# Technical Annex

# Building a Nature-Positive Energy Transformation

## Why a Low-Carbon Economy is Better for People and Nature

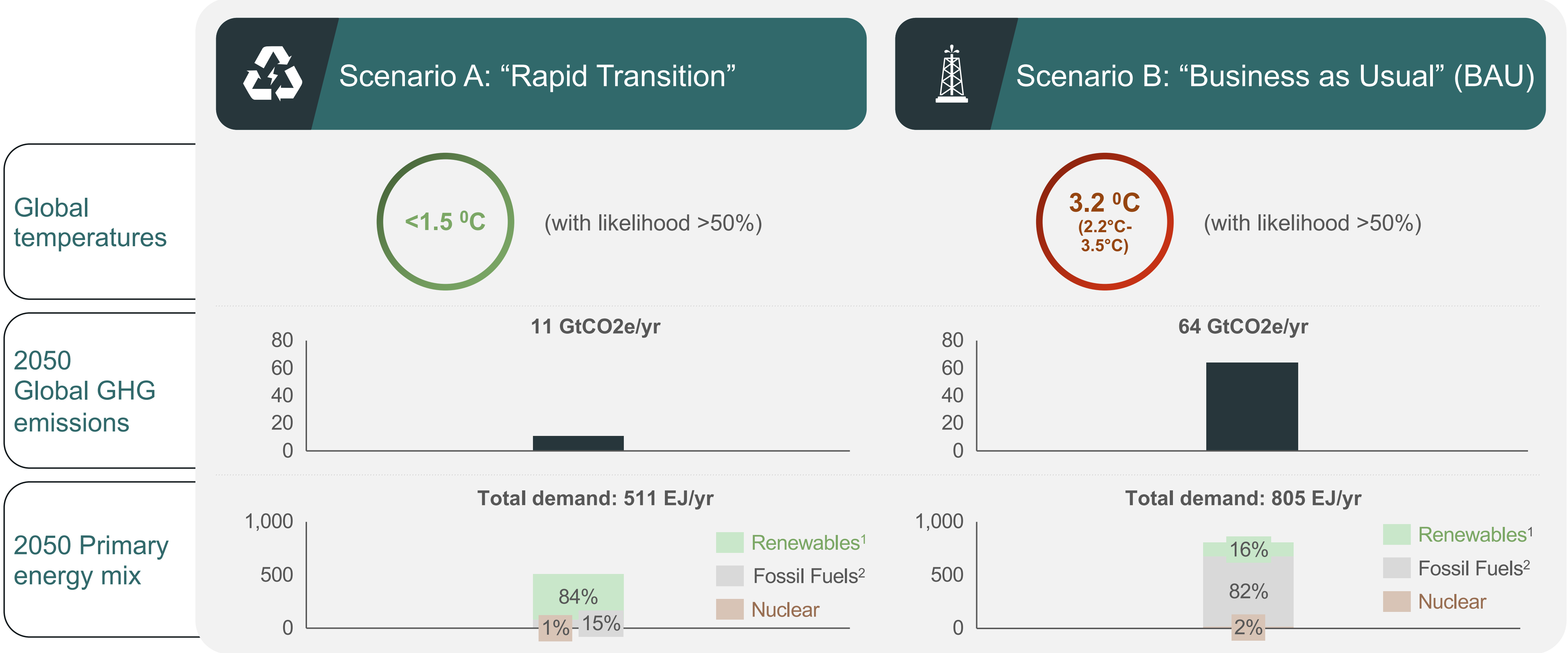
wwf.earth/energy-nature

November 2023

# Technical Annex

# A1. Further details on selected scenarios

# The rapid transition scenario represents a <1.5 $^0$C world with significantly less emissions, energy demand, and fossil fuels




1. Includes wind, solar, geothermal, hydro and biomass 2. Includes coal, gas and oil; GHG = greenhouse gas; EJ/ = exajoule; GtCO2e = gigatons of CO2 equivalent. Source: IPCC AR6; BCG analysis

# The two scenarios have very different energy mixes and levels of electrification

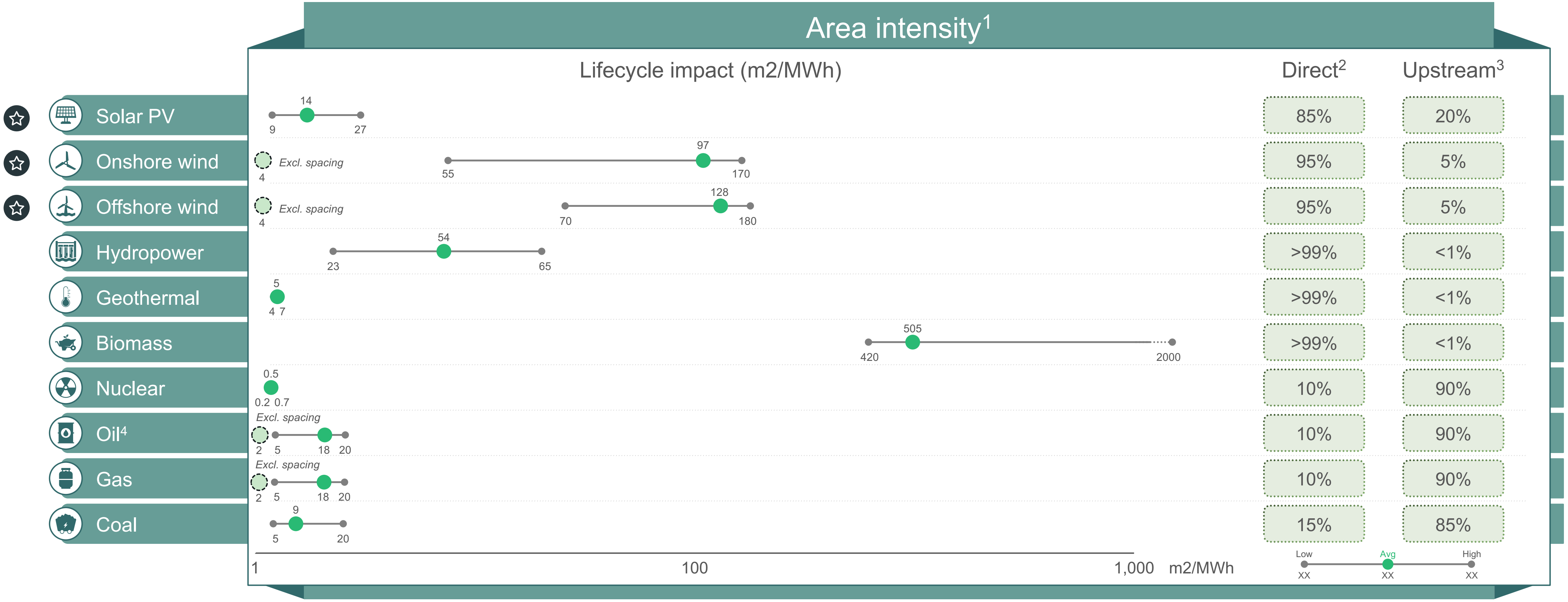
| Primary Energy Source | Scenario A: Rapid Transition (2050) | | Scenario B: Business as Usual (BAU) (2050) | |
|---|---|---|---|---|
| | Supply (EJ/yr) | % of total | Supply (EJ/yr) | % of total |
| Solar | 211 | 41% | 26 | 3% |
| Onshore wind | 73 | 14% | 20 | 3% |
| Offshore wind | 16 | 3% | 2 | <1% |
| Hydro | 24 | 5% | 15 | 2% |
| Geothermal | 9 | 2% | 1 | <1% |
| Biomass | 98 | 19% | 68 | 8% |
| Oil | 45 | 9% | 197 | 24% |
| Gas | 30 | 6% | 251 | 31% |
| Coal | 2 | <1% | 211 | 26% |
| Nuclear | 4 | 1% | 13 | 2% |
| **Total primary energy** | **511** | **100%** | **805** | **100%** |

| Electrification | Scenario A: Rapid Transition (2050) | Scenario B: Business as Usual (BAU) (2050) |
|---|---|---|
| Electricity generation capacity (TW) | 52 | 13 |
| Electricity for freight transportation (EJ/yr) | 15 | 5 |
| Electricity for passenger transportation (EJ/yr) | 37 | 6 |

Source: IPCC AR6

# A2. Land and marine footprints

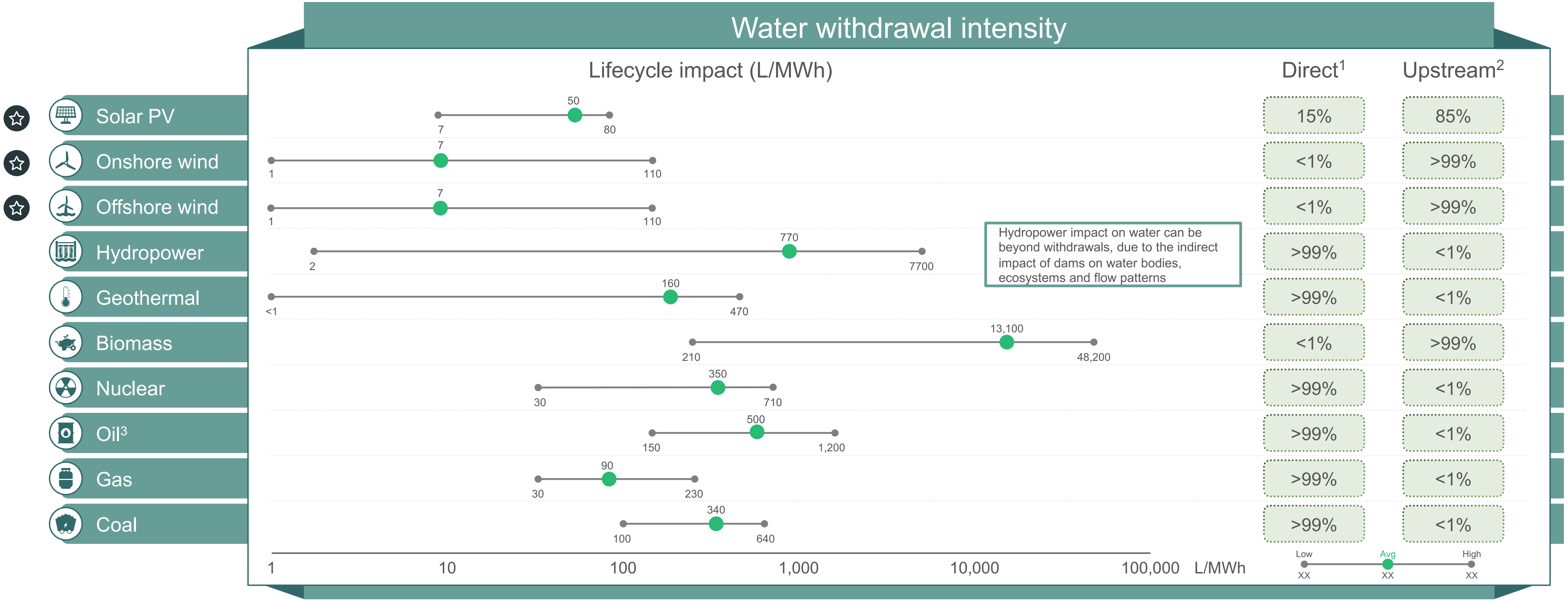
# Biomass and wind have the biggest area footprints over the lifecycle




*Deep dives in following pages*

1. Corresponds to land or ocean, depending on the technology; 2. “Direct” impact is the footprint associated with the installation, operation and maintenance of the power plant facility; 3. “Upstream” impact is the footprint associated with upstream value chain processes and activities, including the extraction and purification of raw material and manufacturing of components (end of-life land and water footprint negligible for all technologies assessed here); 4. Oil intensity assumed to be similar to gas given the intertwined value chains and limited literature on the distinction
Source: IEA, EIA, NREL, EPRI, UNEC, DOE, Expert Interviews, BCG analysis

# Among energy sources, biomass requires far more water than others

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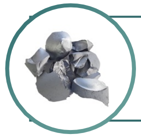
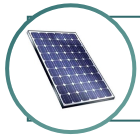
1. "Direct" impact is the footprint associated with the installation, operation and maintenance of the power plant facility; 2. "Upstream" impact is the footprint associated with upstream value chain processes and activities, including the extraction and purification of raw material and manufacturing of components (end of-life land and water footprint negligible for all technologies assessed here);
3. Oil intensity assumed to be similar to gas given the intertwined value chains and limited literature on the distinction; Source: IEA, EIA, NREL, EPRI, UNEC, DOE, Expert Interviews, BCG analysis

# Solar power's impact on nature arises from upstream and downstream segments of the value chain

| | Upstream (indirect) impact | | Direct (downstream) impact | |
|---|---|---|---|---|
| Value chain |  Mining and purification |  Wafer/Cell/Module manufacturing |  Installation and connection to grid |  Operations and maintenance |
| Description | Quartz mining is used to produce polysilicon (a very pure form of silicon) which is a key material due to its properties as a semiconductor | Polysilicon is sliced into wafers and processed to construct PV cells (these cells are subsequently made into solar PV modules) | Construction activities to install PV modules, trackers, inverters, cables, transformers and connections to electricity grid (Dx[2] or Tx[3]) | All operations and maintenance activities that support power generation and transmission at the solar farm |

## Key parameters affecting solar power's impact on nature

### Technology

The impact on nature from mining depends on the raw material used in the PV modules (Silicon photovoltaics is the dominant technology today with a market share of about 95%[1])

### Installation type

Rooftop solar (typically residential) has a far smaller land footprint over its lifecycle compared to ground-mounted solar (typically utility scale)

### Capacity factor (CF)

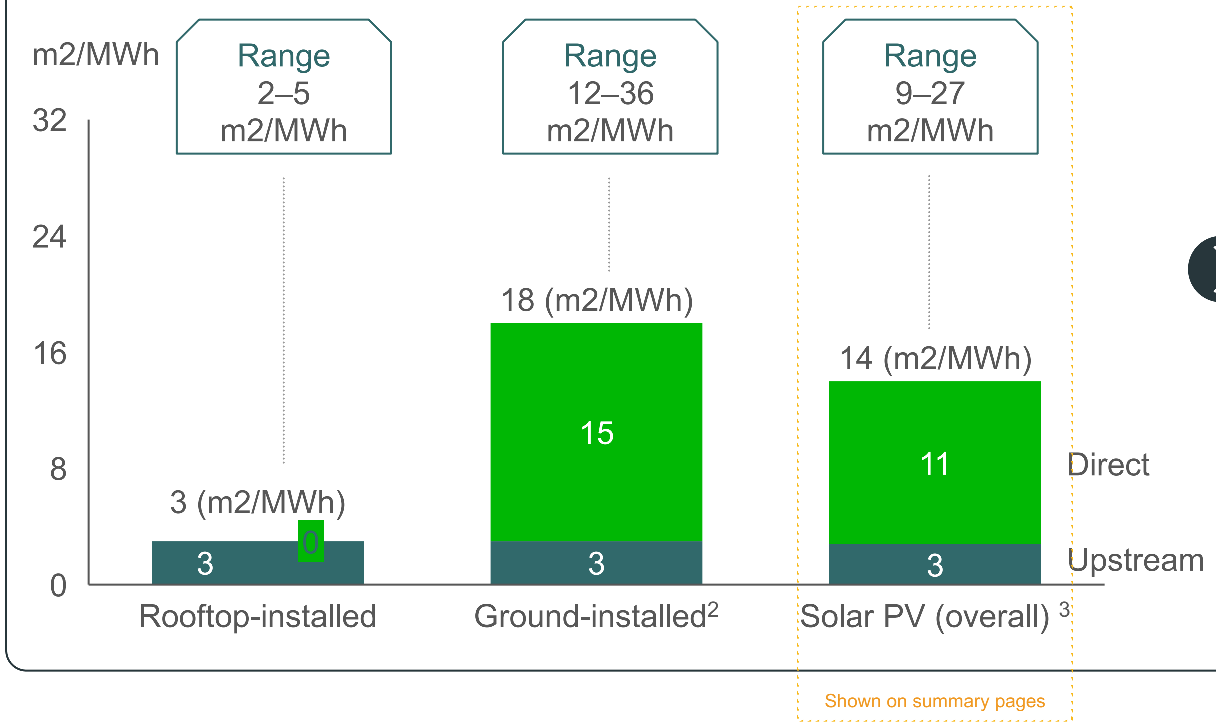
A higher capacity factor reduces the impact on nature (arising from land and marine footprints) per megawatt-hour of electricity generated

