG emissions are depicted in Fig. 6, with the width of the flow corresponding to the magnitude of emissions. Electricity is the major driver of carbon emissions throughout the entire process chain (52%–69%), while other upstream process inputs have only little impact (12–23%). The most emission-intensive steps are polysilicon and Cz-crystal production due to their high electricity requirements. Transport accounts for approx. 3% for the Chinese production, with transoceanic ship transport as the largest contributor, while transport makes up 1% for production in the EU and Germany. At end-of-life stage, the material recovery of frame, glass and cabling yields environmental benefits, yet the recycling process also requires energy and the incineration and landfilling of the polymer and silicon components entails emissions. The results show that these burdens of the modelled recycling slightly outweigh the benefits, leading to a small net contribution of end-of-life stage to the overall carbon emissions (1.6–2.5%). It needs to be noted that silicon is not recycled in this inventory and that future high-yield recycling of silicon is expected to create further environmental benefits [57].

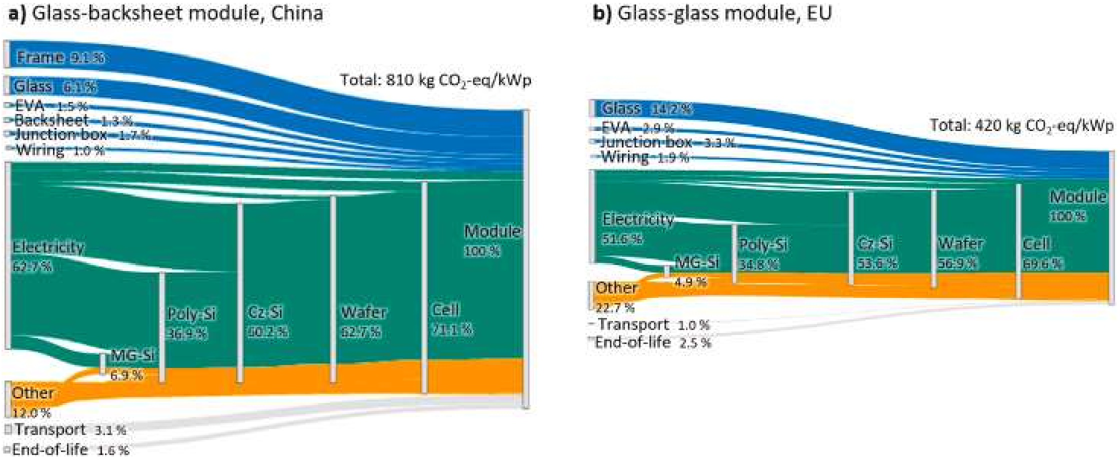


Fig. 6. Climate change: Sankey diagram of percentual contributions of module production steps, module components and electricity to the indicator Global Warming Potential (GWP) using IPCC 2013 100-year method for 1 kW_p of glass-backsheet sc-Si PERC module ($P=366\ W_p$, $\eta=19.79\%$) produced in China (a) and glass-glass sc-Si PERC module ($P=359\ W_p$, $\eta=19.40\%$) produced in EU (b). The other cases are shown in the supplementary information. Including production, transport and end-of-life. Excluding BOS, installation and operation. Thickness of flows corresponds to magnitude of emissions. LCI listed in SI.

