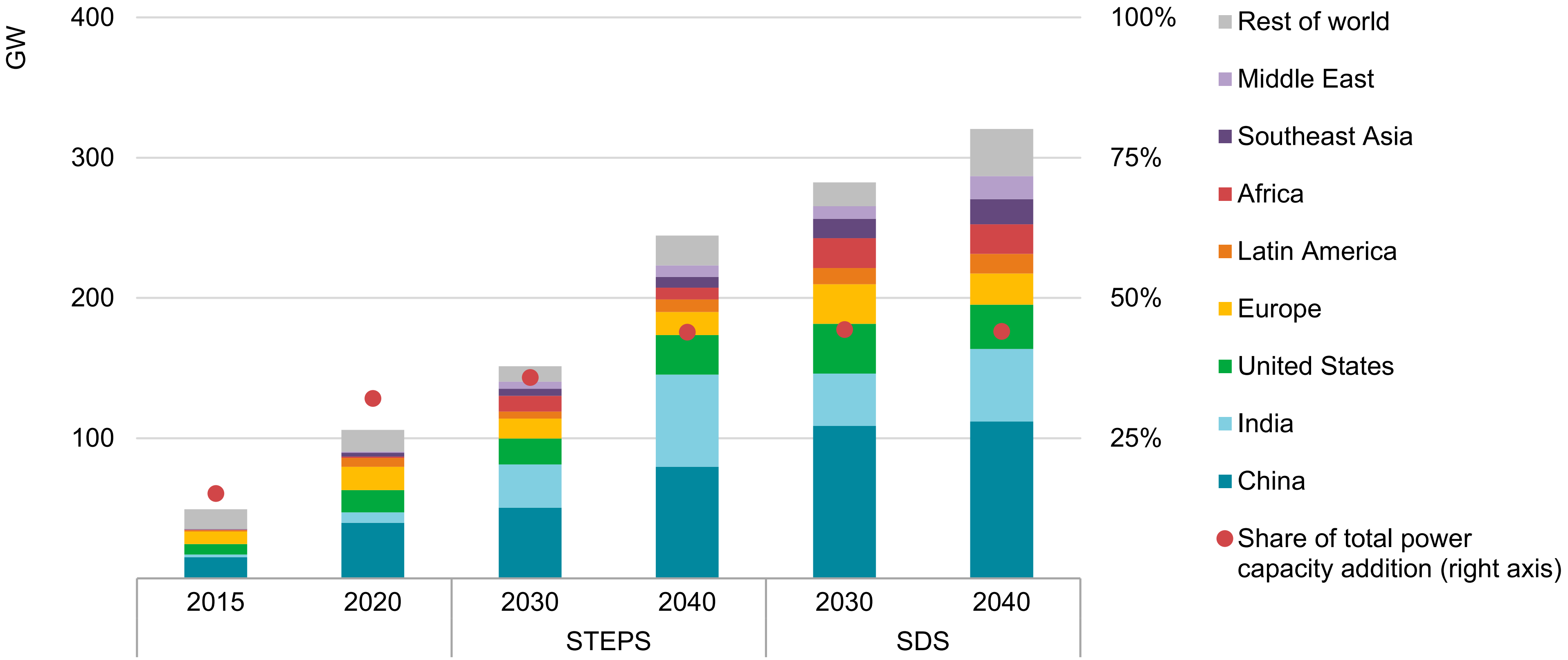
Solar PV: Annual deployment of solar PV triples in the SDS by 2040, driven by huge growth in emerging economies

Annual solar PV capacity addition by region and scenario



Note: GW = gigawatt. China = People's Republic of China.
Source: IEA (2020c).

Solar PV: Mineral use in solar PV varies widely by module type, currently dominated by crystalline silicon

Worldwide solar PV capacity has increased by almost 20 times over the past decade, spurred by declining costs and strong policy support in key regions (IEA, 2020c). With sharp cost reductions over the past decade, solar PV now offers some of the lowest levelised electricity costs in most countries, cheaper than new coal- or gas-fired power plants. In both the STEPS and SDS, solar sets new records for deployment each year after 2022, representing 45% of total power capacity additions by 2040. Innovation in solar PV technologies has also enabled remarkable advances in efficiency. For instance, the average module efficiency of commercial wafer-based silicon modules increased from about 12% to 17% in the past decade (Fraunhofer ISE, 2020), while cadmium telluride (CdTe) module efficiency doubled from 9% to 19%.

Solar PV plants are mainly composed of modules, inverters, trackers, mounting structures and general electrical components. For utility-scale solar PV plants, differences in mineral intensities come primarily from differences in module types. Crystalline silicon (c-Si) modules have become the dominant PV technology, followed by the “thin-film” alternatives: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si). By weight, c-Si PV panels typically contain about 5% silicon (solar cells), 1% copper (interconnectors), and less than 0.1% silver and other metals (IRENA, 2016). Thin-film technologies require more glass but less minerals overall than c-Si. CdTe and CIGS panels use no silver or silicon, but instead require cadmium and tellurium (CdTe) or indium, gallium and selenium (CIGS). Distributed solar PV systems tend to have string inverters or microinverters, requiring about 40% more copper than utility-scale projects, which typically use central inverters. Other mineral intensities are similar between utility-scale and distributed applications.

Innovation in the manufacturing and design of c-Si panels over the past decade has contributed to large reductions in materials intensity. Since 2008 silicon intensity has more than halved as wafer thickness diminished substantially (Fraunhofer ISE, 2020), while silver intensity fell by 80% thanks to more efficient and less silver-intensive metallisation pastes (ITRPV, 2020).

Since silicon and silver are among the most expensive elements in solar PV cells, advances in material intensity are expected to continue, with further assumed reductions of around 25% and 30% in 2030 for silicon and silver respectively. The intensities of other minerals are also expected to decrease as overall efficiency improves, including through the use of new technologies such as bifacial, n-type or half-cut cells, multi busbars, dual-glass modules and string inverters.

Solar PV: Rapid deployment of solar PV in the SDS underpins more than doubling of mineral demand for solar PV by 2040 despite continued intensity reductions

c-Si modules dominate the solar PV market, accounting for 95% of global solar PV capacity additions in 2020. They are expected to continue to dominate over the coming decades, as costs continue to decrease with further automation and larger, more durable cells. In addition, innovation is improving c-Si cell efficiency with the development of passivating contacts, the switch to n-type materials, and multi-junction/tandem solar cells, which helps cement c-Si's leading position. Silicon-based cells can also be combined with perovskite technologies with the aim of addressing their instability/lifetime issue and lowering the barriers to mass production of perovskite solar cells.