1. Crystalline Si PV assumed as the default technology in this analysis given the small share of other technologies (e.g., Cadmium telluride thin films) in the market today; 2. Dx = Distribution; 3. Tx = Transmission; Source: Wood Mackenzie; BCG Analysis

# Ground solar has a far bigger land footprint over its lifecycle than rooftop

**The lifecycle land footprint of rooftop is 6x lower than ground solar due to its near-zero direct (downstream) land impact**

Average lifecycle land footprint of solar power[1]



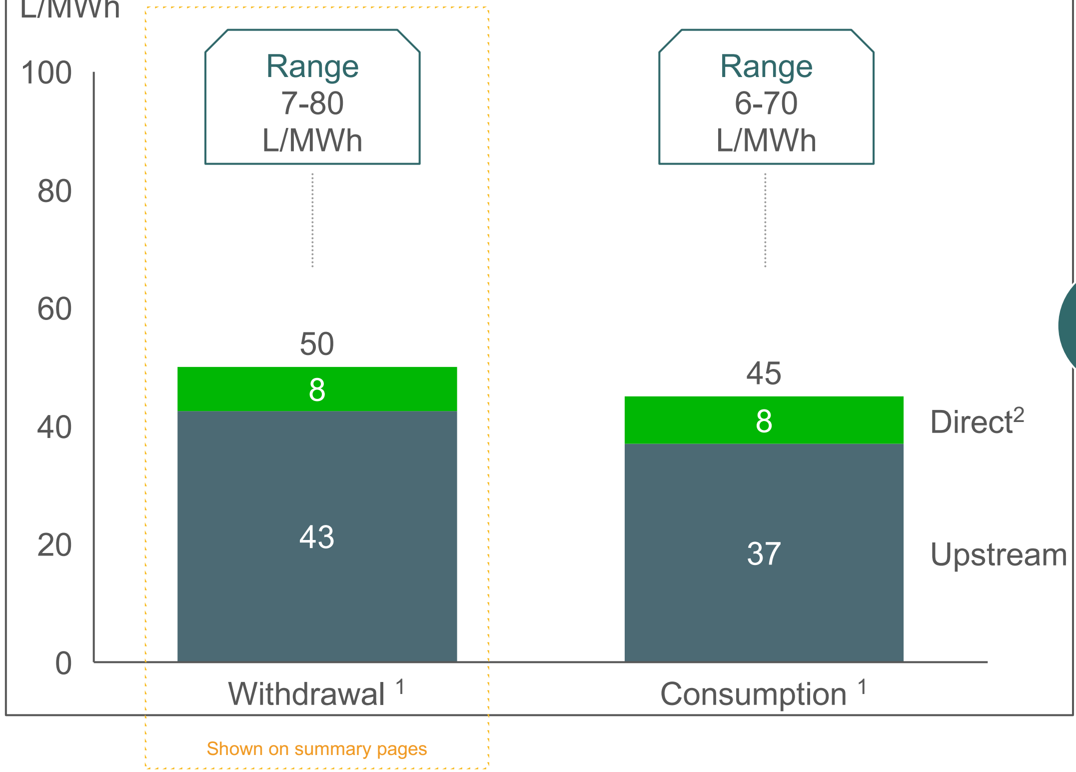

**Key insights**

- All the land impact from rooftop solar (usually residential) is from upstream activities (e.g., mining and manufacturing of components)
- In contrast, a bigger share of the lifecycle land footprint of ground-installed solar (usually utility-scale) is attributable directly to the solar farm area
- On average, the split in most countries is expected to be about 30% rooftop and 70% ground-installed by 2050, leading to an average solar lifecycle land footprint of about 14 m2/MWh

1. Averaged across fixed, single and dual axis solar configuration types, assuming Crystalline Si as the default technology 2. Includes small scale (1-20MW) as well as large scale (>20MW) solar project data, land use requirements for small PV projects were found to be similar to large PV projects (within 5% difference); 3. Assumes 30% solar rooftop share and 70% ground-installed; Source: EPRI, IEA, UN Energy Commission, DOE, Expert interviews, BCG analysis

# Lifecycle water withdrawals for solar PV are about 50 liters per MWh and mainly arise from component manufacturing

Water withdrawals for solar PV power generation

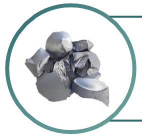
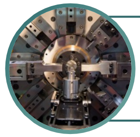



Key insights

- Of the estimated 50 L/MWh of water withdrawals required by solar PV over its lifecycle, most of this (about 45 L/MWh) is consumed
- Water for upstream (indirect) activities, including the processing of silicon and manufacturing of wafers, cells and modules, accounts for more than 80% of total consumption and withdrawals
- Direct usage mainly covers washing solar panels

1. "Withdrawal" refers to water removed from the ground or diverted from a surface-water source for use, and "Consumption" refers to the portion of withdrawn water not returned to the environment; 2. Reference studies assumed the same consumption as withdrawal volume for downstream (i.e, plant operation) due to lack of more granular data; Source: NREL; Meldrum et. al ("Lifecycle Life cycle water use for electricity generation: a review and harmonization of literature estimates"); Jin et al. ("Water use of electricity technologies: A global meta-analysis"), Expert interviews, BCG analysis

# Wind power's impact on nature can be mitigated using careful site management and better capacity factors

| | Upstream (indirect) impact | | Direct (downstream) impact | |
|---|---|---|---|---|
| Value chain |  Mining and metals processing |  Component manufacturing |  Installation and connection to grid |  Operation & maintenance |
| Description | The mining and processing of metals and raw materials – mainly steel (which accounts for 70-80% of the weight of a turbine), but also aluminum, copper, fiberglass/plastics and rare earth elements | The manufacturing of wind turbine components including the tower, transformer, gearbox, shaft, nacelle, rotor hub and rotor blades | Site construction and installation of the turbine as well as supporting components, including power lines to connect to the electricity grid (Dx[1] or Tx[2]) | All operations and maintenance activities that support power generation and transmission at the wind farm |

## Key parameters affecting wind power's impact on nature

### Site management

Turbines and other equipment typically occupy less than 5% of the wind farm area (both for offshore and onshore). Wind's impact on nature can be reduced by carefully managing unused space to preserve habitats and/or repurposing this space for other uses, such as agriculture.

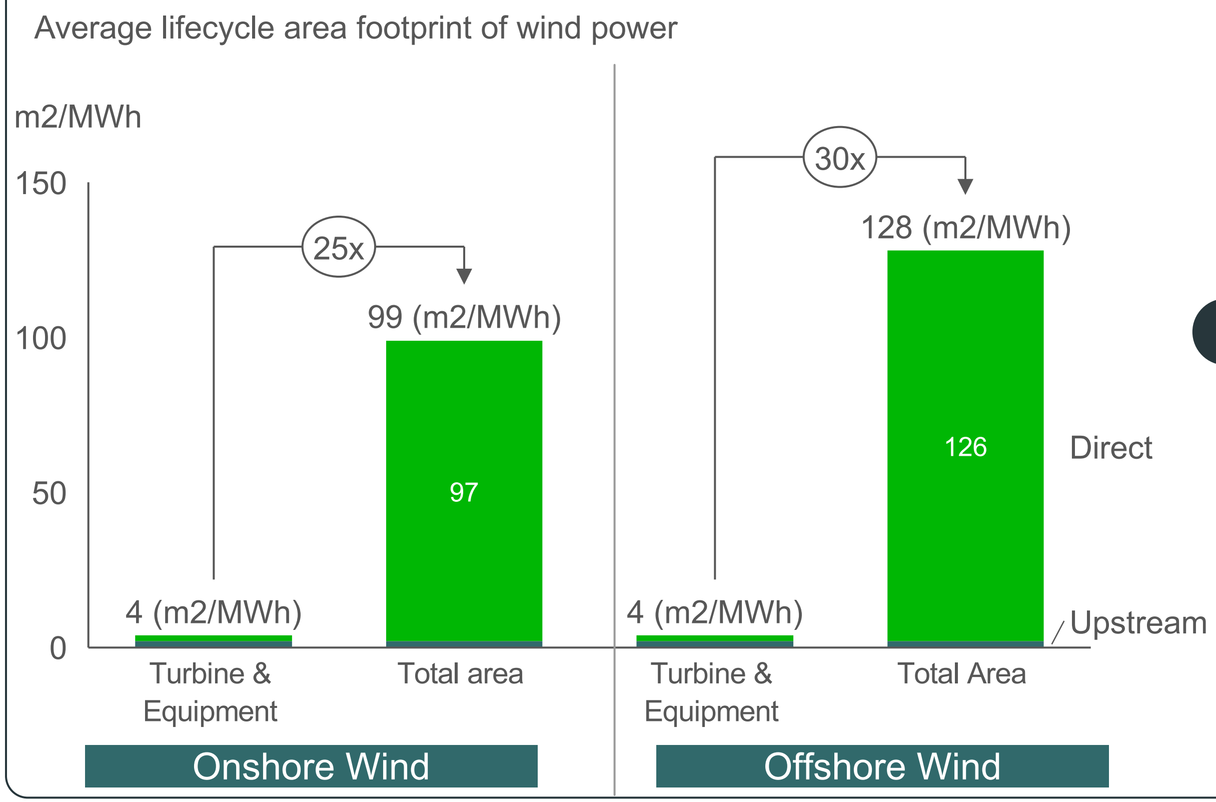
### Capacity factor (CF)

A higher capacity factor reduces the impact on nature per MWh of power generated. Capacity factors can be improved by deploying newer turbine technology and selecting sites with higher wind potential

1. Dx = Distribution; 2. Tx = Transmission; Source: NREL, Expert interviews

# Wind turbines and equipment occupy just a small part of wind farms due to spacing

## The average lifecycle area footprint of wind power



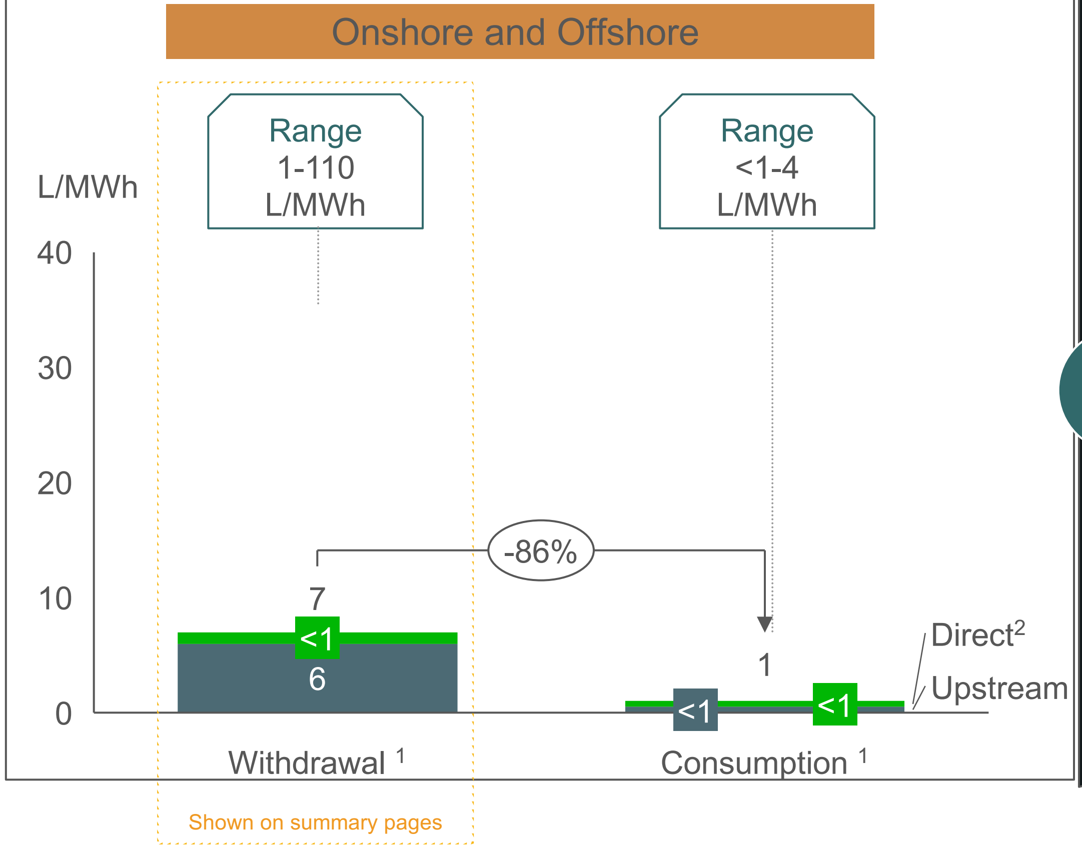

## Key insights

- Because of turbine spacing requirements, a wind farm's total area is typically 25-30 times greater than the area occupied by turbines and equipment
- Wind power's lifecycle area footprint is dominated by direct wind farm activities, with only about 2 m2/MWh attributable to upstream activities such as mining and component manufacturing
- The area footprint of offshore wind farms is about 30% higher than for onshore (126 m2/MWh vs. 97 m2/MWh), primarily due to greater spacing needed to mitigate wake effect