3.2. Carbon footprint per kWh produced electricity

The GHG emissions per kWh of produced electricity, excluding BOS, are shown in Fig. 7, ranging from 13.3 to 25.9g CO_2-eq/kWh based on calculation method by LCA guideline [13] and from 12.9 to 29.9g CO_2-eq/kWh based on our own calculation method using module power warranties. For both calculation methods, the carbon intensity of modules produced in Germany is lower than in China, while EU is the lowest. Moreover, the carbon intensity of G-G modules is lower than of G-BS modules in each production location. However, the difference between the two module designs is more pronounced when using real-world warranty data (25% reduction for G-G compared to G-BS modules in Germany) than when following LCA recommendations (10% reduction for G-G compared to G-BS modules in Germany). This is because the 438 evaluated warranties assume different average lifetimes (25.44 years for G-BS and 29.89 years for G-G modules) and different average degradation rates (0.64% vs. 0.45%), whereas the LCA guideline does not account for differences in system performance parameters between different crystalline silicon PV module designs [13], see Table 3. Interestingly, the use of module warranty data leads to higher carbon footprints per kWh for G-BS modules than when using the LCA recommendations because the warranted degradation rate for G-BS modules is relatively high (0.64%/yr) and the warranted service lifetime is much lower (25.4 instead of 30 years), leading to lower lifetime electricity generation.

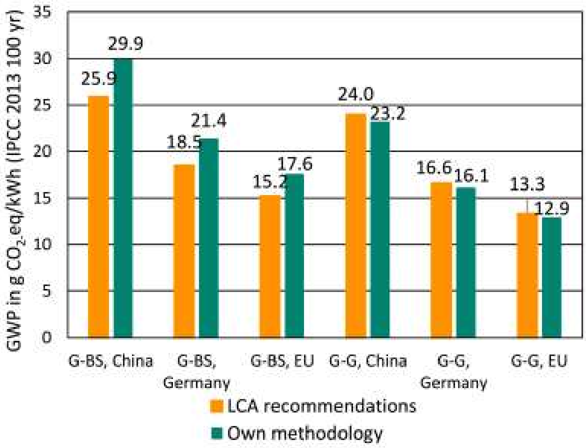


Fig. 7. Climate change: Global Warming Potential (GWP) in g CO_2-eq/kWh of sc-Si glass-backsheet and glass-glass modules produced in China, Germany or the EU using IPCC 2013 100-year method. Including production, transport and end-of-life. Excluding BOS, installation and operation. Installation location is an average European location (1391 kWh/(m^2yr) solar irradiation). Orange: calculation based on recommendations of IEA PVPS 2020 for LCA of PV systems (LT=30 yr, PR=0.75, DR included in PR). Green: calculation based on own methodology using average of module performance warranties given by PV module producers (LT=25.44 yr (G-BS), 29.89 yr (G–G), PR=0.85, $DR_{1st\ year}$=2.67% (G-BS), 2.55% (G–G), $DR_{following\ years}$=0.64% (G-BS), 0.45% (G–G). Including production, transportation and end-of-life; excluding BOS, installation and operation. LCI listed in SI. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

As BOS is required to produce electricity, a full assessment of impacts per kWh of produced electricity needs to add the emissions of BOS, too. For example, [30] calculates the carbon footprint of BOS based on Ecoinvent v3.6 to amount to 8 g CO_2-eq/kWh, when produced with the European electricity mix, and 17 g CO_2-eq/kWh, when produced with the Chinese electricity mix.

3.3. Sensitivity analysis

3.3.1. Module materials

Fig. 8 shows the results of the sensitivity analysis for 3 of the 16 environmental impact categories (all results are given in the SI). Both module designs show similar results for the sensitivity analysis because of their similar material composition, except the higher glass consumption and lack of frame and backsheet in the G-G design. Some factors have a high influence on all impact categories, e.g. module efficiency, due to the linear decrease of required module area with increased efficiency. Other factors, e.g. backsheet and EVA, have a relatively low influence on all impact categories, indicating their low relevance for potential environmental improvements. Moreover, most factors show a varying impact for different environmental impact categories, e.g. 10% reduction in energy requirements leads to 5.7–6.4% reduction in climate change but only 0.7–1.0% reduction in resource use (minerals and metals). This underlines the importance of a comprehensive analysis of the contribution of materials to different impact categories, which is necessary to identify and avoid possible shifts of burden from one impact category to another. Concerning climate change, the sensitivity analysis identifies module efficiency, process energy requirements, wafer thickness, frame and glass as the most influential factors.