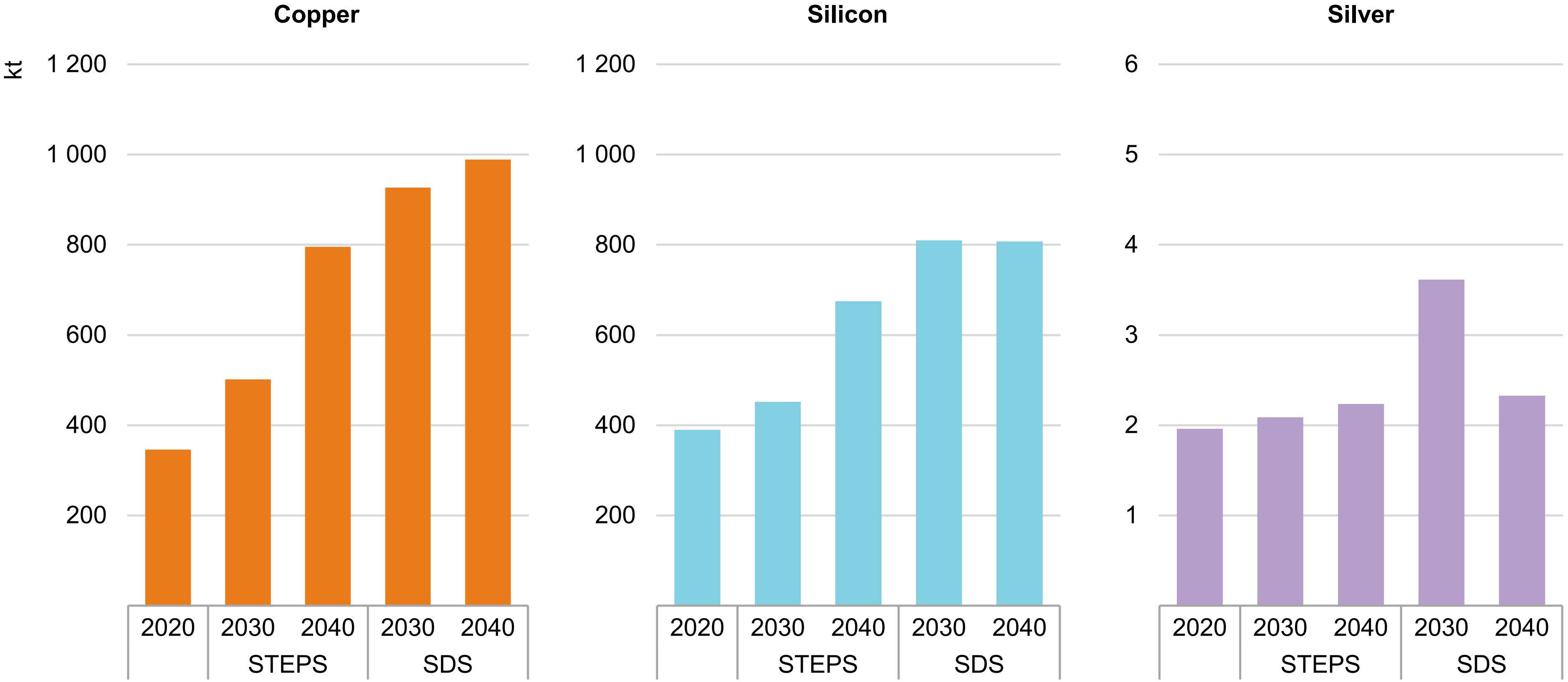
In our base case, thin film technologies remain niche over the coming decades, despite seeing further efficiency gains and cost reductions. Their use may be limited to applications where lower weight and/or greater flexibility is required, mostly in distributed and building applications.

In the SDS, capacity additions in 2040 are triple those of 2020, resulting in a near tripling of copper demand from solar PV. Material intensity reductions help to significantly dampen demand growth for silver and silicon. Despite higher annual capacity additions, demand for silver and silicon is lower in 2040 than in 2030, and only 18% and 45% higher than in 2020.

Capacity additions in 2040 in the STEPS are 25% lower than in the SDS. However, slower assumed improvements in material intensity for silver and silicon offset the lower capacity additions, resulting in similar demand for silver and silicon in the two scenarios.

Solar PV: Copper demand more than doubles by 2040, but continued innovation to reduce mineral intensity helps to offset demand growth for silicon and silver

Demand for copper, silicon and silver for solar PV by scenario

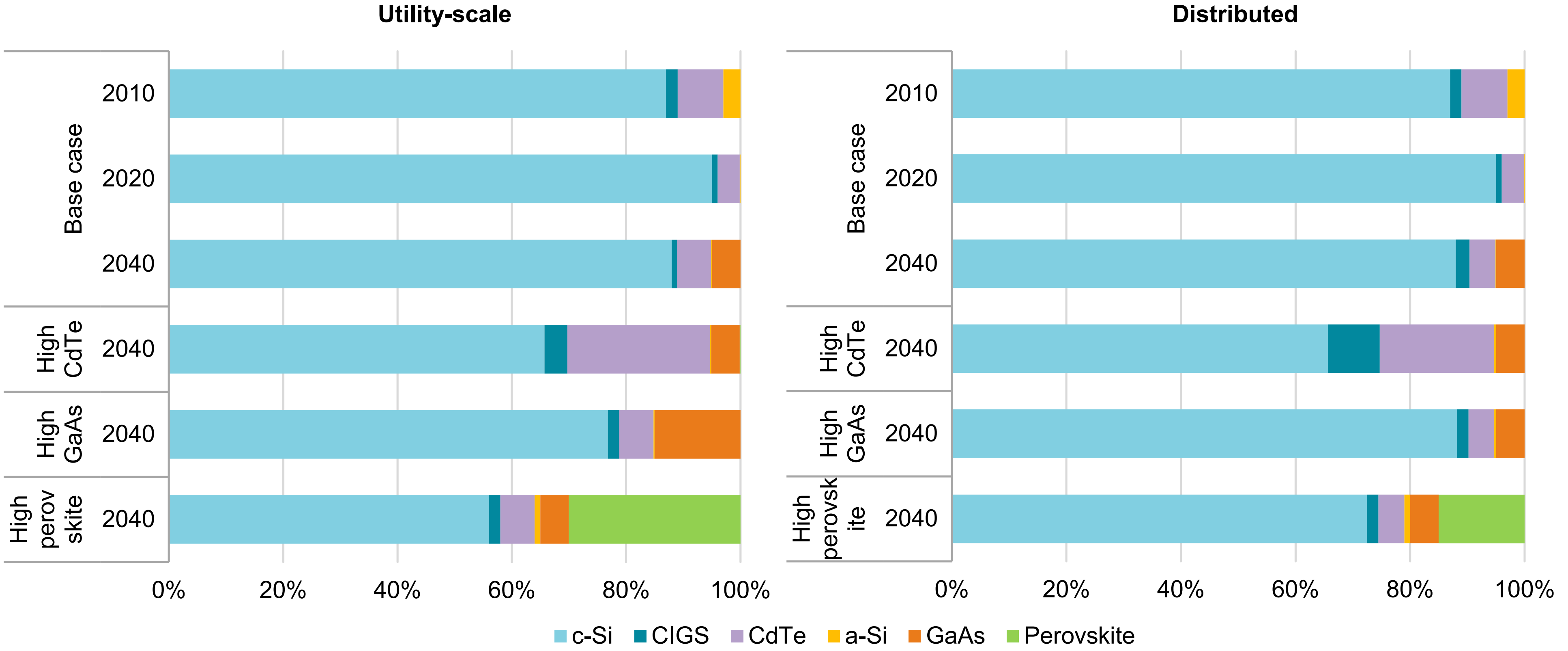


IEA. All rights reserved.

Note: kt = thousand tonnes.

Solar PV: Crystalline silicon is expected to remain the dominant PV technology, but further progress on alternative technologies could see them taking significant market share by 2040

Share of annual capacity additions by PV technology under different technology evolution scenarios



IEA. All rights reserved.

Notes: c-Si = crystalline silicon; CIGS = copper indium gallium diselenide; CdTe = cadmium telluride; a-Si = amorphous silicon; GaAs = gallium arsenide.