Source: EPRI, NREL, UN Energy Commission, Expert interviews, BCG analysis

# Lifecycle water withdrawals for wind power are about 7 Liters per MWh, driven by upstream activities

## Wind power water withdrawals

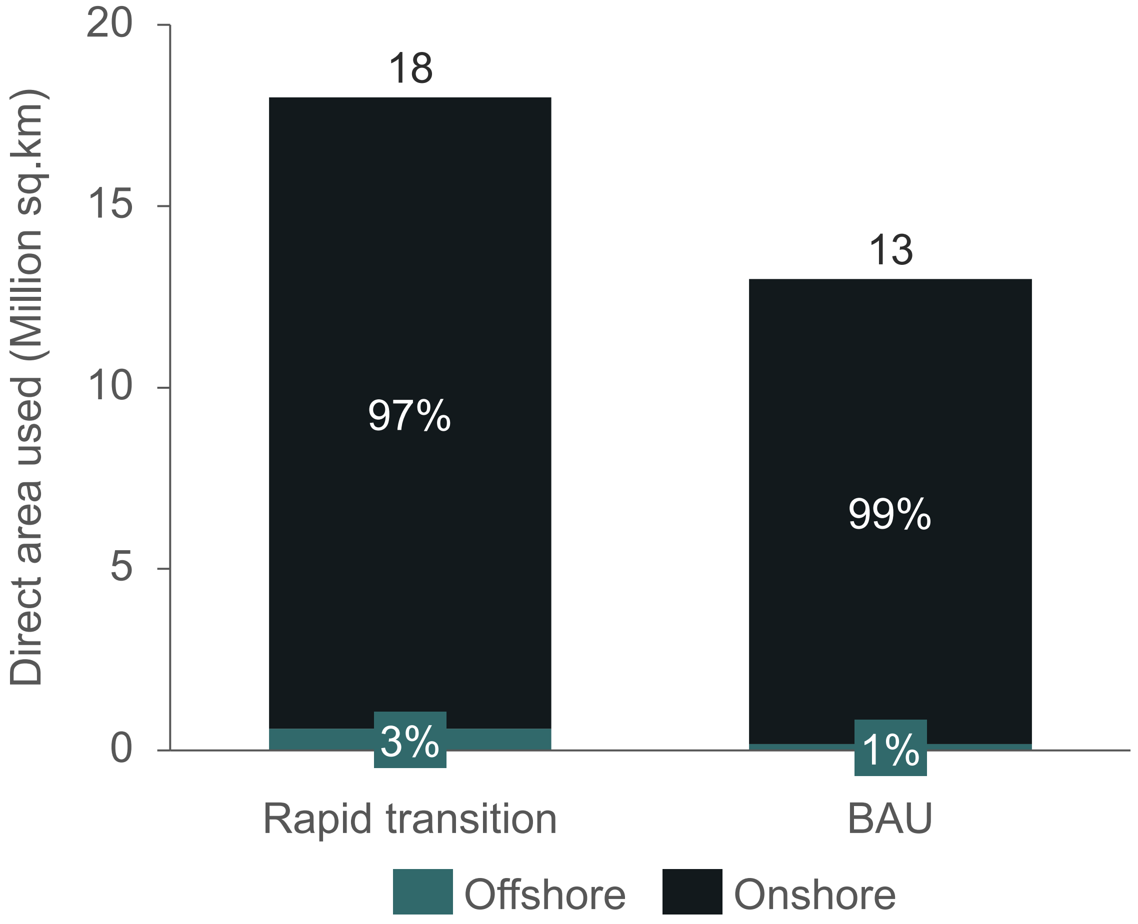



## Key insights

- Offshore and onshore wind farms have similar lifecycle water withdrawals per MWh
- Lifecycle water withdrawals are dominated by upstream activities, including mining and component manufacturing
- Of the 7 gallons per MWh of water withdrawals required by wind power, <10 is expected to be consumed

1. "Withdrawal" refers to water removed from the ground or diverted from a surface-water source for use, and "Consumption" refers to the portion of withdrawn water not returned to the environment; 2. Reference studies assumed the same consumption as withdrawal volume for downstream (i.e, plant operation) due to lack of more granular data; Source: NREL; Meldrum et. al ("Lifecycle Life cycle water use for electricity generation: a review and harmonization of literature estimates"); Jin et al. ("Water use of electricity technologies: A global meta-analysis"), Expert interviews, BCG analysis

# Offshore wind has a smaller role to play than onshore, but has a bigger impact on nature



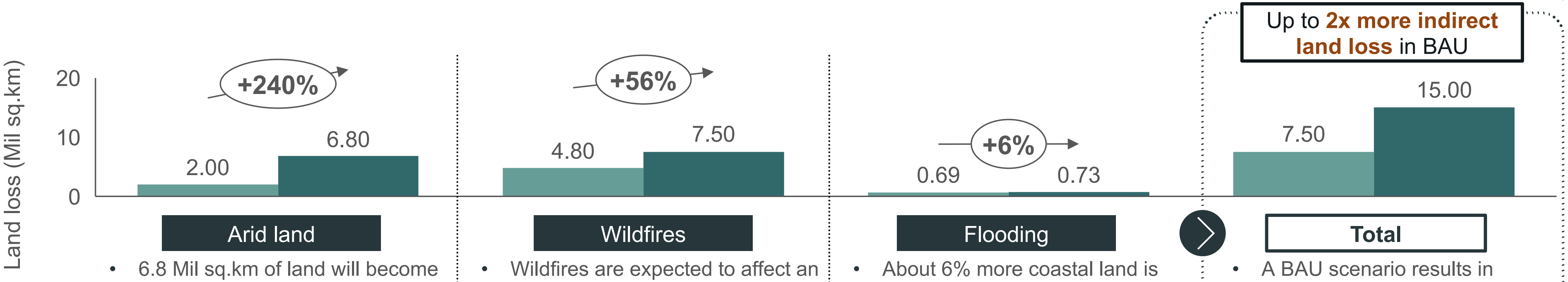

**Key insights:**

- Overall, offshore wind energy production has a much smaller role to play than onshore in both scenarios, requiring far less land
- In a rapid transition scenario, the offshore area required for direct activities (wind farms) is three times greater than in a BAU scenario as a percentage of the total..
- The negative impacts on nature are greater with offshore wind power, in both scenarios, reinforcing the need for careful planning to reduce impacts through siting and environmental management

Source: Library of Congress; The Week; IPCC AR6; BCG Analysis

# Indirect land loss could be up to two times greater in a BAU scenario due to climate change effects

## Indirect land loss due to climate change-related impacts (Mil sq.km)




**Arid land**

- 6.8 Mil sq.km of land will become arid in a BAU sceniario, 240% greater than the amount in a rapid transition scenario
- About 500 million people will live in an arid climate in a BAU scenario
- Higher temperatures and low precipitation will cause land to dry, particularly in South America and southern Europe

**Wildfires**

- Wildfires are expected to affect an area about 55% bigger than in a rapid transition scenario[1,2]
- Climate change and rising temperatures expected to increase the frequency and intensity of fires, especially in forested regions

**Flooding**

- About 6% more coastal land is situated below the *1 in 100-year flood plain* in BAU
- Flooding risks due to higher sea levels and eroded shorelines due to climate change
- Floods disproportionately impact populations near coastlines (about 340 million people live below projected annual flood levels)

**Total**

- A BAU scenario results in indirect land loss up to 2x greater than in a rapid transition scenario
- In BAU, the indirect climate change impacts (up to 15 Mil. sq.km) exceed direct impacts (13 Mil sq.km); This aligns with an independent UN estimate of a ~16 Mil sq.km land deterioration from climate change globally by 2050

Rapid transition | Business as usual

1. Weighted average of 3°C and 4°C to get burned area (BA) projection for a 3.2°C BAU world 2. Global mean burn area (BA) calculated from projections in increased mean frequency of extreme fire weather, measured in days per year, under 1.5°C and 3.2°C scenarios; Source: Spinoni et al. 2021 "How will the progressive global increase of arid areas affect population and land-use in the 21st century?"; Jones et al. 2022 "Global and Regional Trends and Drivers of Fire Under Climate Change"; Brown et al. 2018 "Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300"; Kulp & Strauss 2019 "New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding"; UNCCP; BCG analysis

# A3. Transmission & distribution infrastructure impact

# Grid expansion requires a relatively small land area, but it can still pose significant risks to habitats

The estimated land area required globally by 2050 for wind and solar power generation and for additional transmission and distribution lines in a rapid transition scenario

| Transmission | Distribution | Wind + Solar |
|---|---|---|
| ~0.5 million km of new lines[1] | ~11 million km of new lines[2] | (for comparison) |
| ~4 (1000 Sq.km) | ~22 (1000 Sq.km) | ~3,600 (1000 Sq.km) |

Despite the relatively small land area required, transmission lines can be especially problematic for habitats due to:

- Large linear footprint and habitat fragmentation potential
- Elevated risk of electrocution (especially for birds)
- Elevated risk of natural disasters and wildfires

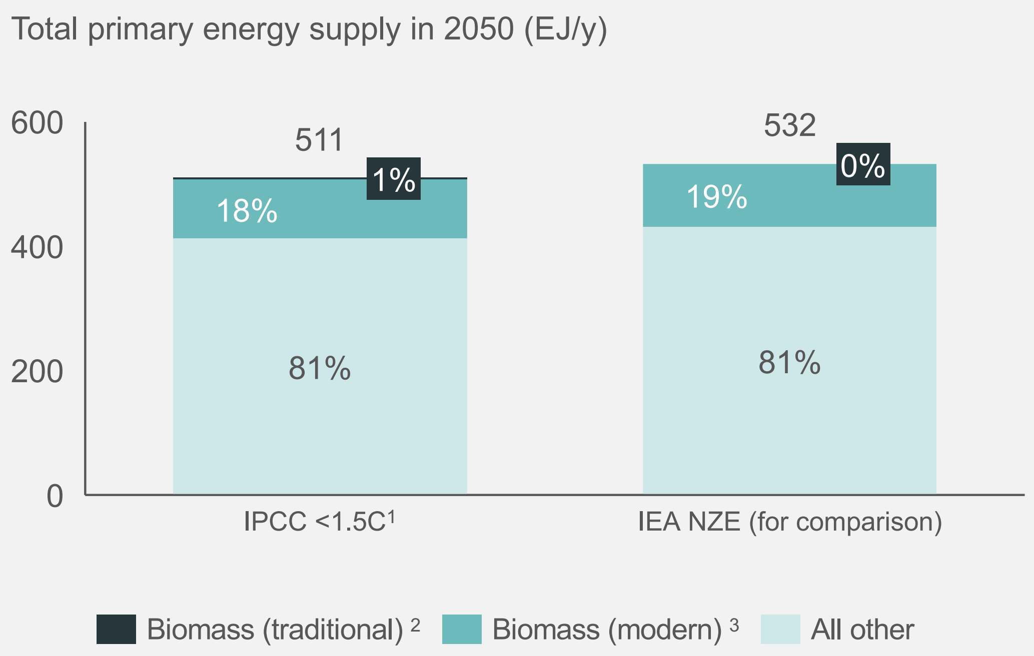
Negative impacts can be mitigated by rigorous siting and permitting criteria and burying transmission lines underground

Notes: 1. Equal to ~2x the total length of US transmission lines today 2. Equal to ~1.3x the total length of US distribution lines today; Source: IEA, IPCC, BCG analysis

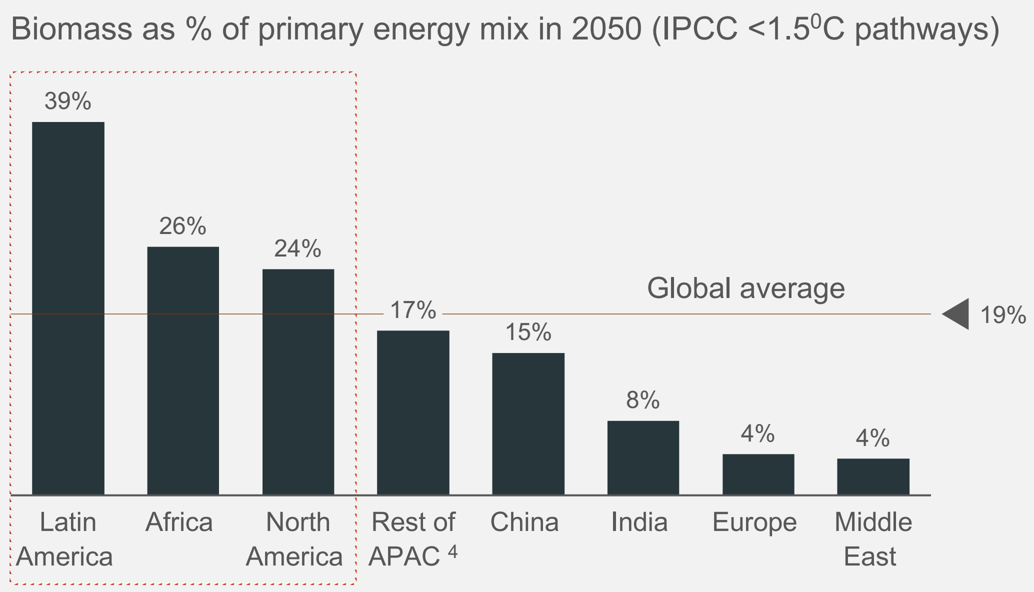
# A4. Biomass sensitivity analysis

# Despite requiring a large amount of land, biomass is projected to be a significant part of a 1.5°C future

## Both IPCC and IEA climate-positive scenarios predict about 19% of energy globally will come from biomass by 2050




## Biomass will likely represent a large share of the energy mix in Latin America, Africa and North America, driven by availability and cost




1. Based on the IPCC C1 Shifted Pathways (SP) Illustrative Mitigation Pathway (IMP) 2. Traditional biomass is un-processed biomass used directly for heating (e.g., wood stoves) 3. Modern biomass includes all forms of manufactured bioenergy (purpose-grown/collected biomass) 4. Includes all countries in Asia Pacific, except China and India (shown separately); Source: IPCC AR6; IEA; BCG analysis

# Shifting biomass demand to wind or solar, and using crops with a higher energy yield, can significantly improve land use

## Case study: Estimated land area saved in Africa and Latin America by 2050 (Mil sq.km)

% improvement in crop energy yield per unit area (columns); % of energy demand shifted from biomass to solar & wind (50/50 split) (rows)

| Africa | 2% | 4% | 6% | 8% | 10% |
|---|---|---|---|---|---|
| **1%** | 0.06 | 0.08 | 0.11 | 0.13 | 0.15 |
| **2%** | 0.10 | 0.12 | 0.15 | 0.17 | 0.19 |
| **3%** | 0.14 | 0.16 | 0.18 | 0.21 | 0.23 |
| **4%** | 0.18 | 0.20 | 0.22 | 0.25 | 0.27 |
| **5%** | 0.22 | 0.24 | 0.26 | 0.29 | 0.31 |