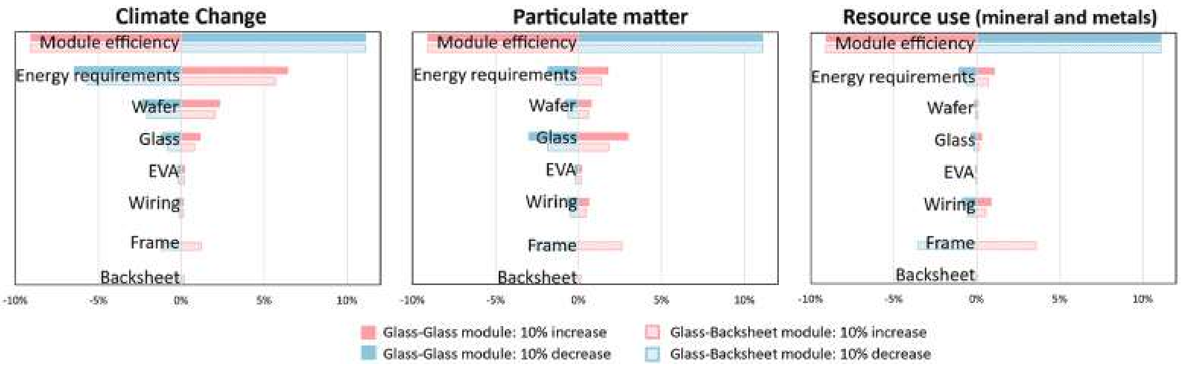


Fig. 8. Sensitivity analysis of various module parameters for the impact categories climate change, particulate matter and resource use (mineral and metals) for glass-glass and glass-backsheet modules produced in Germany. Each parameter is increased or reduced by 10%. The results indicate the percentual changes of the overall impact for the environmental indicator. The plot for module efficiency is asymmetric because the calculation divides by this parameter, resulting in non-linearity. Results for the other 13 impact categories are given in the SI.

3.3.2. Comparison of life cycle inventories

The sensitivity analysis shows that the choice of life cycle inventory data and potential adjustments to these has a significant impact on the final potential environmental impacts, as shown in Fig. 9 for selected impact categories. Concerning climate change, using the original Ecoinvent v3.7 and PVPS 2015 LCI causes 4.3 times and 3.2 times higher emissions than in this study, respectively. Substituting the selective choice for low-carbon energy during some production steps in Ecoinvent v3.7 and PVPS 2015 inventories with the average European electricity mix throughout the entire production results in a further slight increase in impacts for both datasets, see dotted lines in Fig. 9. Adjusting the module efficiency to current values (η_{orig} 14% to η_{adjust} 19.8%) reduces the difference in emissions to 3.0 and 2.3 times the GHG emissions of this study for Ecoinvent v3.7 and PVPS 2015 LCI, respectively. The large remaining gap in emissions between the module-efficiency-adjusted publicly available life cycle inventories and this study stems from the significant reductions in material consumption and energy consumption along the process chain as listed in Table 4, which are caused by the technological developments of recent years [23], mainly driven by a reduction in silicon consumption. This shows that merely adjusting the module efficiency of older LCIs to current levels without revising material and energy consumption along the process chain is insufficient to model the current environmental impacts of PV systems.