Solar PV: Demand for silicon falls in the alternative cases, but demand for other semiconductor materials rises

While c-Si modules are expected to continue to dominate the solar PV market, further progress on alternative technologies could see these technologies achieving growing market shares by 2040, which we explore in three alternative cases: high CdTe, high perovskite, and high GaAs.

High CdTe case

Further progress in CdTe technologies could lead to higher cell efficiency, longer lifetimes and reduced costs. The High CdTe scenario sees mass production of CdTe cells starting around 2030. The penetration of CdTe would be faster in distributed applications, where their lower weight and higher flexibility are an advantage.

In the High CdTe scenario, demand for cadmium and tellurium grows sevenfold by 2040 in the SDS to 1 300 tonnes and 1 400 tonnes respectively. This rapid growth would put pressure on supply capacities, which are currently around 23 000 tonnes for cadmium and 500 tonnes for tellurium (USGS, 2021).

High perovskite case

Perovskite solar cell technology has received a lot of research attention in the past decade as it holds the promise of much higher efficiency levels, starting at around 9.7% in 2012 (Kim et al., 2012) and exceeding 25% today (NREL, 2019). However, in order to challenge the dominance of silicon in photovoltaics, perovskites will have to overcome significant technological hurdles. Most pure perovskite solar cells that have shown high efficiency are no larger than a fingernail and need to be scaled up enormously to match the output of commercial c-Si solar cells. The second major drawback for these cells is their stability. Perovskites are compounds that are highly soluble in water and even in the moisture in the air. This means that the perovskite layer thickness reduces rapidly within just an hour of exposure to ambient conditions even at a relatively low humidity of 40% (Shirayama et al., 2016). The final concern comes from the chemistry of the most frequently reported perovskite structure for solar cell applications (such as methylammonium lead triiodide or “MAPI”), which uses up to 10% lead by weight in pure perovskite solar cells (Saliba et al., 2018) and could hamper its adoption in certain jurisdictions. Alternative lead-free technologies are being studied, but are still far from reaching the record efficiencies synonymous with the lead-based counterparts (Zhao et al., 2017).

A pure perovskite solar cell does not contain silicon or most of the materials that are used in the fabrication of crystalline silicon solar cells. However, given the limitations of pure perovskite solar cells described above, the easiest path to scale up and industrialise perovskite technology and circumvent many of its challenges is to combine it with the crystalline silicon technology (Nature Energy, 2020). This could be the fastest route to market for perovskites primarily because of the large market share held by silicon. Silicon solar cells have almost reached their physical efficiency limit in laboratory devices, but researchers at Oxford PV have demonstrated perovskite/silicon tandem solar cells that reach laboratory efficiencies of up to 28%, outperforming both perovskite and silicon single-junction devices (NREL, 2019).

In light of the constant development and strong research interest, this case assumes that perovskite/silicon tandem solar cell technology will capture 30% of the market for utility-scale PV and 15% for distributed PV by 2040. This would reduce silicon demand in 2040 by over 10%, while raising lead demand by around 45% compared to the base case in the SDS context.

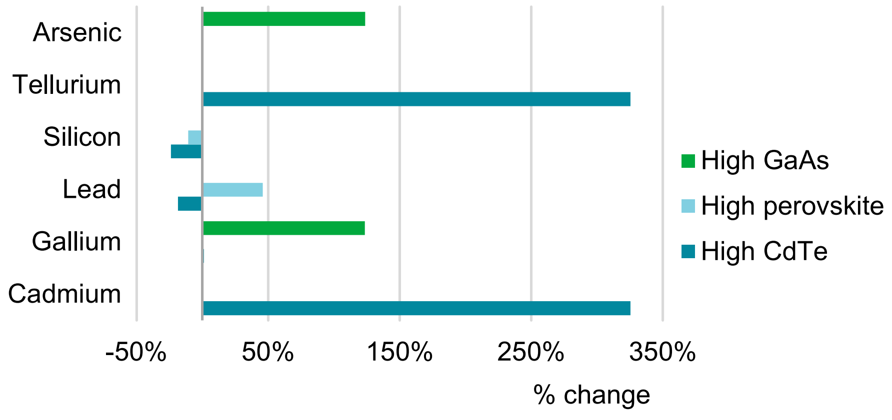
High GaAs case

There are semiconducting materials whose physical and chemical characteristics make them much better candidates for solar cell technology than silicon. The III-V semiconductors such as GaAs, indium arsenide (InAs), gallium nitride (GaN) and indium phosphide, are a family of materials developed as binary compounds between elements from group 13 and group 15 of the periodic table. GaAs has the optimal bandgap energy for solar cell applications. It also has a crystalline structure that makes it much more suitable for fabricating multi-junction solar cells by growing layers of different III-V crystalline materials on top of each other. The advantage of a multi-junction solar cell over a single-junction solar cell is that it allows the absorption of a wider range of the solar spectrum, thereby increasing the power conversion efficiency of the resulting solar cell. The research efficiency of GaAs-based multi-junction solar cells fabricated at the National Renewable Energy Laboratory (NREL) in the United States and Fraunhofer ISE in Germany is rapidly approaching 50%, making them the most efficient solar PV technology known to date (NREL, 2019). GaAs became the most commonly used material for photovoltaic arrays in satellites in the early 1990s and remains the preferred choice for aerospace applications. For terrestrial applications, GaAs-based multi-junction solar cells are most often employed in concentrator solar photovoltaic projects.

The main challenge to overcome for GaAs-based solar cells is the cost of raw materials and wafer manufacturing. It is reported that a wafer of GaAs is roughly 50 times more expensive than a wafer of c-Si of comparable size (Bleicher, 2010). This significant cost differential is what has prevented GaAs-based solar cells from entering the commercial solar PV market for terrestrial applications. However, latest developments indicate that this situation may not persist for long. In 2020 researchers at NREL reported a breakthrough in III-V cell technology that could significantly bring down costs (Willuhn, 2020). Recent studies (Horowitz et al., 2018) suggest ample scope for major cost reductions via scaling up production volumes, reducing the cost of epitaxial crystal growth, lower substrate costs through recycling and lower metallisation costs. This could bring prices closer to c-Si within the next 10 to 15 years. Although direct competition with c-Si may not be possible, such cost reductions combined with advantages in weight, flexibility, energy density, temperature stability, radiation hardness etc. could make them attractive for use in very large terrestrial applications that cannot be served by silicon today.

Although GaAs represents a small share in the base case (5% in 2040), in the High GaAs case we assume a market share of 15% for utility-scale and 5% for distributed applications in 2040. Compared to the base case, this would add 8 kt of arsenic demand (25% of global production today), 3.5 kt of gallium (10 times more than high-purity refined gallium production today), and 0.1 kt of indium demand by 2040 in the SDS. This implies that scaling up the high GaAs technology needs to go hand in hand with efforts to recover more materials from a by-product stream of bauxite, zinc, copper and gold processing or via recycling.