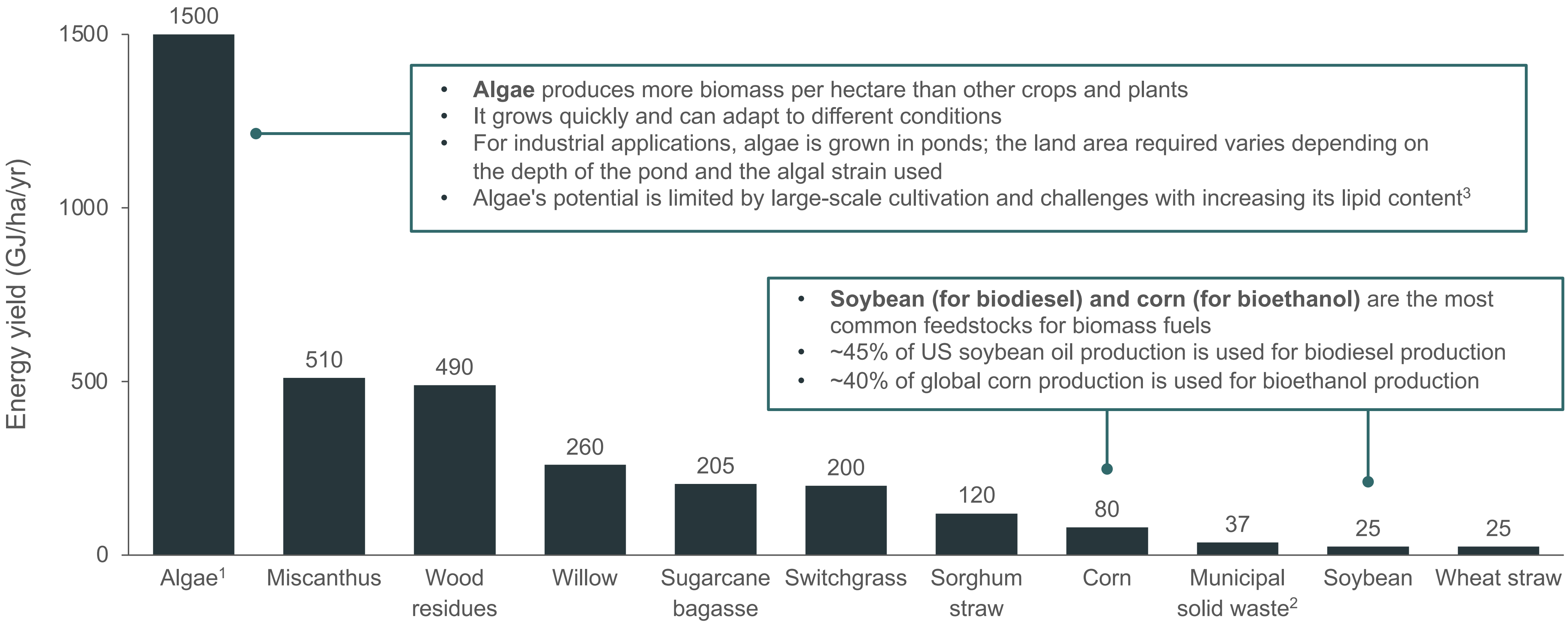
| Latin America | 2% | 4% | 6% | 8% | 10% |
|---|---|---|---|---|---|
| **1%** | 0.11 | 0.16 | 0.21 | 0.27 | 0.32 |
| **2%** | 0.17 | 0.22 | 0.27 | 0.33 | 0.38 |
| **3%** | 0.23 | 0.28 | 0.33 | 0.38 | 0.44 |
| **4%** | 0.29 | 0.34 | 0.39 | 0.44 | 0.49 |
| **5%** | 0.35 | **0.40** | 0.45 | 0.50 | 0.55 |

By 2050, if 5% of the total energy demand was shifted from biomass to wind or solar and the energy yield of biomass crops was improved by 10%:

- 300,000 sq.km of land could be saved in Africa **(equal to ~1% of Africa's total land area, or 30% of Egypt's land area)**
- 550,000 sq.km land could be saved in Latin America **(equal to ~2% of LATAM's total land area, or 6% of Brazil's land area)**

Note: estimations are based on estimated demand and energy mix in IPCC regional <1.5$^0$C pathways
Source: IPCC AR6; BCG analysis

# Selecting biomass feedstocks based on energy yield can reduce the amount of land required



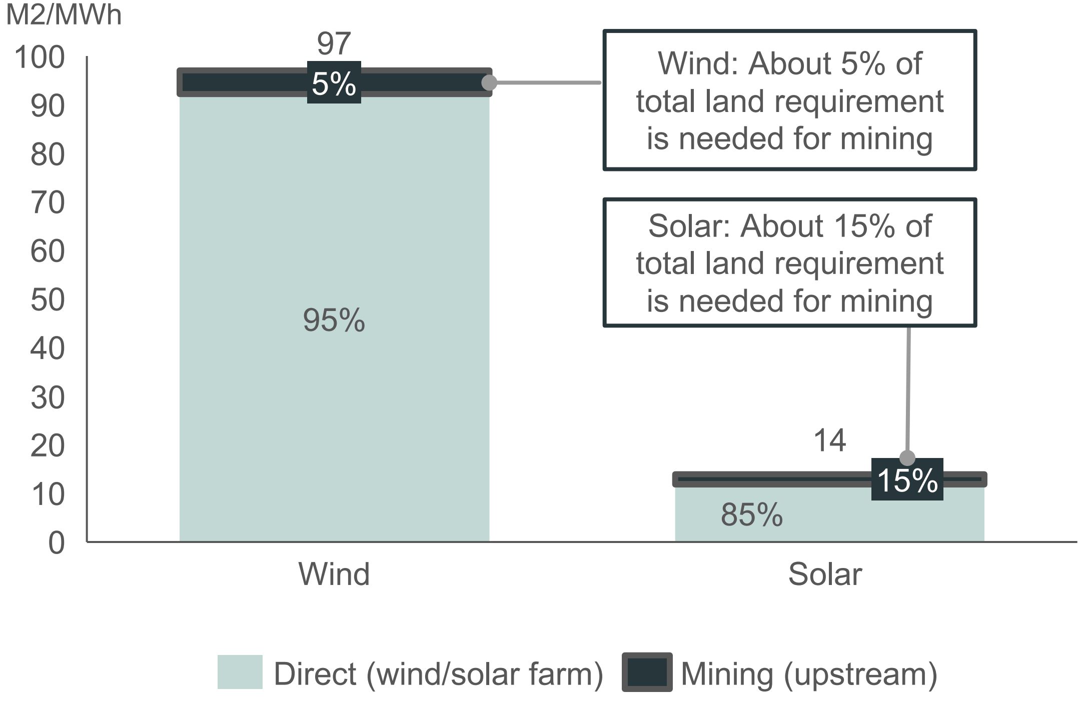

Notes: 1. The annual average cultivation productivity yield of algae in 2020 was 18.4g/m2/day, equivalent to ~67,000kg/ha/year; 2. Production yield per area input not available. Input estimated based on US municipal solid waste production compared to total urban land area; 3. Shell, BP, ExxonMobile ended green algae biofuel investments in 2023, citing commercial and biological limitations; Source: US DoE; Oak Ridge National Laboratory; NREL 2020 "Algal Biomass Production via Open Pond Algae Farm Cultivation"; The World Bank; BCG analysis

# A5. Mining impact

# In a rapid transition scenario, mining will make up a small part of the lifecycle land footprint of wind and solar

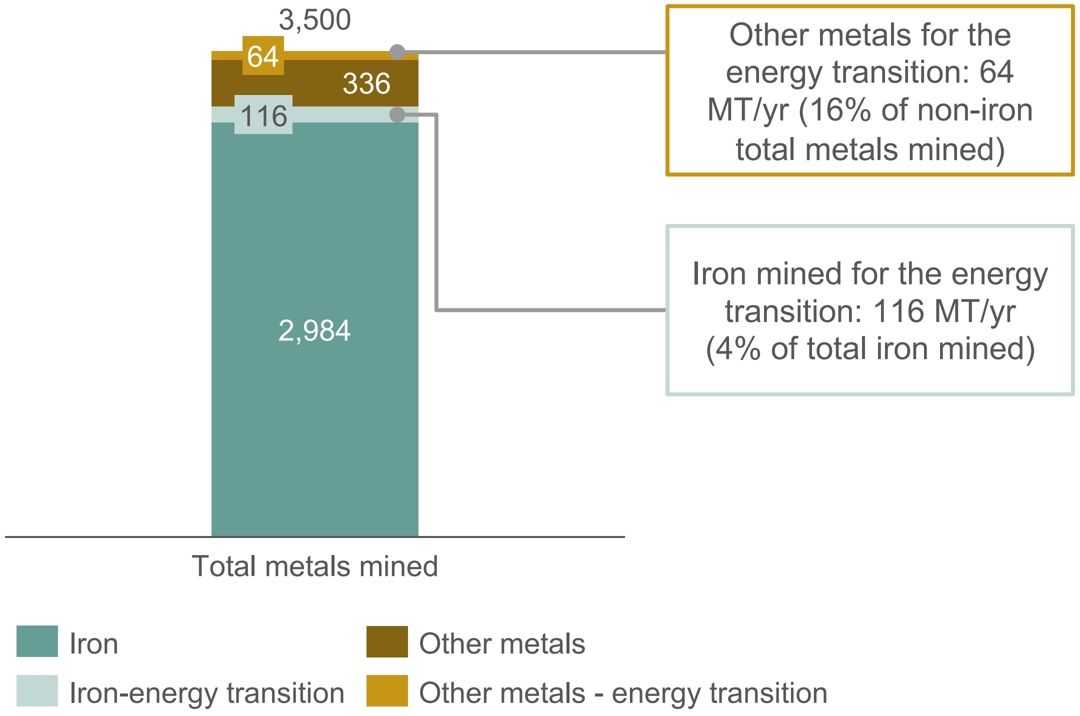
## Land for mining will represent a small portion of the lifecycle land footprint of wind and solar

Estimated land required for wind and solar in 2050 in a <1.5 $^{0}$C scenario




## Metals for the energy transition will make up only about 5% of global metals production in 2050

Estimated mining production in 2050 in a rapid transition scenario (Mil tonnes/yr)




Source: Source: IEA, EIA, NREL, EPRI, UNEC, DOE, Expert Interviews, IMF, BCG analysis

# The supply of key energy transition materials is dominated by a handful of nations today

| Material *Ranked* | Demand by 2050 (Mt/yr) Energy transition[1,2,3] | Total | Share of global supply today (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Iron | 116 (4%) | 3,100 | Australia | 37% | Brazil | 19% | China | 14% | Other | 30% |
| Graphite | 19 (66%) | 28 | China | 59% | Mozambique | 11% | Brazil | 8% | Other | 21% |
| Aluminum | 15 (10%) | 155 | China | 56% | China | 6% | Russia | 6% | Other | 32% |
| Copper | 9 (21%) | 43 | Chile | 29% | Peru | 11% | China | 8% | Other | 52% |
| Lithium | 7 (70%) | 10 | Australia | 51% | Chile | 27% | China | 11% | Other | 11% |
| Nickel | 3 (50%) | 6 | Indonesia | 31% | Philippines | 13% | Russia | 11% | Other | 45% |
| Zinc | 2 (8%) | 24 | China | 33% | Peru | 11% | Australia | 10% | Other | 46% |
| Silicon | 2 (16%) | 12 | China | 70% | Russia | 7% | Brazil | 5% | Other | 18% |
| Manganese | 1 (3%) | 32 | South Africa | 28% | Australia | 18% | Gabor | 15% | Other | 39% |
| Cobalt | <1 (<30%) | 3 | Congo D.R. | 69% | Rushia | 5% | Australia | 4% | Other | 22% |
| Chromium | <1 (<2%) | 50 | South Africa | 40% | Kazakhstan | 17% | Turkey | 15% | Other | 28% |
| Rare earth elements[4,5] | 0.05 (10%) | 0.5 | China | 60% | USA | 15% | Myanmar | 12% | Other | 13% |

1. Includes demand for renewables generation, battery storage and electricity transmission/distribution 2. Values in parentheses represent % of total global demand 3. Concrete is another material needed for energy transition infrastructure, but its demand expected to be lower in a net zero world compared to business as usual and therefore not included in this analysis 4. Includes sum of Neodymium (Nd), Dysprosium (Dy), Praseodymium (Pr) and Terbium (Tb) 5. Rare earth element demand in 2050 for clean energy is estimated to be between 10-100k tonnes per year, mid range shown here; Source: USGS, European Commission, IMF, Tesla Masterplan Part III, IEA, Expert interview, BCG analysis

# By 2050, land needed for mining energy transition minerals will be far smaller than land stranded from legacy coal mines

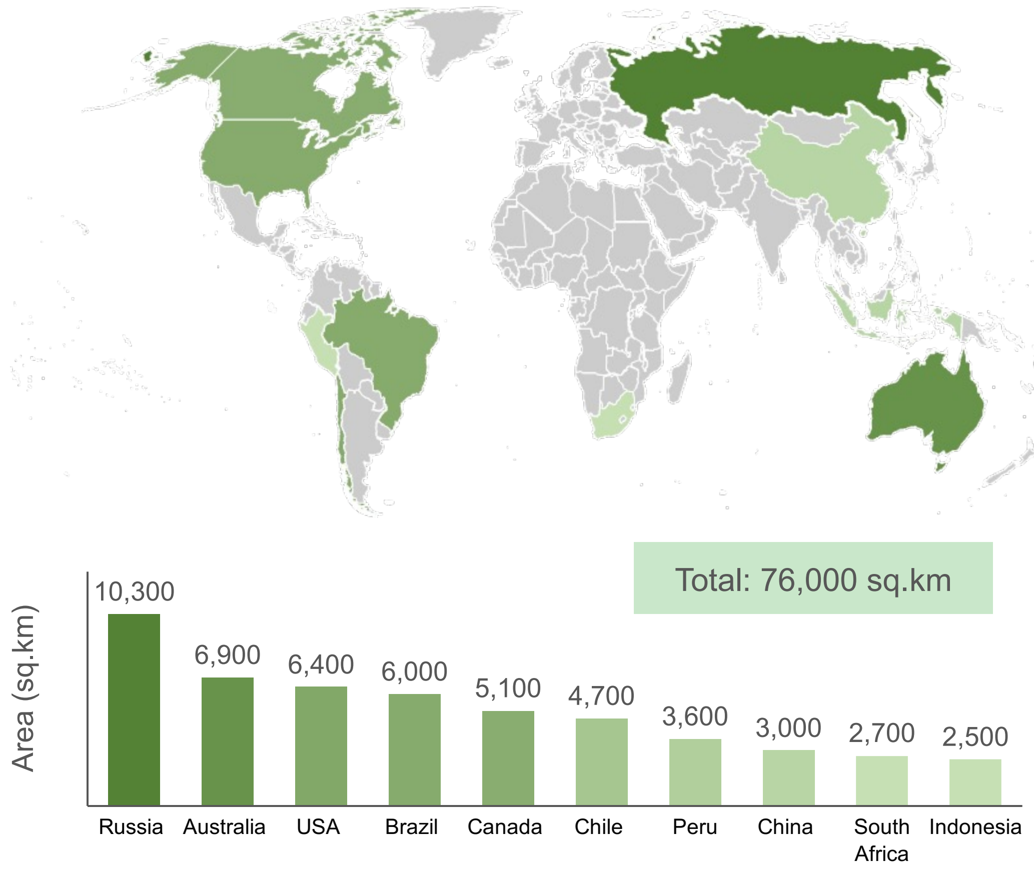
| Country | Additional land mined for energy transition minerals by 2050[1] (sq km) | As % of country's total land area | Land stranded from legacy coal mines by 2050[2] (sq km) | As % of country's total land area |
|---|---|---|---|---|
| China | 360 | <0.01% | 7,800 | 0.41% |
| Australia | 250 | <0.01% | 1,800 | 0.06% |
| Chile | 120 | 0.02% | 0 | <0.01% |
| Indonesia | 110 | 0.01% | 5,600 | 0.30% |
| DRC | 100 | <0.01% | 0 | <0.01% |
| South Africa | 90 | 0.01% | 1,000 | 0.20% |
| Brazil | 70 | <0.01% | 0 | <0.01% |
| Russia | 60 | <0.01% | 1,500 | 0.02% |
| Philippines | 50 | 0.02% | 0 | <0.01% |
| Canada | 50 | <0.01% | 0 | <0.01% |
| Peru | 40 | <0.01% | 0 | <0.01% |
| USA | 40 | <0.01% | 1,900 | 0.05% |
| India | 40 | <0.01% | 2,100 | 0.25% |
| Kazakhstan | 30 | <0.01% | 400 | 0.04% |
| Rest of the World | 270 | | 4,000 | |
| **Total (Global)** | **~1,800 (sq km)** | **-** | **~26,700 (sq km)** | **-** |