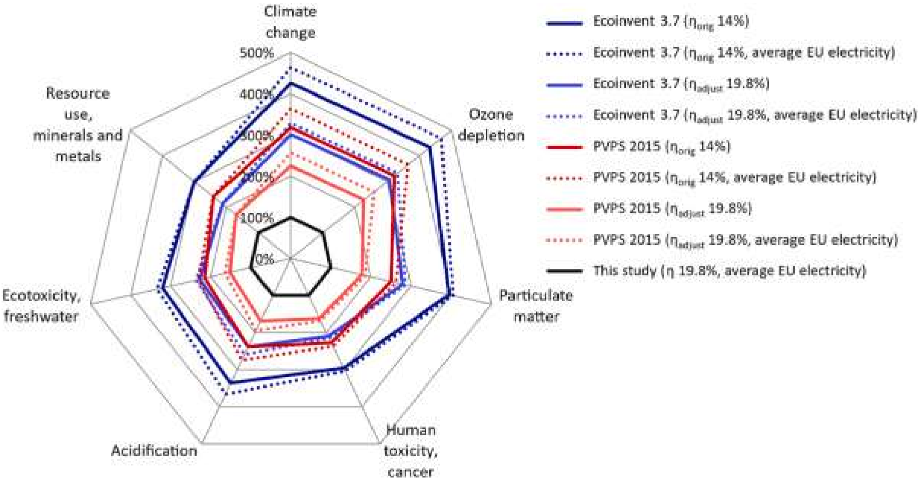


Fig. 9. Comparison of glass-backsheet (G-BS) modules in this study with publicly available LCIs: Ecoinvent v3.7 [22] and IEA PVPS 2015 [3] for selected environmental impact categories. The results for all 16 impact categories and absolute values can be found in the SI. For simplification, only G-BS modules produced in the EU were compared. BOS, installation, transport and end-of-life are excluded. Blue lines refer to Ecoinvent v3.7, red lines to PVPS 2015, black line to this study. Darker shades have original module efficiency ($\eta_{orig.}$ = 14%), lighter shades have module efficiency adjusted to this study's ($\eta_{adjust.}$ = 19.8%), dashed lines have harmonized electricity sources (average European electricity mix of the year 2017) instead of various sources as listed in Table 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

In view of the urgency for climate action and the limited length of this paper, only the impact category climate change is discussed in detail.

4.1. Impact of module designs

Despite slightly higher material consumption due to lower module efficiency, glass-glass modules show lower environmental impacts per kW_p than conventional glass-backsheet modules, mainly because of the elimination of the aluminium frame. The better environmental performance of G-G modules is further enhanced for the lifetime electricity production (impact per kWh), if the longer potential lifetime and lower degradation rates of G-G modules [32] are used in the yield calculation, approximated with the real-life power warranties in this analysis. This emphasizes the need to assess not only the influence of module design choices on material and energy savings in production (leading to reductions per kW_p) but also to critically investigate the impact of these design choices on system performance (leading to further reductions per kWh). Yet, the standardized yield calculation method as recommended by IEA PV LCA guideline [13] does not account for the better system performance of glass-glass module designs, concealing the potential reductions in emissions per kWh due to higher, design-specific electricity yields.

The only comparison of glass-glass and glass-backsheet module designs found in the literature by Luo et al. [34] finds 821 kg CO_2-eq/kW_p and 29.2 g CO_2-eq/kWh for multi-crystalline silicon (mc-Si) glass-backsheet modules and 767 kg CO_2-eq/kW_p and 20.9 g CO_2-eq/kWh for mc-Si glass-glass modules, including BOS, see Table 2. Yet, their analysis uses a relatively high DR for G-BS modules (1%/year) and low DR for G-G modules (0.2%/year), which may not be representative for the technologies. Moreover, they only consider multi-crystalline silicon, not single-crystalline silicon, do not account for recent improvements in the PV production and assume production to take place in Singapore [34]. As the electricity mix in Singapore emits only 485 g CO_2-eq/kWh and multi-crystalline silicon is less energy intensive than single-crystalline silicon, their results are still in the same magnitude as in this study (420–810 kg CO_2-eq/kW_p and 13–30 g CO_2-eq/kWh, excluding BOS), although their LCI does not account for the recent technological developments and includes BOS. If sc-Si was used and the different assumptions were harmonized, the results of [34] would be significantly higher than this study.