Changes in mineral demand in alternative technology evolution cases in the SDS context

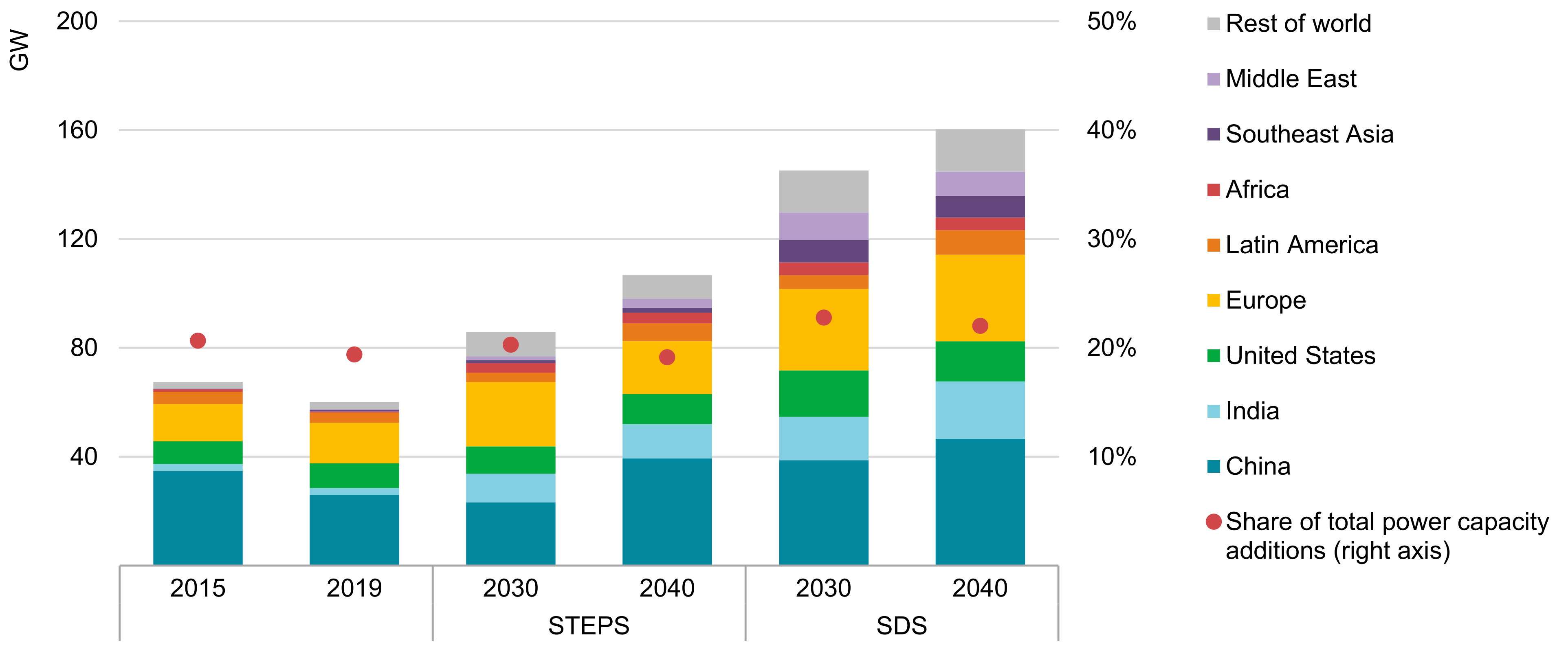


IEA. All rights reserved.

Note: Relative change compared to the base technology evolution case in the SDS.

Wind: Wind deployment is expected to accelerate over the coming decades, thanks to falling costs, policy targets and increased investor confidence

Annual wind capacity addition by region and scenario



Source: IEA (2020c).

Wind: Larger turbines – particularly offshore – help to accelerate annual capacity additions over the coming decades

Global installed capacity of wind power has nearly quadrupled over the past decade, spurred by falling costs, which have declined by about 40% on average globally, and policy support in more than 130 countries (IEA, 2020c). In both the STEPS and SDS, wind power is set for strong growth, with the offshore wind industry maturing and adding to developments in onshore wind on the back of technology improvements and low-cost financing. Annual capacity installations for wind in the SDS are expected to more than double by 2040 to 160 GW, representing more than a fifth of overall power capacity additions. Installations are currently concentrated in China, Europe and the United States, but the regional picture is set to become diverse with particularly strong growth in Southeast Asia, India, Latin America and the Middle East.

The share of offshore in total wind deployment is poised to grow considerably. Cost reductions and experience gained in Europe's North Sea are opening up huge opportunities in many parts of the world. Offshore wind offers higher capacity factors than onshore wind thanks to larger turbines that benefit from higher and more reliable wind speeds. There are further innovations on the horizon, such as floating turbines that can open up new resources and markets.

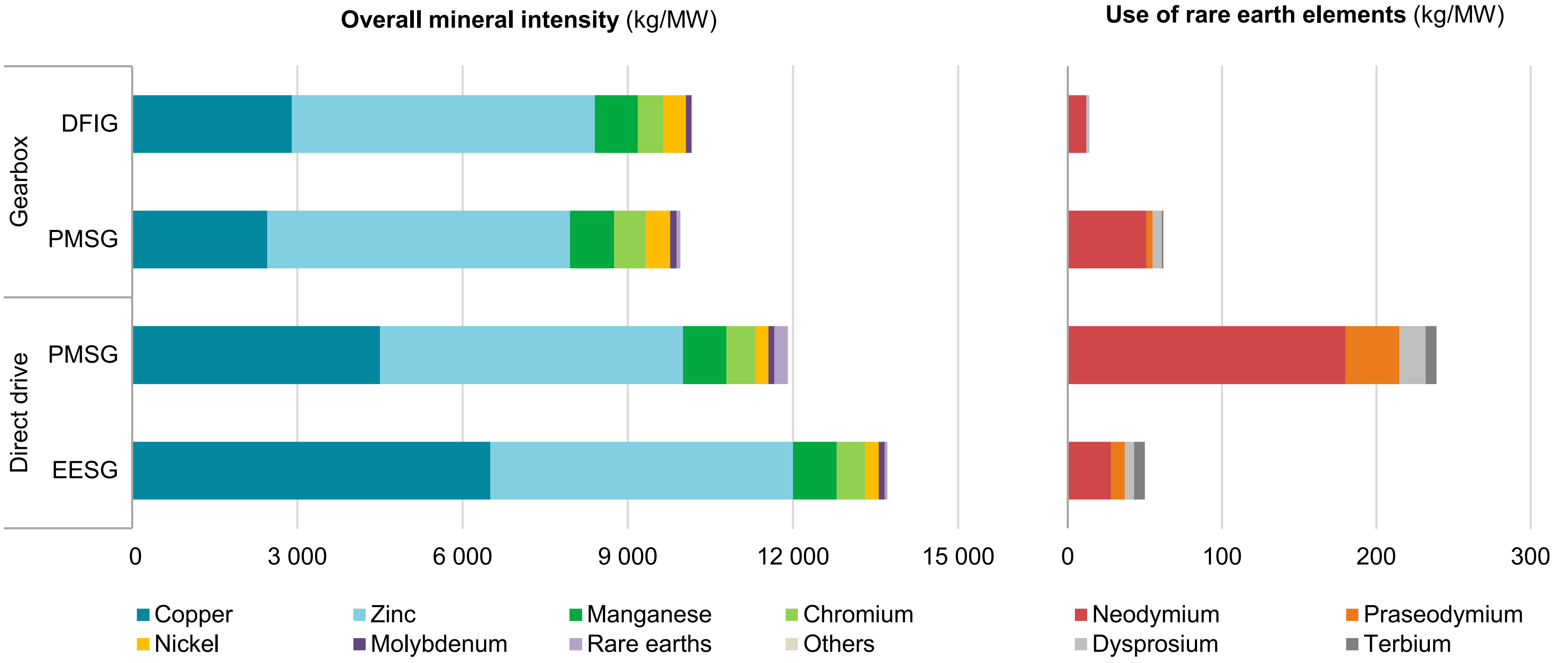
Turbine size has also grown considerably, from a global weighted average of 1.9 megawatts (MW) for onshore turbines installed in 2010 to 2.6 MW in 2018 (IRENA, 2019). Manufacturers are offering 5 MW onshore turbines in 2021. Turbine size has grown even more quickly in offshore wind, with an average rated capacity of 5.5 MW installed in 2018, compared with the newest turbine designs offering capacities of 10-14 MW. Even larger turbines are expected in the coming years, with promises of 20 MW turbines already on the horizon.