1. Includes all demand needed for renewables generation, battery storage and electricity transmission/distribution, assuming the Net Zero Scenario; 2. Assumes >95% reduction in global coal demand to reach net zero; Note: analysis assumes that the proportion of production of metals and minerals for renewables continues to be the same as today; Source: USGS, IMF, Tesla Masterplan Part III, IEA, BCG analysis

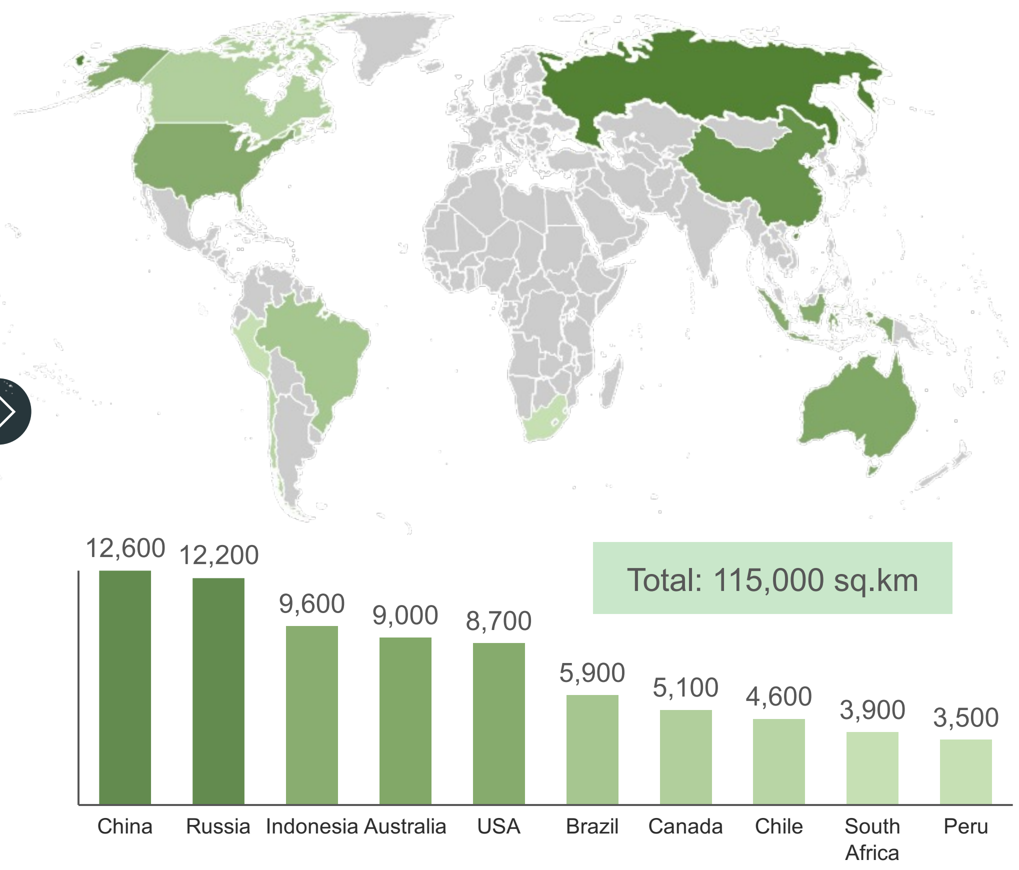
# By 2050, the total land area that is actively mined will be one-third smaller in a rapid transition scenario due to the decommissioning of mines

Directional and approximate

Top 10 countries by **active mining area in a 2050 rapid transition** scenario




Top 10 countries by **active mining area in a 2050 BAU** scenario

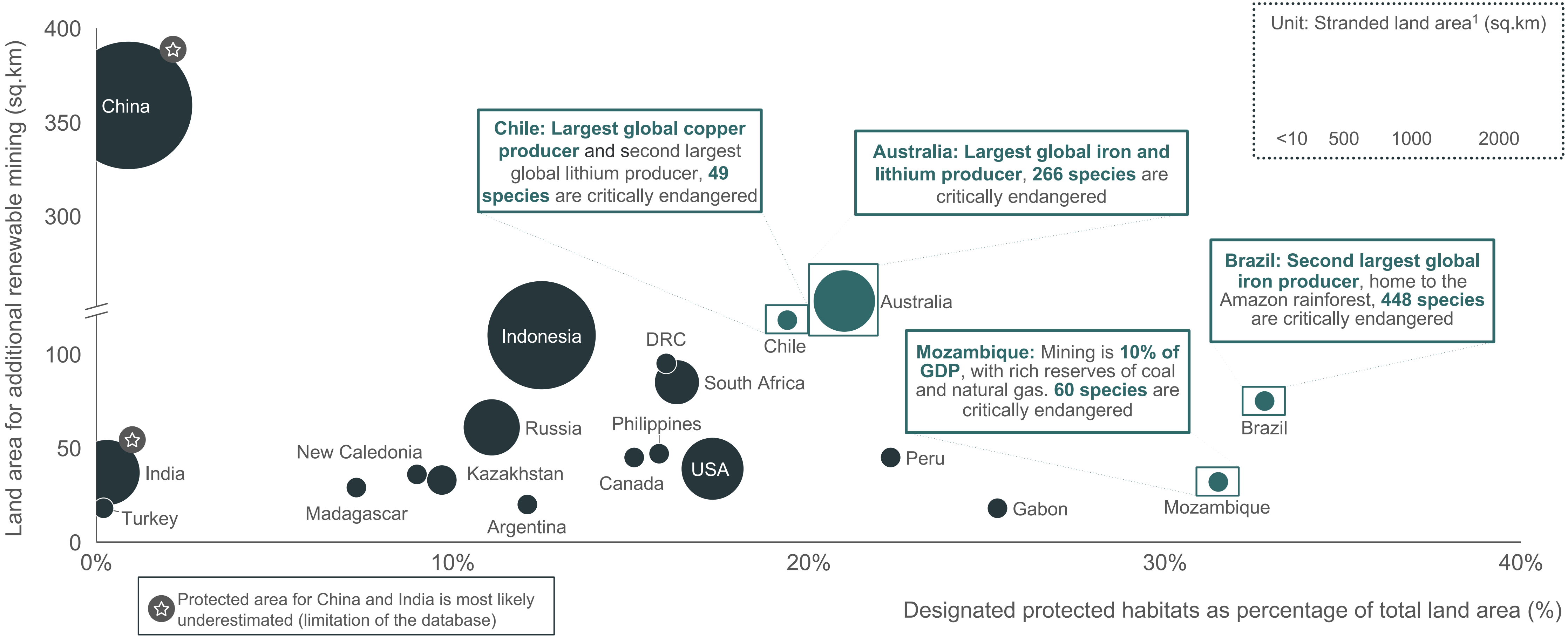



Note: active mining area calculated as today's mining area, plus/minus areas projected to be added/stranded based on energy demand shifts in each scenario
Sources: Jasansky et al. 2023 "An open database on global coal and metal mine production"; BCG analysis

# Even in a rapid transition scenario, countries that are mining hotspots and have substantial protected habitats will require particular support

## Top 20 countries by land area needed for mining materials for a rapid energy transition

Country-by country ecological risk assessment needed to better understand impacts




1. Corresponds to legacy coal mines expected to become stranded in a 2050 Net Zero world; Note: Protected areas for China and India is likely underestimated
Source: USGS, IMF; Tesla Masterplan Part III; IEA; The World Bank; Protected Planet (IUCN/WDPA protected habitats database); BCG analysis

# Mining can harm water quality through various mechanisms, with acid rock drainage posing the highest risk

Directional; further analysis needed to understand mining water impact attributable to energy transition

Higher risk → Lower risk

| Contamination Mechanism: | Mitigation Potential | Open-pit mining<br>• >90% of global metals production<br>• ~60-80% of global coal production | Underground mining<br>• <10% of global metals production<br>• ~20-40% of global coal production |
|---|---|---|---|
| **Acid rock drainage**<br>Oxidation and acidification of mining rocks (especially sulfide minerals) and leaching to water bodies | **Low**<br>Includes better management of wastewater to limit contact with natural waterways | Larger volumes (due to more rocks being excavated), but lower risk of direct contamination of aquifers | Less volume but higher risk of contact with groundwater sources |
| **Erosion and sedimentation**<br>Residual rocks carry sediments into underground or surface waters | **Low**<br>Includes better management of sediments to minimize carry-over to waterways | Larger volumes of sediment (due to more rocks being excavated), but lower risk of direct contamination of aquifers | Less volume but higher risk of contact with groundwater sources |
| **Heavy metal leaching**<br>Metals (e.g., arsenic, cobalt and cadmium) contained in excavated rock can come into contact with water bodies | **Moderate**<br>Open-pit wastewater can be treated for heavy metals; less levers available for underground mining | Impact largely depends on rock composition, overall impact less for open-pits since wastewater can be mostly contained and treated | Less excavation but limited levers to mitigate leaching to aquifers |
| **Processing chemicals**<br>Chemicals used in processing ore are leached, leaked, or spilled from the mining area into the nearby bodies of water | **High**<br>Processing wastewater can be fully contained and treated, especially for open pit mines | Similar impact for both methods | Similar impact for both methods |

Lower water risk ← → higher water risk

Note: Other methods of mining such as dredging, and in-situ mining are less prevalent
Source: DOE; USGS; Safewater.org; BCG analysis

# Among mining activities, coal extraction poses the highest water risk globally

A decline in coal mining will most likely reduce global water risk, though the impact is highly localized and difficult to quantify

**Calculated total water risk based on WWF water risk filter (2020)**

Risk estimates based on proximity of all global active mines (~3170), mapped against high-risk water basins

| Commodity[1] | Demand shift | Number of active mines | Overall water risk (1: lowest ; 5:highest) | Water risk category score (1: lowest ; 5:highest) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physical | Regulatory | Reputational | Water scarcity | Flooding | Water quality status | Ecosystem services |
| Coal | ↓ | 1,270 | 3.3 | 3.0 | 2.3 | 3.7 | 2.2 | 3.5 | 3.5 | 3.2 |
| Chromite | ↑ | 43 | 3.3 | 3.4 | 2.2 | 2.8 | 3.1 | 3.2 | 3.4 | 3.0 |
| Bauxite (Aluminum) | ↑ | 55 | 3.2 | 3.0 | 2.5 | 3.5 | 2.3 | 3.4 | 3.1 | 3.0 |
| Zinc | ↑ | 350 | 3.1 | 3.0 | 2.4 | 3.4 | 2.3 | 3.3 | 3.2 | 2.8 |
| Copper | ↑ | 405 | 3.1 | 2.9 | 2.5 | 3.1 | 2.5 | 3.1 | 2.9 | 2.7 |
| Iron | ↑ | 229 | 3.1 | 2.8 | 2.3 | 3.5 | 2.3 | 3.1 | 2.9 | 2.7 |
| Lithium | ↑ | 16 | 3.0 | 2.8 | 2.2 | 3.6 | 2.5 | 2.8 | 2.4 | 2.5 |
| Nickel | ↑ | 94 | 2.9 | 2.7 | 2.3 | 3.2 | 2.3 | 3.0 | 2.7 | 2.5 |
| Cobalt | ↑ | 72 | 2.9 | 2.6 | 2.5 | 3.2 | 2.2 | 2.9 | 2.6 | 2.7 |

1. Only commodities relevant to the energy transition shown here, longer list available in the reference study

Source: WWF Water Risk Filter Research Series: An analysis of water risk from mining (2020)

# Mining analysis method summary:

**Material selection:**

- Mining analysis in this section was focused on minerals with significant projected shift due to energy transition.
- Minerals with net increase between now and 2050 included iron, graphite, aluminum, copper, lithium, nickel, zinc, silicon, manganese, cobalt, chromium and 4 rare earth elements (Neodymium, Dysprosium, Praseodymium, and Terbium).
- Coal was the only mineral with projected net negative change in our analysis.
- Other minerals that are contributors to global mining area today but were not projected to materially shift as result of energy transition (namely, gold, silver and diamond) were not considered in our assessment.

**Land area estimate:**

- To calculate the land area shifts, incremental change in total production mass (tonne/year) for each of the minerals above was multiplied by global mining area intensity (sq km/tonne) specific to that mineral in respective country, for each of the future scenarios (rapid transition vs. business as usual).
- To delineate impact on individual countries, it was assumed that the current share of global commodity supply for each country, as well as the mining area intensities, will remain the same between now and 2050.
- To estimate the stranded mining area, it was assumed that~98% of coal production will be halted by 2050 in a rapid transition scenario, and associated coal mines will be proportionally decommissioned in each country (as an example, if a country has 100 acres of active coal mining today, it was assumed that active area is declined to 2 acres by 2050, with the remaining 98 acres stranded as legacy mines).

# A6. Energy sources' impact on species

# Among energy sources, wind and solar have the lowest impact on species

Lower impact
Higher impact

| Energy source | Impact on species |
|---|---|
| Solar | • Bats, birds and insects face habitat changes due to panel shading effects on blooming vegetation<br>• Migrating birds mistake reflective surfaces of PV panels for water and collide with hard structures ("lake effect") |
| Onshore wind | • Birds and bat can collide with turbine blades, resulting in their death, or be electrocuted by distribution lines |
| Offshore wind | • Whales, dolphins, sea turtles are exposed to loud noise and can collide with construction vessels<br>• Seabirds and migratory birds can collide with turbines |
| Biomass | • Freshwater species experience habitat loss from erosion and agricultural run-off due to land-use changes<br>• Monocultures reduce biodiversity, increase pest and disease outbreaks, and displace or slow growth rates of vulnerable native species |
| Hydro | • Migratory freshwater fish and aquatic species disrupted by dam reservoirs and face spawning interruptions<br>• Permanent changes in water and sediment flow block the movement of species up- and downstream and cause riverbed incision and delta shrinking, making them uninhabitable for local species |
| Fossil fuels | • Fish and animals face habitat destruction and death from explosives-based drilling, seismic noises, and toxic pollutants released into the air and water during operations<br>• Contaminated wastewaters containing oil and heavy metals poison trees and have destroyed >130,000ha of mangrove vegetation since 1960s – areas essential for coastal species<br>• Catastrophic events such as oil spills cause irreversible damage to habitats (e.g., Deepwater Horizon impacted an estimated 800,000 birds and 26,000 sea mammals; while an oil spill in the Arctic could wipe out the entire bowhead whale population) |



Source: WWF; The Biodiversity Consultancy; The Wildlife Society; Center for Biological Diversity; Duke (2016) "Oil spill impacts on mangroves"; BCG analysis

# The negative impacts of wind and solar on terrestrial and aquatic species can be mitigated using siting and operational strategies

## Low impact siting

Place turbines or solar panels away from sensitive areas; use land that has already been degraded