4.2. Impact of production location

As the majority of carbon emissions is caused by the electricity consumption during production (see Fig. 6), the carbon intensity of the electricity mix at production location is one of the highest levers for reducing the carbon footprint of PV systems [20,21,40,58]. Although the energy intensive silicon production should ideally take place in countries with low-carbon electricity mixes [40], China, which has a carbon-intensive coal-based electricity mix, dominates the market by producing 68% of polysilicon, 96% of wafers, 76% of cells and 71% of PV modules in 2019 [38]. Given the dominance of production in China, geographically representative inventories based on Chinese companies need to be developed [47], contrasting the predominantly European data sources in Ecoinvent v3.7 [22] and IEA PVPS 2015 [3].

A partial shift of production to regions with low-carbon electricity mixes, decarbonization of the Chinese electricity mix [28,43,59,60] or production of selected high-energy intermediate materials in low-carbon regions are potential options for improvements. This study shows that the carbon emissions from transportation of final modules from China to Europe are small compared to the additional carbon emissions caused by production in China, a finding supported by other studies [27,28,30,47]. Thus, it can be concluded that transcontinental transport of selected high-energy precursor products is expected to be negligible in comparison to the savings from using a low-carbon electricity mix. Most savings can be achieved by relocating the production of polysilicon and Cz-crystal, the most energy-intensive precursor products, see Fig. 6.

Finally, a discussion of the impact of the electricity mix in producing countries is incomplete without also drawing attention to the importance of the electricity mix in the country of installation. Although the GWP of the total PV system is independent of the electricity mix in the country of installation as PV systems do not notably consume electricity during operation, the actual carbon savings achieved by a PV system lie in the difference between the carbon intensity of the replaced electricity mix at the installation location and of the PV electricity. Thus, maximum GHG emission savings can be achieved when PV systems are produced in low-carbon locations and installed in locations with a carbon-intensive electricity mix and high solar irradiation [40,61].

4.3. Recommendations for future studies

As the comparison of the PV LCIs from Ecoinvent, IEA PVPS 2015 and this study has shown, the commonly used inventories fail to reflect the current state-of-technology, and, even if adjusted for increased efficiencies, still overestimate the environmental impacts of current PV systems by a factor of 2.3 or more. The recently published IEA LCI update in 2020 [29] can be seen as a long-awaited response to the need for current, high-quality and publicly available LCI for PV technologies [48,62]. The comparison of inventories also emphasizes the need for LCA practitioners to critically engage with the published inventories and to avoid updating old inventories with superficial modifications only. As PV technologies are expected to continue to undergo significant technological improvements [23], public LCIs ought to be regularly and systematically updated to reflect these dynamic future improvements [21].

For an analysis of regionalized production, the exact modelling of the electricity mixes is vital. This study uses the average medium voltage electricity mixes for China, Germany and EU as given in Ecoinvent v3.7, which are based on the year 2012 for China and 2017 for Germany and the EU, and emit 1 023, 582 and 405 g CO_2-eq/kWh, respectively [22]. Recent estimations, however, project the direct carbon intensity for the German electricity mix at 401 g CO_2-eq/kWh for 2019 [63] and for the Chinese electricity mix at 821–861 g CO_2-eq/kWh for 2020 [64]. Although these sources only include direct and not indirect emissions, the trend for the total CO_2-intensity can be expected to have decreased, too. If current, lower carbon-intensities of the electricity mixes were used, the resulting carbon emissions of PV systems in this study would be even lower [[65], [66], [67]]. Since 52–69% of the greenhouse gas emissions of the investigated PV systems stem from the electricity used in the PV production processes, the carbon intensity of the used electricity mix has an immediate influence on the overall results. Hence, this study flags outdated electricity mixes as a source for overestimation of emissions for PV and motivates future studies to conduct LCAs on PV systems with current electricity mixes. It also calls for more frequent updates of country-specific electricity mixes in LCA databases to keep track of the emission reductions in the electricity sector.