The growing size of turbines is an important contributor to the increase in capacity factor and the reduction in material use. Taller towers, larger rotors and lighter drivetrains have enabled higher capacity factors, which have risen from an average of 27% in 2010 for newly commissioned onshore projects to 34% in 2018.

These trends have also helped to reduce the material intensity for some materials in wind power. For example, on a kilogramme (kg) per MW basis, a 3.45 MW turbine contains around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine (Elia et al., 2020).

Wind: Mineral needs for wind power depend on the turbine type, with particularly high sensitivity for rare earth elements

Mineral intensity for wind power by turbine type



Notes: DFIG = double-fed induction generators; PMSG = permanent-magnet synchronous generator; EESG = electrically excited synchronous generator. The intensity numbers are based on the onshore installation environment. More copper is needed in offshore applications due to much longer cabling requirements.

Sources: Carrara et al. (2020); Elia et al. (2020)

Wind: The growing market for turbines with permanent magnets – particularly for offshore projects – could dramatically increase rare earth demand over the coming decades

Wind turbines – which consist of a tower, a nacelle and rotors erected onto a foundation – require concrete, steel, iron, fibreglass, polymers, aluminium, copper, zinc and REEs.

Mineral intensities not only depend on the turbine size, but also on the turbine type. There are four main types of turbine: gearbox double-fed induction generator (GB-DFIG), gearbox permanent-magnet synchronous generator (GB-PMSG), direct-drive permanent-magnet synchronous generator (DD-PMSG) and direct-drive electrically excited synchronous generator (DD-EESG).

Turbines based on PMSGs require neodymium and dysprosium. DD-PMSGs generally contain larger amounts of REEs compared to GB-PMSGs for smaller overall size and lower weight and higher efficiency. Zinc is evenly used among turbine types as a protective coating against corrosion.

The onshore wind market is currently dominated by GB-DFIGs, accounting for more than 70% of the global market. DD-PMSGs have doubled their market share over the past 10 years from around 10% in 2010 to 20% in 2020. In the offshore sector, DD-PMSG turbines are the main choice, with around 60% of the market worldwide. Requiring taller and larger turbines, offshore wind sites generally opt for DD-PMSG configurations due to their lighter and more efficient attributes as well as lower maintenance costs. In addition to REEs, copper intensity for offshore projects can be more than twice as high as onshore, with substantial copper usage in submarine collector and larger cables.

With increasing power per tower as turbines become taller and larger, lighter and more efficient configurations of PMSG technologies are becoming increasingly preferred. In the base case, PMSG technologies account for around 95% of the offshore market in 2040 and 40% of the onshore market.

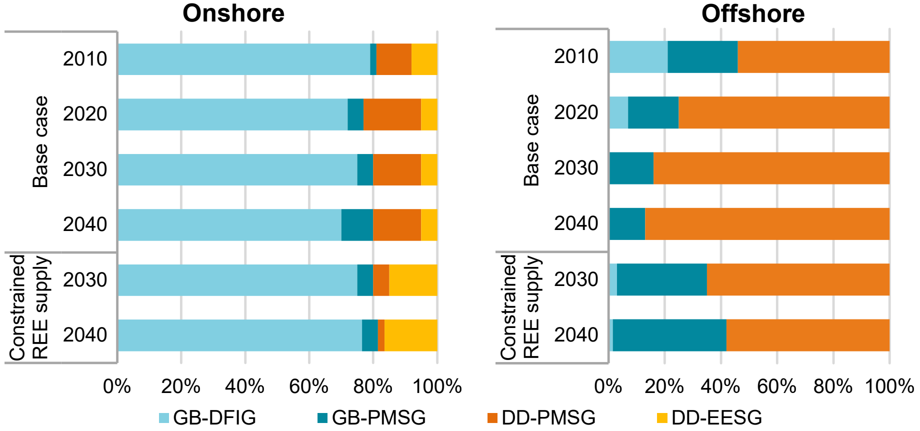
In the SDS, demand for REEs in wind – neodymium and praseodymium in particular – is set to more than triple by 2040, driven by the doubling of annual capacity additions and a shift towards turbines with permanent magnets. Copper demand reaches 600 kt per year in 2040, propelled by offshore wind requiring greater cabling. Offshore wind accounts for nearly 40% of copper demand from wind despite accounting for only 20% of total wind capacity additions.

Constrained REE supply case

However, mounting demand for REEs from a variety of clean energy technologies such as wind and EVs, coupled with concerns around rising prices and geopolitical events, could lead to different technology choices. This is explored in the Constrained REE supply case, which sees manufacturers gradually switching to non-magnet technologies and project developers adopting hybrid configurations with a gearbox and a smaller magnet. Onshore projects move towards DD-EESGs while, in offshore projects, DD-PMSGs cede some market share to technologies with lower REE use such as DD-EESGs. However, there would be no notable switch back to GB turbines given the technical fitness of DD turbines in the offshore environment and industry-wide efforts to reduce REE intensity in DD turbines.

In this case, neodymium demand in the SDS is contained to around 8 000 tonnes in 2030 and 40% lower in 2040 compared to the base case. Demand for praseodymium and dysprosium are 15% and 32% lower, respectively, compared to the base case in 2040.