## Reduce risks of collision and electrocution

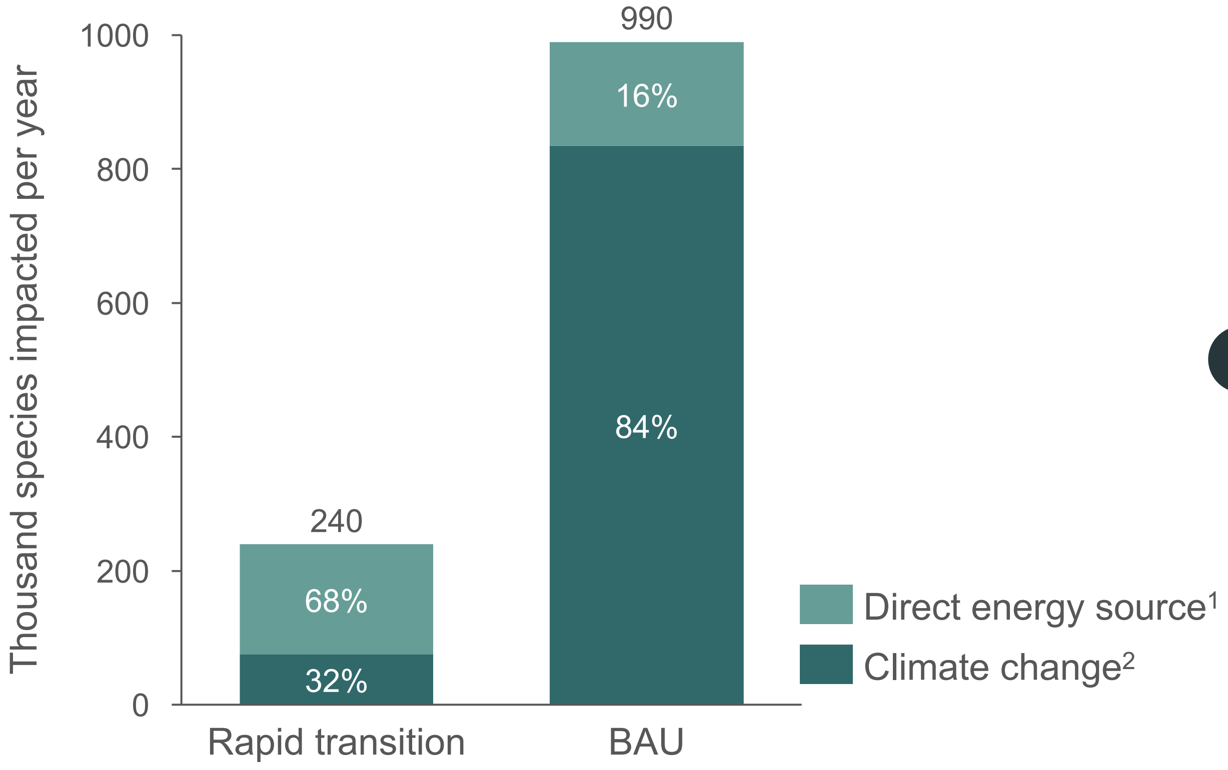
Enhance the visibility of turbines, add acoustic deterrents to avert birds and animals, make transmission lines visible with bird flight deflectors or bury lines in the ground

## Make infrastructure habitable

Design off-shore turbines with artificial reefs, and solar panels with substrates underneath, to support local habitats

# Due to climate change, negative impacts on biodiversity are significantly higher with a BAU scenario

Direct energy source vs climate change impacts on biodiversity




Key insights

- A renewables-heavy global energy system will reduce damage to biodiversity by about 4 times, preventing adverse impacts to about 750,000 species each year
- About 84% of adverse impacts on habitats in a BAU scenario are driven by climate change, while in a rapid transition scenario direct impacts from energy sources play a bigger role
- Biomass accounts for most direct energy source impacts under a rapid transition scenario, primarily due to land occupation and transformation

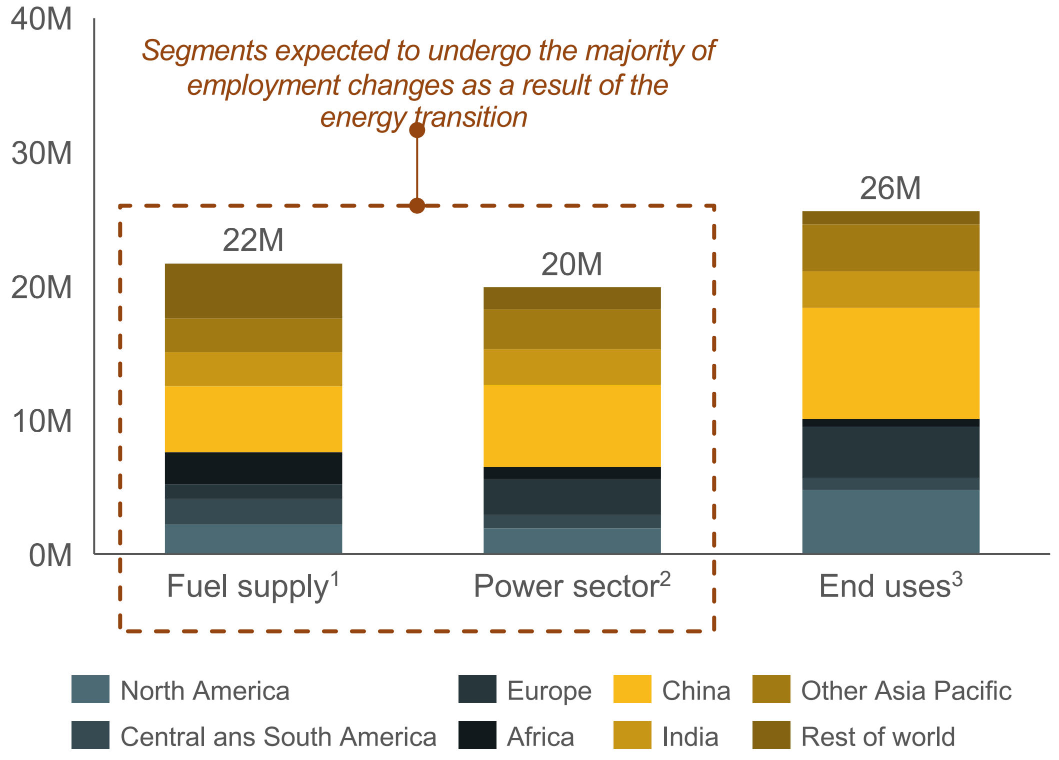
1. Direct energy source impacts on species arise from eutrophication, acidification, land occupation/transformation, and ecotoxicity; 2. Climate change impact is associated with indirect change in habitats and ecosystems driven by global warming; Source: Gibon et al. 2016 “Health benefits, ecological threats of low-carbon electricity"; BCG analysis

# A7. Socioeconomic metrics

# By 2050, a rapid transition scenario is expected to create about 2.6 times more net jobs

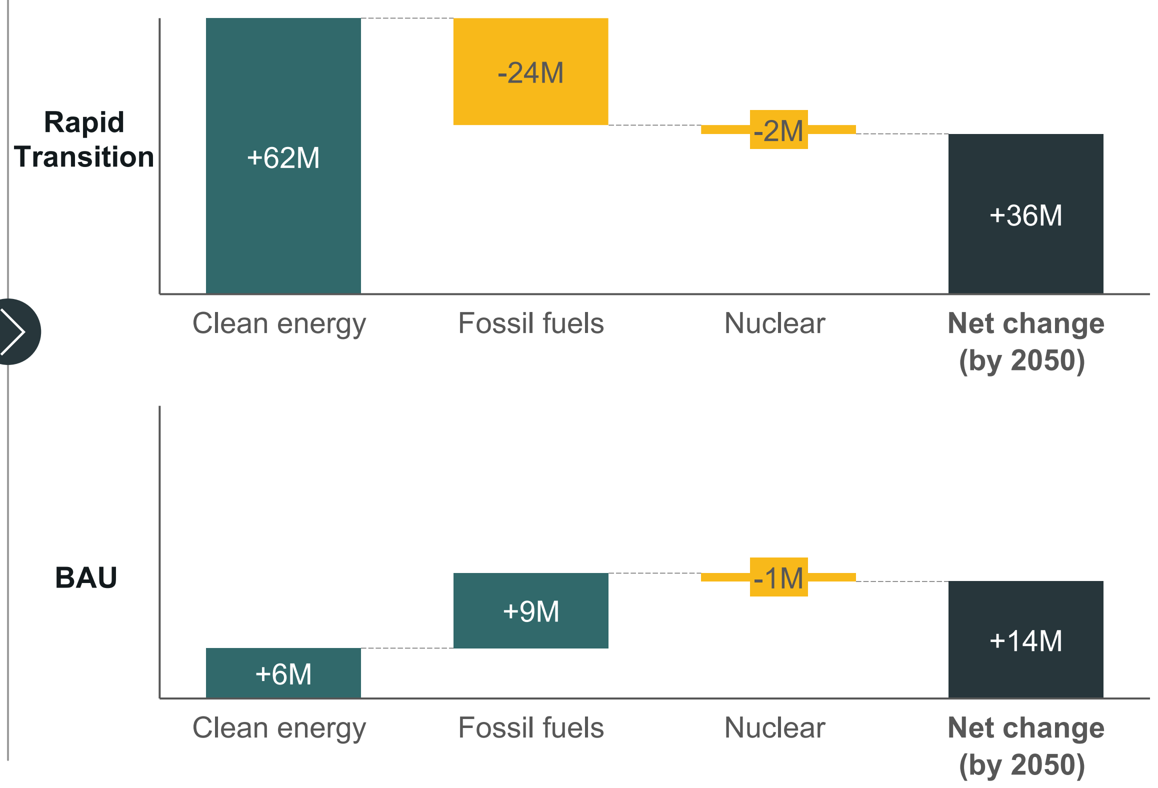
## Estimated energy employment by region and sector, 2019

Total of ~68 million employed in the energy industry globally[4]




## Projected change in employment for each scenario by 2050

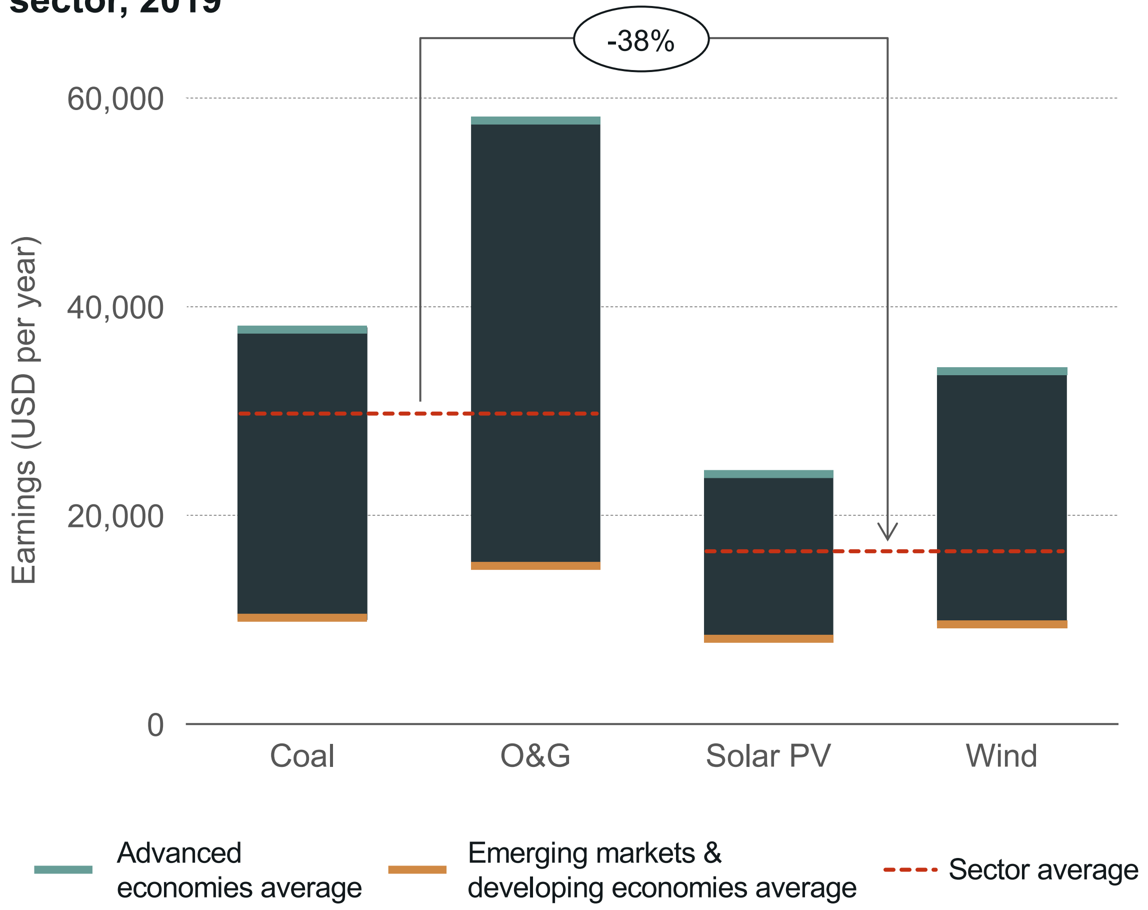
Million Job-Years created or lost




1. E.g., coal, oil, gas and bioenergy production 2. E.g., generation, transmission and distribution of electricity 3. vehicles manufacturing and energy efficiency for buildings and industry 4. Part time employments converted to full time to allow for aggregation; Source: IEA World Energy Employment Report; Wei et al. "Putting renewables and energy efficiency to work"; BCG analysis

# Clean energy jobs pay less than fossil fuel jobs due to lower union representation, compensation for hazards, and skill requirements

**Average global annual earnings per employee by energy sector, 2019**




**Energy worker earnings**

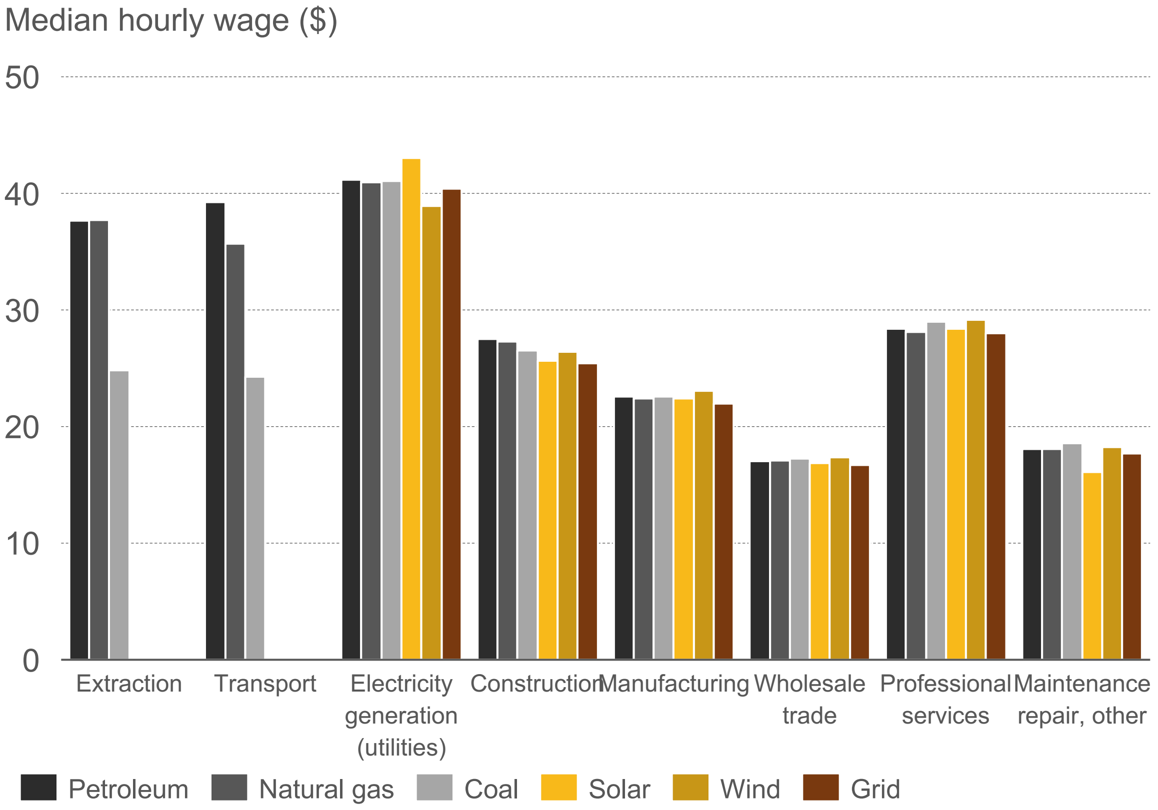
- Wages in the energy industry are 10-50% higher than the average across the global economy, and energy demands more highly skilled workers than other industries
- However, wages in clean energy sectors (e.g., solar and wind) are on average ~38% lower than those in more established sectors (e.g., nuclear, oil and gas)
- The disparity can be explained by the following factors:
  - Lower labor protection and union representation (especially in emerging market and developing economies)
  - Less compensation for occupational hazards (as the sector is generally safer)
  - Lower skill requirements, with a greater share of part-time and contract workers