Despite official methodological guidelines [13] and the harmonization efforts by the scientific community [21,24], the results of existing PV LCAs remain difficult to compare, see Table 2. While supporting the general need for a more harmonized LCA approach for PV technologies, this study advocates that these harmonized methodologies need to be differentiated enough to account for actual technology- and design-specific differences, such as different lifetime electricity yields of crystalline silicon glass-glass and glass-backsheet modules as demonstrated in this study. Such differentiated guidelines can coherently incentivise the development of more environmentally friendly modules designs.

5. Conclusion

This study investigates the life cycle environmental impact of two different single-crystalline silicon (sc-Si) PV module designs, glass-backsheet (G-BS) and glass-glass (G-G) modules, produced in China, Germany or the EU using current inventory data. Results for all environmental impact categories are lower for the G-G design compared to the G-BS design, while most indicators show lowest values for production in the EU, followed by Germany and China. Concerning climate change, the glass-glass design has a smaller carbon footprint than the glass-backsheet design (8% less in China, 11% less in Germany, 12.5% less in EU) and both module designs emit 30% and 40% less carbon when produced in Germany and the EU compared to China, respectively. This study shows that glass-glass modules have a better environmental profile than glass-backsheet modules, especially if their higher lifetime electricity yield is taken in account. As the mounting structure, which is part of the balance of system (BOS), has been excluded in this study, further research needs to investigate how the different requirements for mounting structures of the two designs influence this comparison.

As this study uses state-of-the-art industry data concerning cell efficiency, wafer thickness, kerfloss, energy and material requirements during production, its results are considerably lower than previous LCAs of sc-Si PV systems that rely on older data. With a carbon footprint of 420–810 kg CO_2-eq/kW_p and 13–30 g CO_2-eq/kWh (excluding BOS), this study shows that current sc-Si PV modules are indeed a low-carbon pillar of the energy transition, emitting even less carbon than previously expected. The comparison of the most commonly used life cycle inventories (LCIs) (Ecoinvent v3.7 [22] and PVPS 2015 [3]) with this study reveals the significant achievements in emission reduction in PV module production in the last 10 years. Simultaneously, it demonstrates that modelling current PV technologies with these established LCIs and only superficially adjusting some technical PV parameters (e.g. module efficiency and wafer thickness), as frequently done in the literature, leads to significant overestimation of the potential environmental impacts. Thus, a critical examination of available LCIs by LCA practitioners and current, high-quality and publicly available LCIs for the PV value chain are vital. In addition, more frequent updates of country-specific electricity mixes in the major databases are important.

This study identifies the energy requirements during silicon processing, material consumption, e.g. by thinner wafers and less kerfloss, and module efficiency to have the highest impact on GHG emissions. Future research should specifically target improvements in these parameters. Module design variations, such as glass-glass modules, can reduce GHG emissions not only by reducing material and energy requirements during production but also by improving system performance, e.g. by longer lifetime or reduced degradation rates, and, thus, providing higher lifetime electricity yields. These design-specific differences need to be anchored in LCA guidelines for PV systems to account for the actual differences in emissions and to incentivise the development of environmentally friendlier module designs.

Author contribution

Amelie Müller: Conceptualization, Investigation, Formal analysis, Methodology, Visualization, Writing – original draft. Lorenz Friedrich: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing. Christian Reichel: Investigation, Validation, Supervision, Writing – review & editing. Sina Herceg: Conceptualization, Investigation, Methodology, Validation, Supervision, Writing – review & editing. Max Mittag: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. Dirk Holger Neuhaus: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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

Acknowledgements

The authors would like to thank Prof. Dr. Stefan Pauliuk and Prof. Dr. Rainer Grießhammer for their helpful feedback and support in an early version of this paper. The authors acknowledge the funding of the work by the German Ministry of Economic Affairs and Energy under Grant No. 03EE1095B “KoMoGER”.

Appendix A. Supplementary data

The following is the Supplementary data to this article:

Multimedia component 1.

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