Turbine shares for wind power capacity additions in the SDS

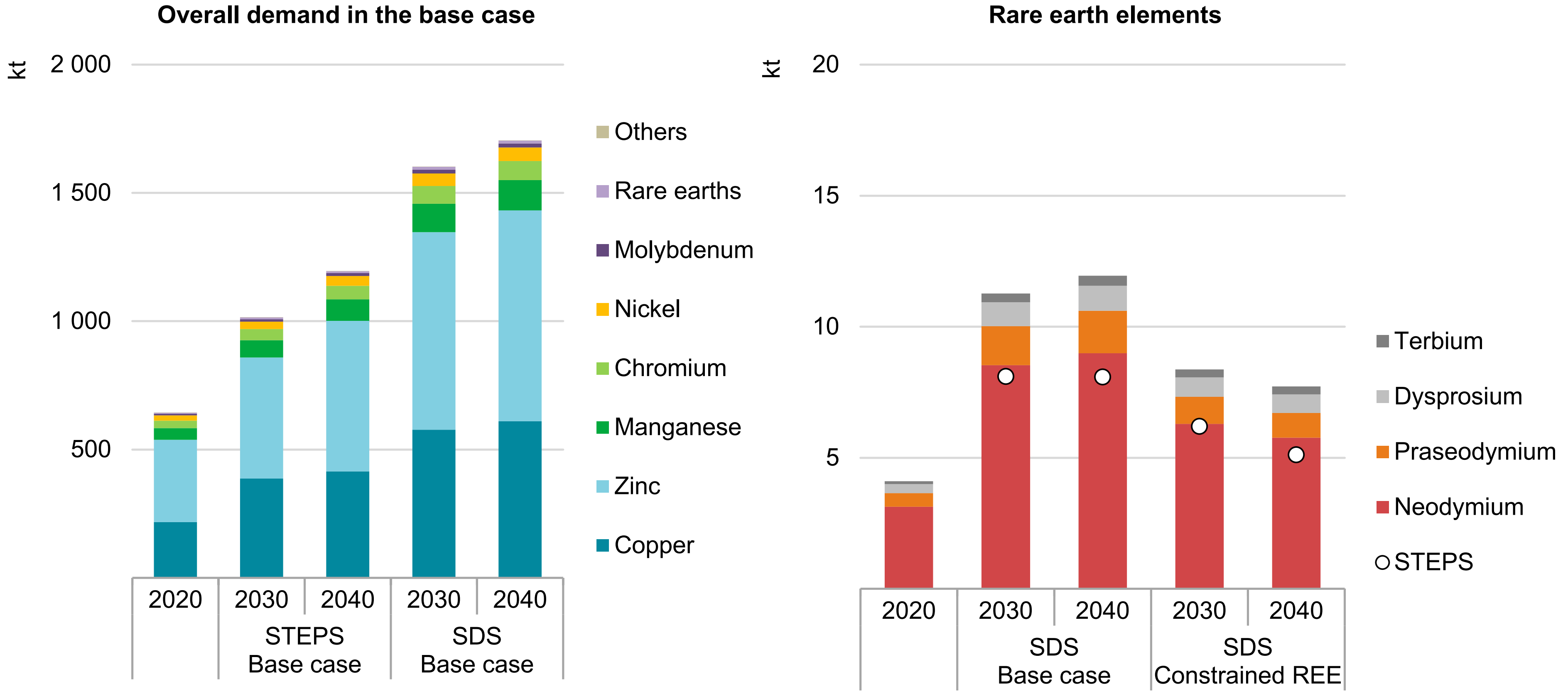


IEA. All rights reserved.

Another option to reduce REE consumption in permanent magnets is to use a high-temperature superconductor (HTS). This offers potentially substantial reductions in mass and size, as they can achieve enormous current densities, but require extremely low temperatures and expensive cryostats. The technology is still at the R&D stage, with multiple designed prototypes and a sole 3 MW industrial-scale turbine developed so far. Despite promising results, HTS wind farms remain far from being competitive with existing wind technologies and we do not expect them to be a game changer in the next decade.

Wind: Demand for rare earths quadruples in the SDS by 2040, although the scale of growth may vary depending on the choice of turbine technologies

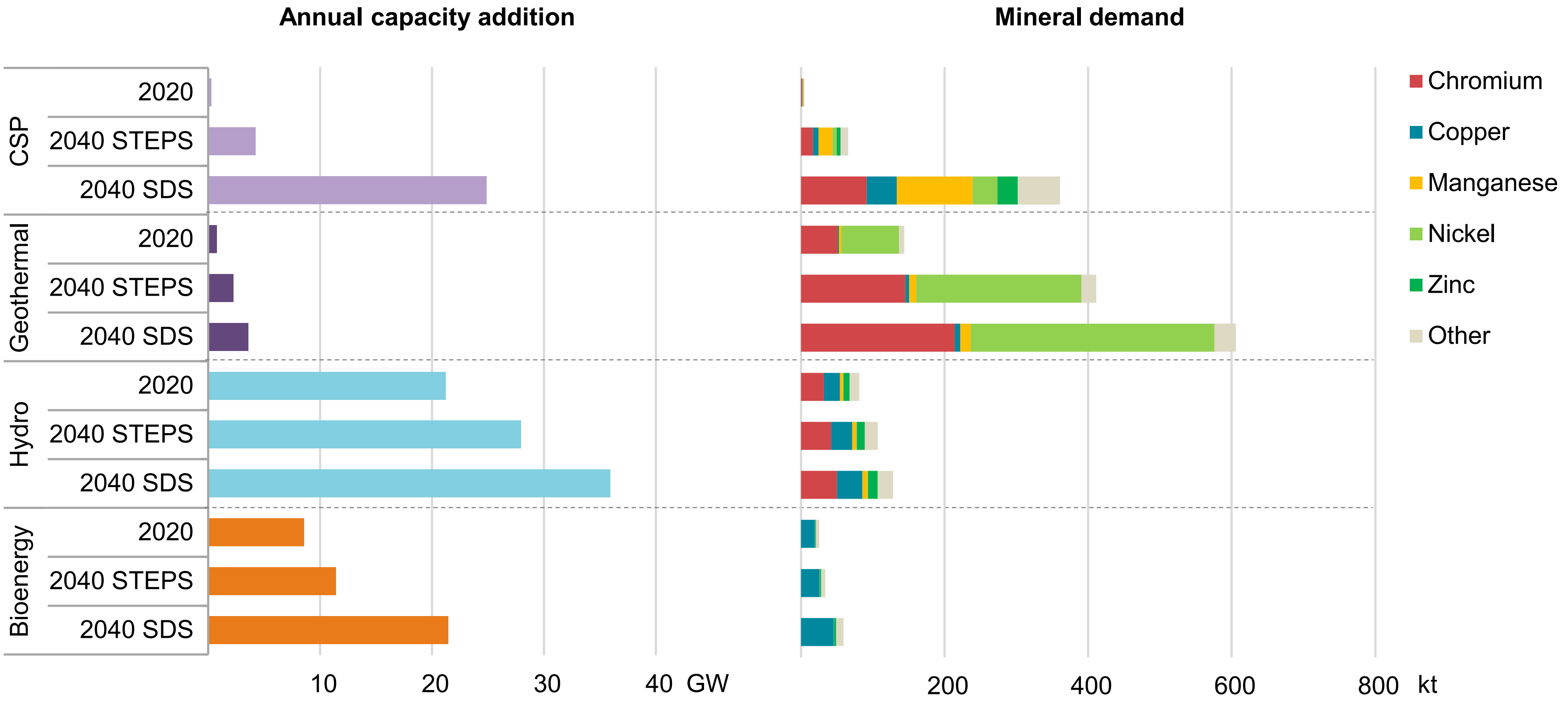
Mineral demand for wind by scenario



IEA. All rights reserved.

Other renewables: Mineral demand from other renewables varies significantly depending on their mineral intensities

Annual capacity addition and mineral demand from other renewable technologies by scenario



IEA. All rights reserved.

Note: CSP = concentrating solar power.

Concentrating solar power: Rapid growth in capacity additions comes with substantial demand for chromium, copper, manganese and nickel

Since 2010 policy and financing initiatives in Spain and the United States have helped to more than double the global installed capacity of CSP. However, overall installed capacity remains low at around 7 GW in 2020 owing to limited suitable geographies, high project costs and long distances to demand centres. In the SDS, installed capacity grows by nearly 40 times between 2020 and 2040 – albeit from a low base – driven by growth in the Middle East, Africa and Asia Pacific.

CSP systems use mirrors to direct solar radiance to a central receiver where energy is transmitted to a heat-exchange fluid used to generate electricity. Two main types of CSP technology – parabolic troughs and central towers – account for most of the installed, planned and projected additions. Parabolic trough systems direct solar radiance to a tube containing a heat-exchange fluid running along the length of a parabolic mirror. Central tower systems very closely track the movement of the sun reflecting and directing solar radiance to a centralised receiver tower containing a heat-exchange fluid.

Central tower systems generally require more materials than parabolic trough systems, including eight times more manganese, four times more nickel, and twice as much silver. However, parabolic trough systems require more than twice as much copper.

Parabolic troughs accounted for over 80% of CSP capacity additions in 2010, but their share has been steadily declining, ceding market share to central tower systems, which have higher efficiency and greater storage capacity (IEA, 2020c). Central towers accounted for around 60% of CSP capacity additions in 2020, and their share is expected to grow to 75% by 2040 in the SDS.