Source: IEA 2022 "World Energy Employment"

# Pay by job function is similar across different energy industry segments, but fossil fuels require a larger share of the higher paying functions

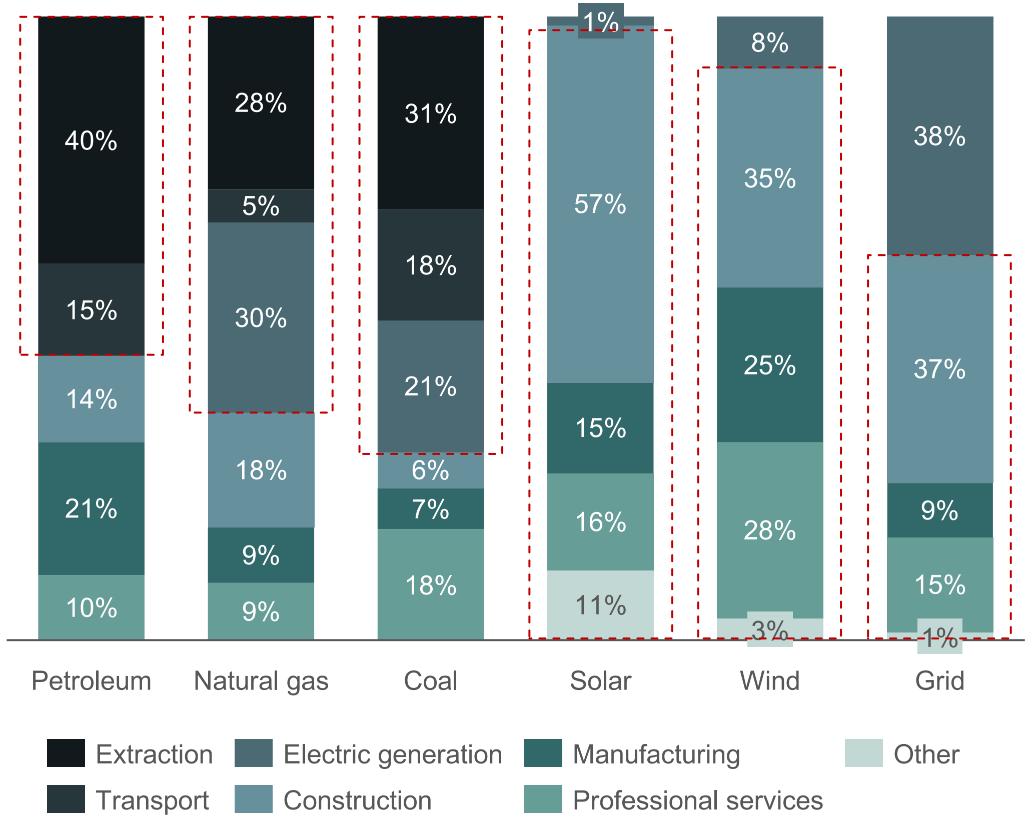
## Average pay by job function is similar across segments...

Hourly pay by energy type and job function (US, 2019)




## ...but fossil fuels has a bigger share of higher skilled jobs

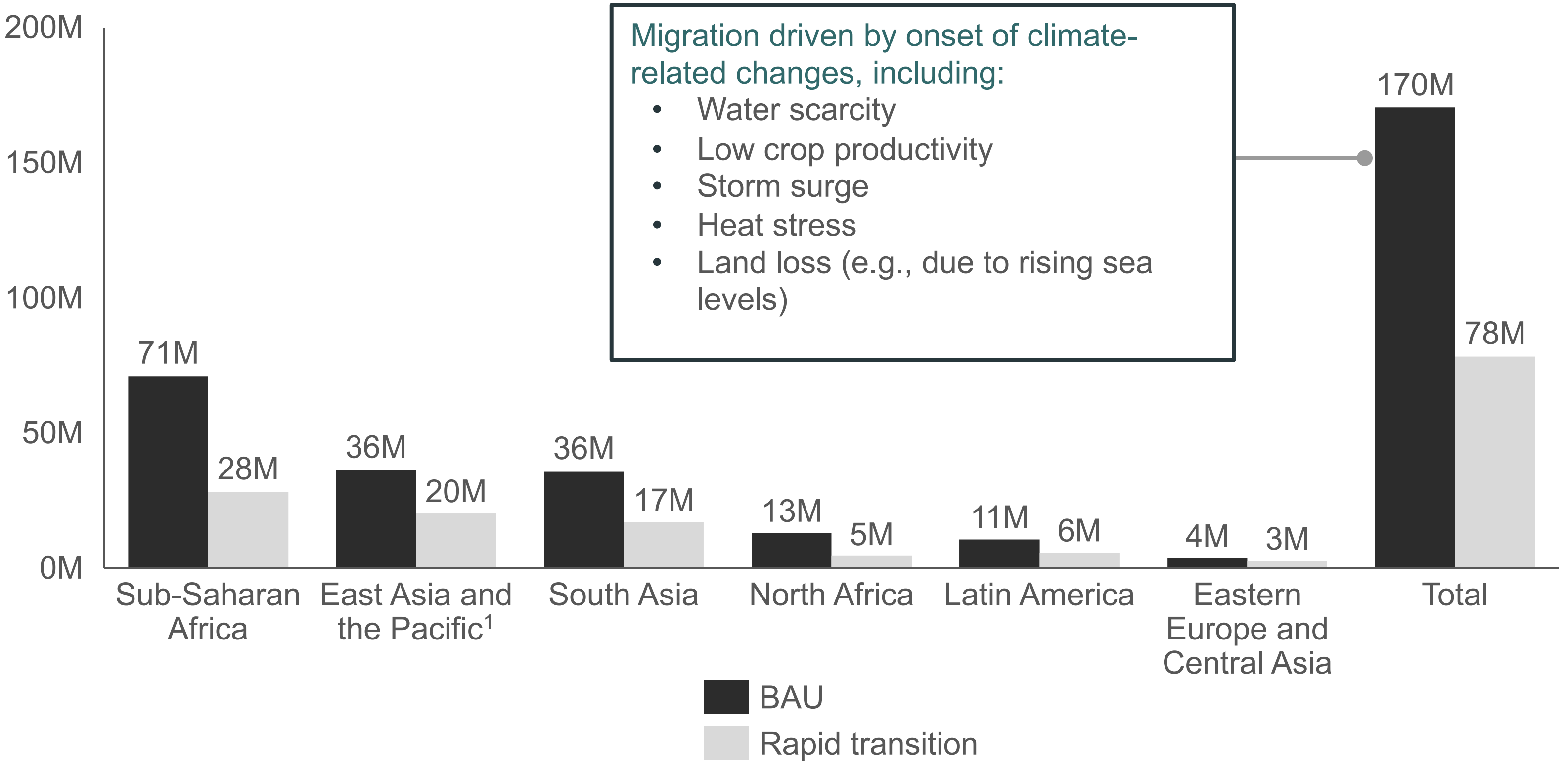
Share of job functions per energy type (US, 2019)




Graphic by Karin Kirk for Yale Climate Connection
Source: Yale Climate Connections; USEER Wage Report (2019)

# By 2050, internal climate migration is projected to increase the most in impoverished and climate-vulnerable regions across both scenarios

## Total number of internal climate migrants, by region (Mil ppl.)[2]




## Insights

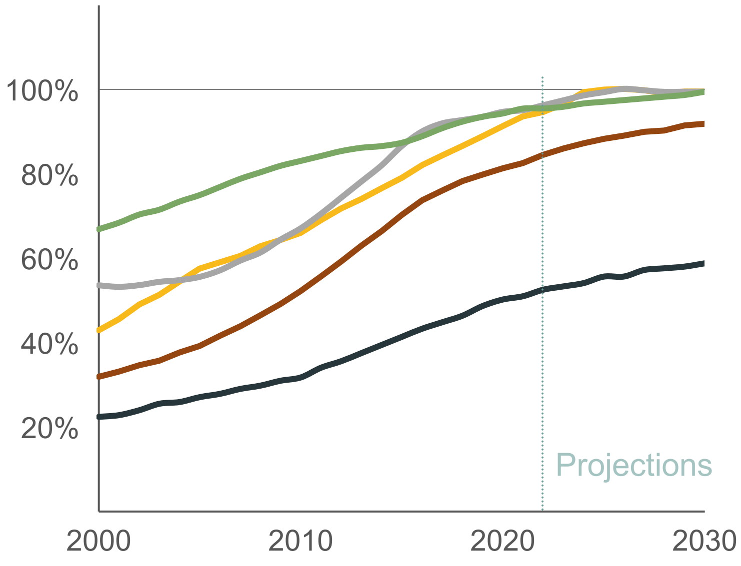
- Resettlement within national and regional borders is poised to dominate climate migration, with the lion's share of internal migrants expected in the Global South.
- ~170M climate migrants are projected in a BAU scenario. Sharp reductions in global GHG emissions by 2050 have the potential to reduce migration by up to 80%. Highest flows will occur in Sub-Saharan Africa (71M), which is highly vulnerable due to its fragile geography and agricultural employment.
- Climate migration hotspots will occur due to many risk factors, such as poor water access and crop yields, rising sea levels, heat stress, and other extreme weather events. Both urban and rural areas are prone to significant impacts.

1. Does not include global north in that region (e.g., Japan, South Korea, Australia and New Zealand) 2. Includes 106 countries across World Bank's six regional units, excluding high-income areas (largely, Eur./N. Am.) and Middle East and Small Island Developing States (SIDS); US and Europe are projected to have lower ecological impact as well as higher resilience, hence an overall significantly smaller share of the overall climate migration; Source: World Bank 2021 "Groundswell Part 2: Acting on Internal Climate Migration"; Institute for Economics & Peace

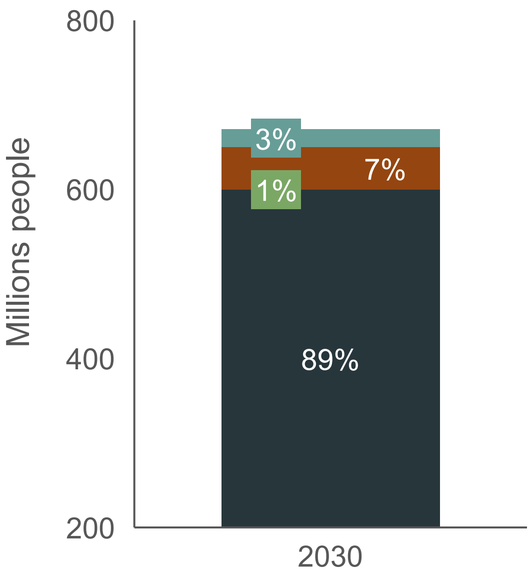
# By 2030, Sub-Saharan Africa will contain about 90% of the global population without access to electricity

## Access to electricity has significantly improved in the past two decades, especially in developing nations in Asia

**Access to electricity by region (as % of population)[1]**




**# of people without access by 2030 by region**




Sub-Saharan Africa | India | Indonesia | Other Southeast Asia | Other developing Asia | Other

## What does this mean for access to electricity in the coming decades?

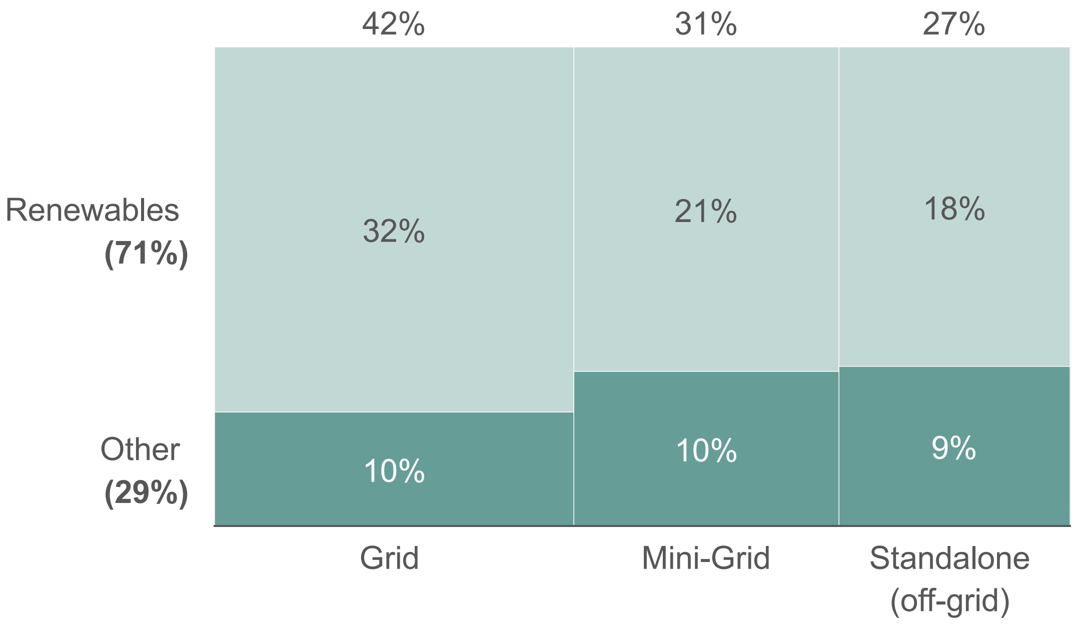
- By 2030, nine out of 10 people without access to electricity will be in Sub-Saharan Africa (SSA)
- Poor access in SSA is primarily due to affordability (e.g., a lack of return on investment for electricity infrastructure projects)
- According to the IEA, accelerating access in the SSA region will require more distributed resources (including mini-grid and off-grid)