The expansion of CSP, driven by material-intensive central tower systems, comes with substantial demand growth for chromium, copper, manganese and nickel. Between 2020 and 2040 in the SDS, chromium demand from CSP grows by 75 times (to 91 kt), copper demand grows by 67 times (to 42 kt), manganese demand grows 92-fold (to 105 kt), and nickel demand grows 89-fold (to 35 kt).

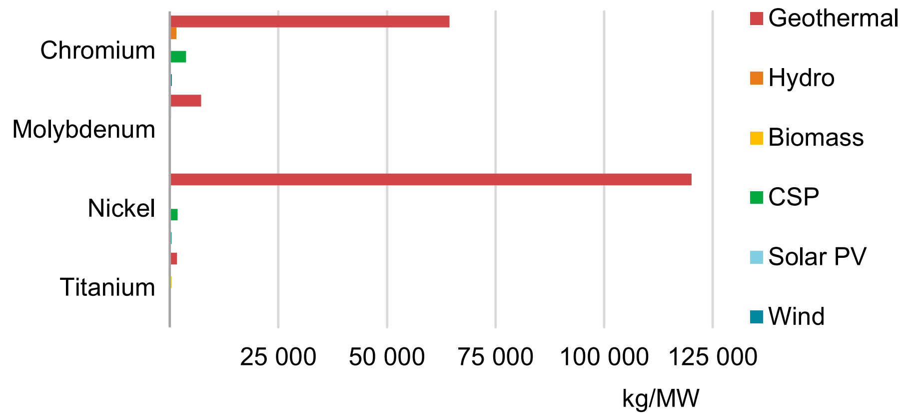
Geothermal: A key driver for growing nickel, chromium, molybdenum and titanium demand from low-carbon power technologies

Around 16 GW of geothermal capacity are currently installed, providing low-carbon baseload power in geo-hotspots such as Kenya, Iceland, Indonesia, the Philippines, Turkey and the United States. In the SDS, installed capacity grows fivefold to 82 GW by 2040.

Geothermal power plants generate electricity by powering turbines using underground hydrothermal resources (steam or hot water) piped to the surface. The very high temperatures and potentially corrosive nature of geothermal reservoirs require the use of specialised steel (high in chromium, molybdenum, nickel and titanium) in order to withstand the harsh operating environment.

In the SDS, mineral demand from geothermal more than quadruples between 2020 and 2040. Despite accounting for less than 1% of all low-carbon power capacity additions in 2040, geothermal power is a major source of demand for nickel, chromium, molybdenum and titanium from the power sector. Of the total mineral demand from all low-carbon power sources in 2040, geothermal accounts for three-quarters of nickel demand, nearly half of the total chromium and molybdenum demand, and 40% of titanium demand.

Mineral intensity of key minerals in geothermal in 2019



IEA. All rights reserved.

Notes: CSP mineral intensity is for central tower systems; solar PV mineral intensity is for utility-scale cSi; wind mineral intensity is for onshore GB-DFIG.

In addition to power, geothermal resources can provide heating and cooling services. However, ground-source heat pumps require relatively minimal steel and instead rely on plastic piping, with some systems relying high-conduction copper for heat exchange.

Hydropower and bioenergy: Limited impacts on mineral demand due to low material intensity

Hydropower is the largest renewable source of electricity, accounting for 17% of global electricity generation in 2020. While it plays an important role in providing flexibility to the power system, its share of total power capacity additions continues to decline in the SDS through to 2040, as high capital costs and geographic constraints limit further growth.

In the SDS, hydropower capacity additions in 2040 are only 70% higher than in 2020, representing the lowest relative growth among all renewable sources. Between 2020 and 2040, nearly 60% of cumulative capacity additions occur in Asia Pacific, with China alone accounting for a quarter of the global total.

While hydropower uses substantially more cement and concrete than any other generation technology, it has a relatively low mineral intensity compared to other sources of low-carbon power. Hydropower does not use REEs, and its current use of copper (1 050 kg/MW), manganese (200 kg/MW) and nickel (30 kg/MW) are among the lowest of all low-carbon sources (Ashby, 2013). Hydropower accounts for 2% and 11% of the total demand for copper and chromium respectively from all low-carbon power capacity additions in 2040 in the SDS.

Bioenergy is a major source of renewable power today, generating as much electricity as solar PV in 2019. In the SDS, annual generation triples by 2040 to 2 150 terawatt hours (TWh), with total installed capacity rising to 420 GW. China, the United States, Russia and India account for over half of the cumulative capacity additions to 2040.

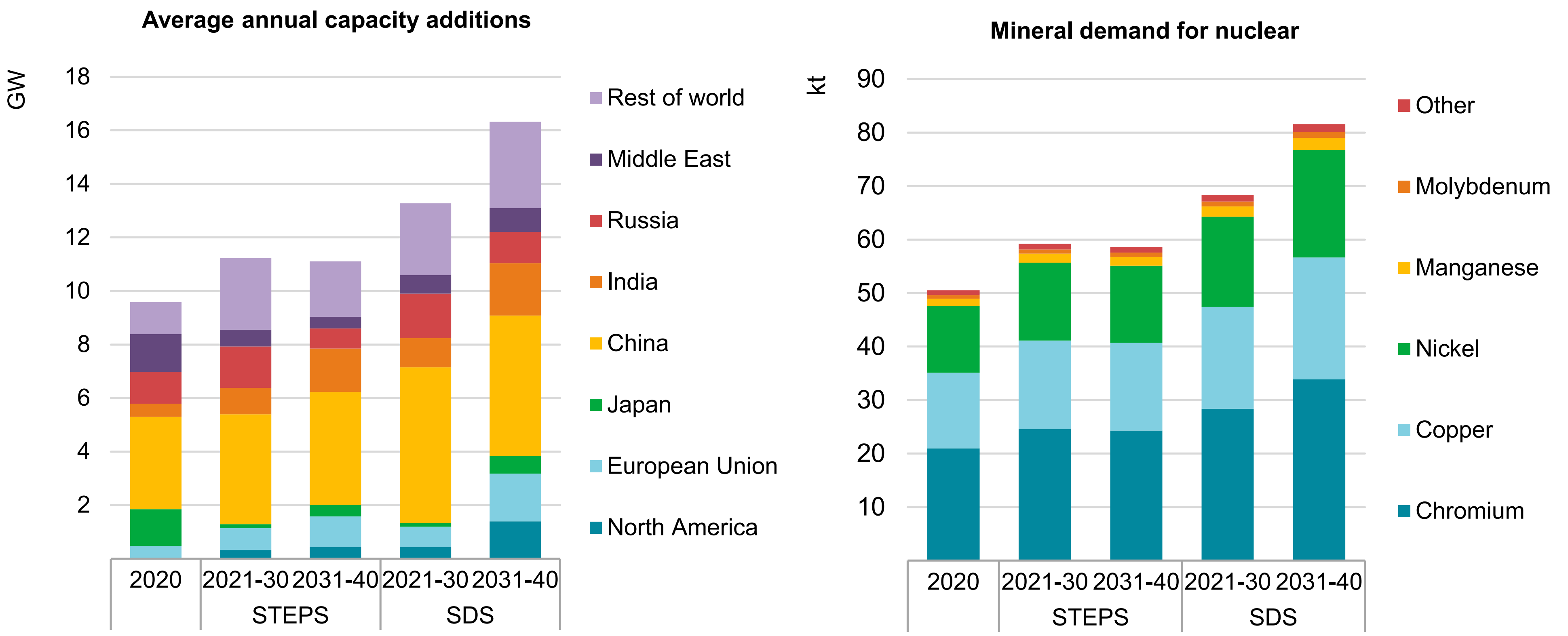
Mineral demand from bioenergy comes mostly from copper (2 270 kg/MW in 2019), which is similar to that of most other renewable generation technologies (Ashby, 2013). While the exact design of bioenergy boilers is different, overall mineral requirements are similar to those of coal and gas-fired power generation. However, bioenergy demands significant levels of titanium (400 kg/MW), which is higher than all other generation technologies except geothermal.