1. Regions not shown had >99% access already by year 2000
Source: IEA (energy access outlook special report)

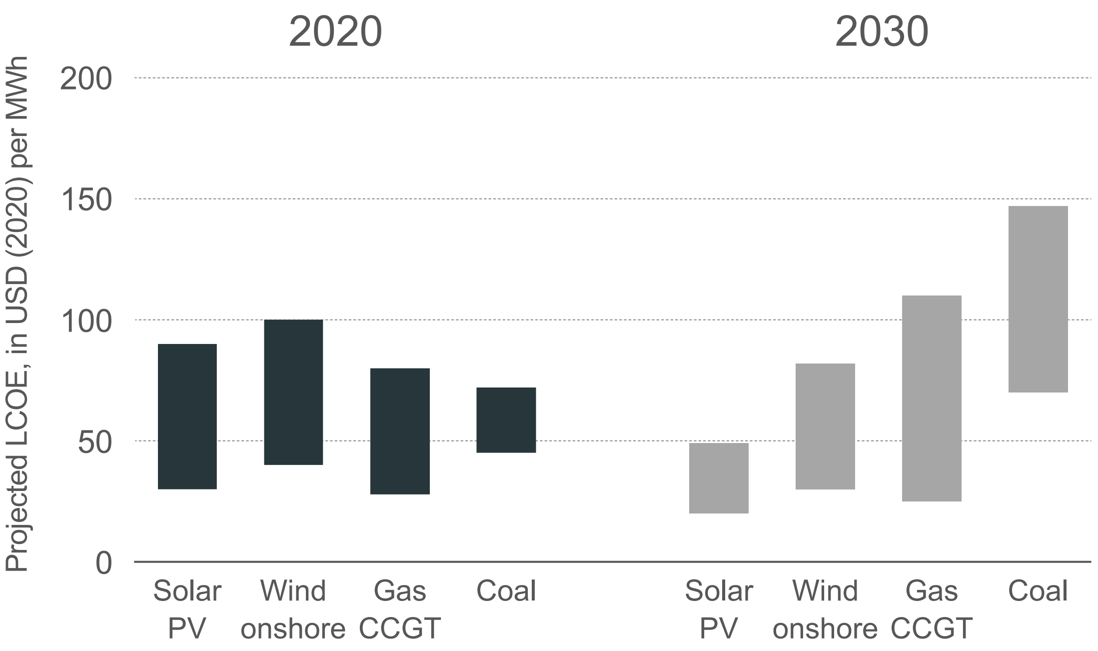
# Improving electricity access in Sub-Saharan Africa will mostly require decentralized renewables, driven by lower costs

## 71% of new access in SSA between now and 2030 will be through renewables, and most of this will be via decentralized solutions (mini-grid and off-grid)

IEA estimates of how people in SSA will gain access to electricity between 2022-2030




## Best–in–class solar PV and wind projects are already cheaper than new gas and coal plants in most parts of SSA, and will be even more competitive by 2030




Note: LCOE = Levelized cost of electricity; CCGT = Combined cycle gas turbine; LCOE represents the average net present cost of electricity generation for a generating plant over its lifetime, including the cost of capital, decommissioning, fuel and CO2 costs, fixed and variable operations and maintenance costs, and financing costs; Source: IEA Africa Energy Outlook

# A8. Selected tools & databases to facilitate a nature-positive energy transformation

# Tools, databases and frameworks that are useful for mitigating negative impacts on nature from the energy transition

| Category | Description | Example |
|---|---|---|
| **Frameworks** | Guidance for structuring overarching nature-related policy, develop nature-based objectives, and lend cohesion to global decision-making | e.g., Nature-Related Risk and Opportunity Management and Disclosure Framework (TNFD) |
| **Siting Tools** | Assist in identifying locations with a low impact on nature and a high suitability for clean power generation, including solar and wind | e.g., Site Renewables Right tool (TNC) |
| **Risk/Impact Assessment Tools** | To gauge ecosystem, biodiversity, and nature-based impacts from deploying new projects | e.g., Biodiversity Assessment Method (BAM) calculator tool |
| **Energy System Modeling Tools** | Analyzers for cost/nature implications of different energy mix choices and project scenarios to aid in investment and decision-making process | e.g., Energy Policy Simulator (RMI) |
| **Biodiversity Databases** | Repositories providing data on species distribution and ecological/ conservation needs to support biodiversity aims | e.g., Key biodiversity areas (KBA) (IUCN) |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (I/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Framework | Kunming-Montreal Global Biodiversity Framework (GBF) | UN CBD | To guide the balanced development and implementation of biodiversity goals/policies | All governments, including subnational and local authorities (e.g., legislators) | • Promotes 4 goals for 2050 and 23 targets for 2030 to achieve vision of nature-harmonious world by 2050<br>• Accompanied by online documentation on monitoring, implementation support, capacity development, and genetic resource agreement |
| Framework | Science-Based Targets for Nature | SBTN | To provide integrated technical guidance for assessing and prioritizing material nature impacts | Companies from a range of industries (e.g., food and beverage, mining, manufacturing, etc.) | • Outlines 5-step framework and technical tools to identify, measure, track nature impacts in value chain<br>• Includes materiality screening tool and data-readiness guide to screen for sector-level environmental issues<br>• Additional manuals/documentation available in 2024 |
| Framework | Nature-Related Risk and Opportunity Management and Disclosure Framework | TNFD | To help identify, assess, manage, and disclose nature-related risks and opportunities for nature-positive financial flows | Regulators, companies, investors, ESG data providers, financial institutions, credit rating agencies | • Interactive dashboard to navigate guidance on reporting risks of biodiversity loss and ecosystem degradation<br>• Includes LEAP integrated assessment tool to locate, evaluate, assess, and prepare for nature-risk reporting |
| Framework | Nature's contributions to people (NCP) | IPBES | To identify and assess status of nature's benefits to people and inform policies and stakeholders | Governments, conservation groups, businesses to identify biodiversity risks of projects | • Organizes 18 reporting categories spanning across regulating, material, and non-material NCP<br>• Leveraged for inclusion of nature preservation considerations in policy/planning (e.g., low-impact siting) |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (II/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Siting Tool | RE-Powering Electronic Decision Tool | EPA | To screen identified sites for solar PV and wind installations on current/ formerly contaminated lands, landfills, mine sites | Current renewable energy site operators to assess potential sites and systems | • Presents a series of questions (Yes/No/Skip) to select contaminated sites, landfills, underutilized sites, etc.<br>• Screens for site characteristics, redevelopment, energy load, policies, and financial considerations<br>• Generates summary report of the screening results |
| Siting Tool | Site Renewables Right | TNC | To identify solar and wind development sites in central USA with wildlife and natural habitat considerations | Companies, utilities, wind and solar developers, regulators, power purchasers | • Synthesizes >100 layers of engineering, land-use, and wildlife data in ArcGIS Pro<br>• Shows areas by color where renewable energy development would avoid wildlife species, natural areas, permitting and cost challenges |
| Siting Tool | Geospatial Energy Mapper | U.S. DOE | To locate areas with high suitability for clean power generation and potential energy transmission corridors | Developers of utility-scale renewable energy infrastructure | • User selects from >190 layers related to energy infrastructure siting considerations<br>• Suitability models identify areas from technology-specific siting criteria |
| Risk/Impact Assessment Tool | Biodiversity Assessment Method (BAM) | Australia | To apply the BAM methodology to a specific project and see assessment results and estimated offsets required | Project developers subject to the NSW jurisdiction biodiversity offset requirements | • Provides a consistent, regulatory-approved and repeatable output on how the biodiversity impacts need to be offset to ensure NNL outcome<br>• Helps users get an estimate of applicable offset credit types and prices |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (III/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Risk/Impact Assessment Tool | Eco-Logical Tool | U.S. DOT | To assess transportation infrastructure project impact at ecosystem level | State and local authorities and infrastructure project developers | • Organizes current methods for avoidance, minimization, and mitigation into a systematic, step-wise process, beginning with transportation planning and concluding with establishing programmatic approaches to recurring natural resource issues implemented at the project level |
| Risk/Impact Assessment Tool | Biodiversity Risk Filter | WWF | To assess biodiversity-related risks of operations, value chains, and investments, and utilize findings to respond | Companies from a range of industries (e.g., food and beverage, mining, manufacturing, etc.) | • Presents location-specific and industry-specific assessments of biodiversity across 33 indicators<br>• Combines sites' industry materiality rating and local biodiversity importance into a scape risk score (0-5) |
| Risk/Impact Assessment Tool | Water Risk Filter | WWF | To assess water-related risks of operations, value chains, and investments, and utilize findings to respond | Companies from a range of industries (e.g., food and beverage, mining, manufacturing, etc.) | • Presents location-specific and industry-specific assessments of basin risks and operational risks, with maps, graphics, and tables to interpret results<br>• Separates risk by risk type, risk category, and indicator |
| Risk/Impact Assessment Tool | Exploring Natural Capital Opportunities, Risks and Exposure (ENCORE) | UNEP, NFCA | To understand nature's economic impacts and integrate natural capital risks into decision-making processes | Financial institutions and regulators | • Highlights impacts and dependencies on natural capital based on user inputs of sector, sub-industry, and production processes<br>• Maps and dashboards used to align portfolios with biodiversity goals and features natural capital hotspots |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (IV/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Risk/Impact Assessment Tool | Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) | Natural Capital Project | To map and value nature-based goods and services and illustrate ecosystem flows for human benefit | Governments, conservation groups, lending institutions, corporations | • Suite of open-source software models that map spatial data, including for supporting/final services, tools to facilitate ecosystem service analyses, supporting tools<br>• Uses production function to quantify and value ecosystem services (e.g., land and water impacts based on changing ecosystem service outputs) |
| Energy System Modeling Tool | Switch Power System Planning Model | UC Berkeley | To optimize investment decisions for generation and transmission assets, EVs and storage and explore system performance scenarios | Policymakers or power system owners that expect to have large shares of renewable energy or storage, regulators | • Capacity planning model in a Python package where users add modules into model that reflect power system aspects<br>• Users can adjust timescales, financials, energy and serve constraints to optimize for long-term renewable transition based on hour-by-hour uses of resources |
| Energy System Modeling Tool | Engage Energy Modeling Tool | NREL | To enable cross-sectoral energy system planning and simulation via models | Governments, including subnational and local authorities, and infrastructure project developers | • Model simulations of energy systems with high variable/other generation and storage and provides visualizations to understand interdependencies<br>• Used to plan electricity generation/transmission assets and analyze land/cost/infrastructure implications |
| Energy System Modeling Tool | Energy Policy Simulator | RMI | To estimate the environmental, economic, and human health impacts of climate and energy policies | Policymakers, regulators, advocates, researchers | • Users control for a variety of policy scenarios relevant to main economic sectors at state level<br>• Provides outputs such as air quality impacts, costs/savings, impacts on job/GDP, electric capacity requirements and import/export implications |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (V/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Energy System Modeling Tool | National Energy Modeling System | EIA | To project technological and policy scenarios on the power sector's production/consumption to inform decision-making | Power market system operators, policymakers, regulators | • Capacity planning model for the power sector with modules, executes iteratively until a supply-demand equilibrium is achieved.<br>• Supply/demand module: solves for cost-min./utility-max. levels of investment and operation<br>• Variable renewable energy and storage (VRE) module: calculates value of VRE generators/storage |
| Biodiversity database | Key Biodiversity Areas (KBA) | IUCN | To identify areas (KBAs) that contribute to the global persistence of biodiversity and drive protection efforts | Governments, conservation groups, private sector (range of industries) | • Identifies global KBAs if at least 1 of 11 criteria are met, themed by threatened, geographically restricted, ecological integrity, biological processes, irreplaceability<br>• Organizes results in map, with categorized habitats and threats. Users can toggle between filters to refine search |
| Biodiversity database | World Database on Protected Areas (WDPA) | WDPA, UN, IUCN | To showcase global terrestrial and marine protected areas in a consolidated database | Governments, conservation groups, businesses to identify biodiversity risks of projects | • Maps ~250,000 protected terrestrial, inland waters, and marine protected areas across ~250 countries<br>• Evaluates protected areas as a % of total land or coastal area, and identifies conservation measures in place |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (VI/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Biodiversity database | Red List of Threatened Species | IUCN | To assess levels of risks facing threatened species and support decisions and conservation actions | Governments, conservation groups, private sector (range of industries) | • Assesses risks to more than 150,300 species and provides up-to-date data on world biodiversity health<br>• Divides species into nine categories: Not Evaluated, Data Deficient, Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered, Extinct in the Wild, and Extinct |
| Biodiversity database | Red List of Ecosystems | IUCN | To assess spatial and functional risks to ecosystems and support conservation efforts | Governments, conservation groups, private sector (range of industries) | • Assesses risk of ecosystem collapse for >4,000 ecosystems through five criteria, and places them into right possible categories of risk. These range from least concern, to endangered, to collapsed<br>• Users toggle between filters including regions, threats, typology, red list categories |
| Biodiversity database | Global Ecosystem Typology | IUCN | To identify high-priority ecosystems critical to biodiversity and conservation efforts | Governments, conservation groups, private sector (range of industries) | • Provides in-depth information on 4 core realms and 6 transitional realms, classifying ecosystems according to functional characteristics (e.g., structural roles)<br>• Map tool allows for regional and local analysis of ecosystem functional groups with realm/biome filters |
| Biodiversity database | Critical Natural Assets Map | Chaplin-Kramer et al. 2022 | To visualize global locations of critical natural assets (i.e., ecosystems providing 14 NCP types) | Governments, conservation groups, private sector (range of industries) | • Published paper and code outputs/underlying data (in R) on mapping critical natural assets, which provide 90% of total magnitude of 14 NCP at 2-km resolution<br>• Informs on overlap with regions of biodiversity and cultural diversity, including population share benefited |

# Online tools and databases can be used to mitigate the energy transition's impact on nature (VII/VII)

| Category | Resource | Provider | Purpose | User(s) | Description |
|---|---|---|---|---|---|
| Biodiversity database | Global Wetlands Map | SWAMP | To geospatially visualize wetlands in tropics and subtropics regions to support impact mitigation | Governments, conservation groups, private sector (range of industries) | • Interactive, web-based map displaying varieties of wetlands at sub-national levels, with GeoTIFF datasets available for download for external analyses<br>• Employs a hydro-geomorphological model to estimate wetland areas based on long-term water supply, seasonal waterlogged soils, and geographic positions |
| Biodiversity database | Global Biodiversity Model for Policy Support (GLOBIO) | PBL Nether-lands | To quantify global human impacts/interactions with biodiversity and inform policymakers | Policymakers, regulators, advocates, researchers | • GLOBIO4 models terrestrial, aquatic, species, and ecosystem services intactness as a function of human actions (e.g., land use and climate change), with maps that correlate human pressures and nature impacts<br>• Mean species abundance (MSA) metric is used to measure local biodiversity intactness, ranging from 0 (locally extinct) to 1 (fully intact) |
| Biodiversity database | Integrated Biodiversity Assessment Tool (IBAT) | IBAT Alliance | To provide integrated access to critical biodiversity information and inform risk assessment and policymaking processes | Governments, conservation groups, private sector (range of industries) | • "One-stop shop" platform for biodiversity data search, with simple reporting templates and functionalities<br>• Hosts and maintains 3 key global biodiversity dataset: Red List of Threatened Species, WDPA, and KBA and STAR Metric to enable informed decisions in policy and implementation measures for both public and private sector interests |