In the SDS, overall mineral demand from bioenergy more than doubles by 2040 compared to 2020, with copper accounting for more than three-quarters of the total. However, copper demand from bioenergy only accounts for 2.5% of the total copper demand from all low-carbon power sources in 2040. Conversely, titanium demand from bioenergy accounts for nearly 60% of all titanium demand from low-carbon power in 2040.

Overall, combined with their modest capacity growth, hydropower and bioenergy are unlikely to face any significant supply constraints for minerals.

Nuclear: Modest growth in mineral demand from nuclear power

Average annual capacity additions and mineral demand from nuclear power



IEA. All rights reserved.

Note: Russia = Russian Federation.

Nuclear: Limited implications for minerals due to low material intensity

Nuclear power is the second-largest source of low-carbon power behind hydropower, accounting for about 10% of global electricity generation in 2020. Global installed capacity of nuclear power grows modestly to 2040 (by 15% in the STEPS and 45% in the SDS compared to 2020), as capacity declines in North America and Europe are offset by growth in emerging economies.

China is on track to become the leader in nuclear power around 2030, overtaking the United States and the European Union, more than doubling its current capacity to around 110 GW in the SDS. Significant programmes underway in India and the Middle East also contribute to the expansion of nuclear power. Capacity additions in 2020 were around 10 GW, and increase to an average of 11 GW in the STEPS and 16 GW in the SDS between 2031 and 2040.

Along with hydropower, nuclear is one of the low-carbon technologies with the lowest mineral intensity. Key mineral needs include chromium (2 190 kg/MW in 2019), copper (1 470 kg/MW), nickel (1 300 kg/MW), hafnium (0.5 kg/MW) and yttrium (0.5 kg/MW) (EC JRC, 2011). Uranium is not within the scope of our analysis, as this report focuses on mineral requirements for production of equipment, and not for operations. Around 16% of the worldwide supply of hafnium is currently used for nuclear reactor applications (EC JRC, 2011). However, the mineral intensity of chromium and nickel are highly sensitive to the use of high-alloy steel in nuclear power plants. Quantities of high-alloyed, low-alloyed and unalloyed steel used in a nuclear power plant are seldom reported.

Considering the maturity of the technology, there are unlikely to be drastic reductions in mineral intensity over the coming decades. As a result, mineral intensity is assumed to be similar in the STEPS, and decline slightly in the SDS.

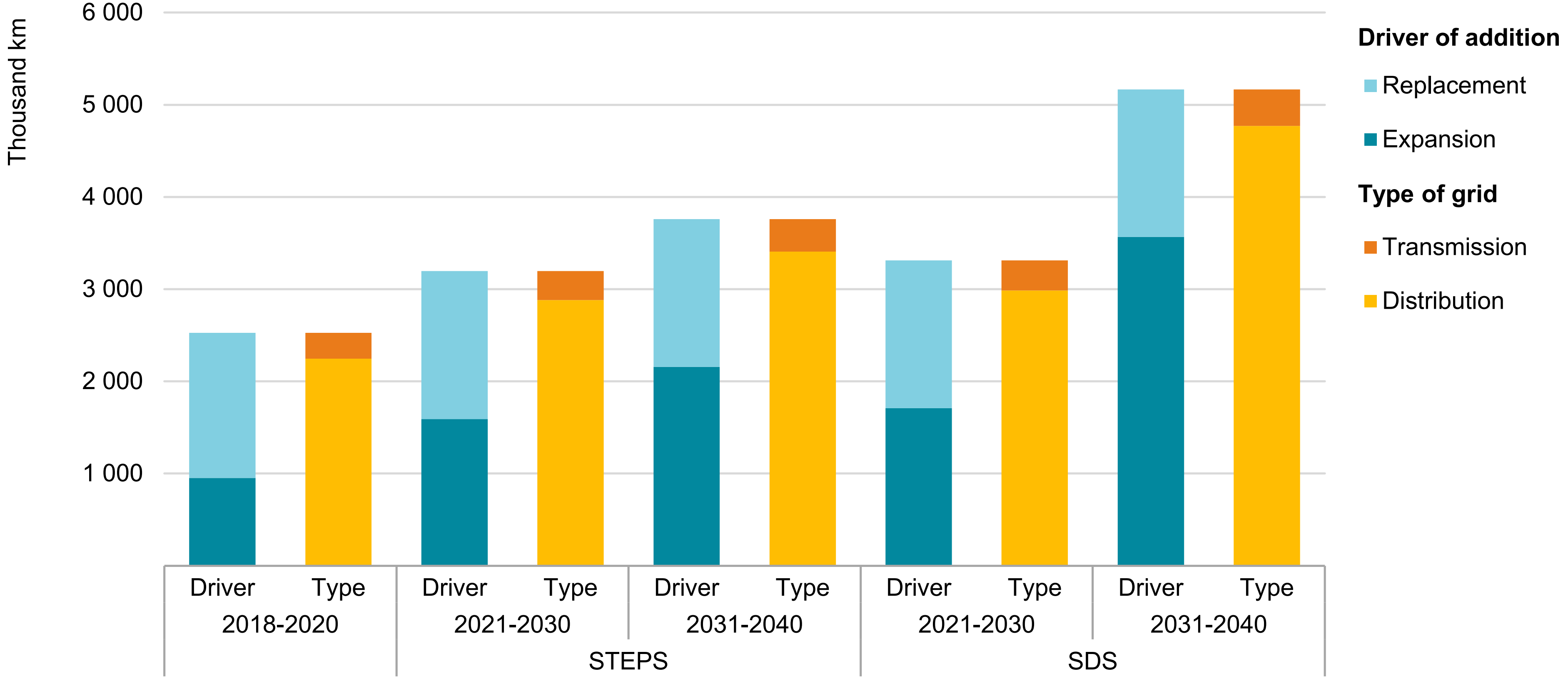
In the SDS, average annual mineral demand from nuclear power between 2031 and 2040 grows by around 60% compared to 2020 levels, reaching 82 kt. It is dominated by chromium (42%), copper (28%) and nickel (25%). Yttrium demand in 2040 is around 7.7 tonnes, or around 0.0015% of current global reserves.

We conducted our assessment based on mineral requirements for light-water reactor technology, which dominates the world's nuclear fleet (accounting for over 80% of all reactors in operation). Both pressurised-water reactors – the dominant choice for future expansion – and boiling-water reactors have similar mineral intensity. However, mineral intensities can be different for small modular reactors or more advanced nuclear technologies, but data for these technologies remains scarce.

Electricity networks

Rising electricity demand, alongside much higher shares of wind and solar PV, requires a significant expansion of electricity networks

Annual average grid expansion and replacement needs by scenario



Source: IEA (2020c).

Electricity networks are the backbone of secure and reliable power systems, and have a vital role in integrating clean energy technologies

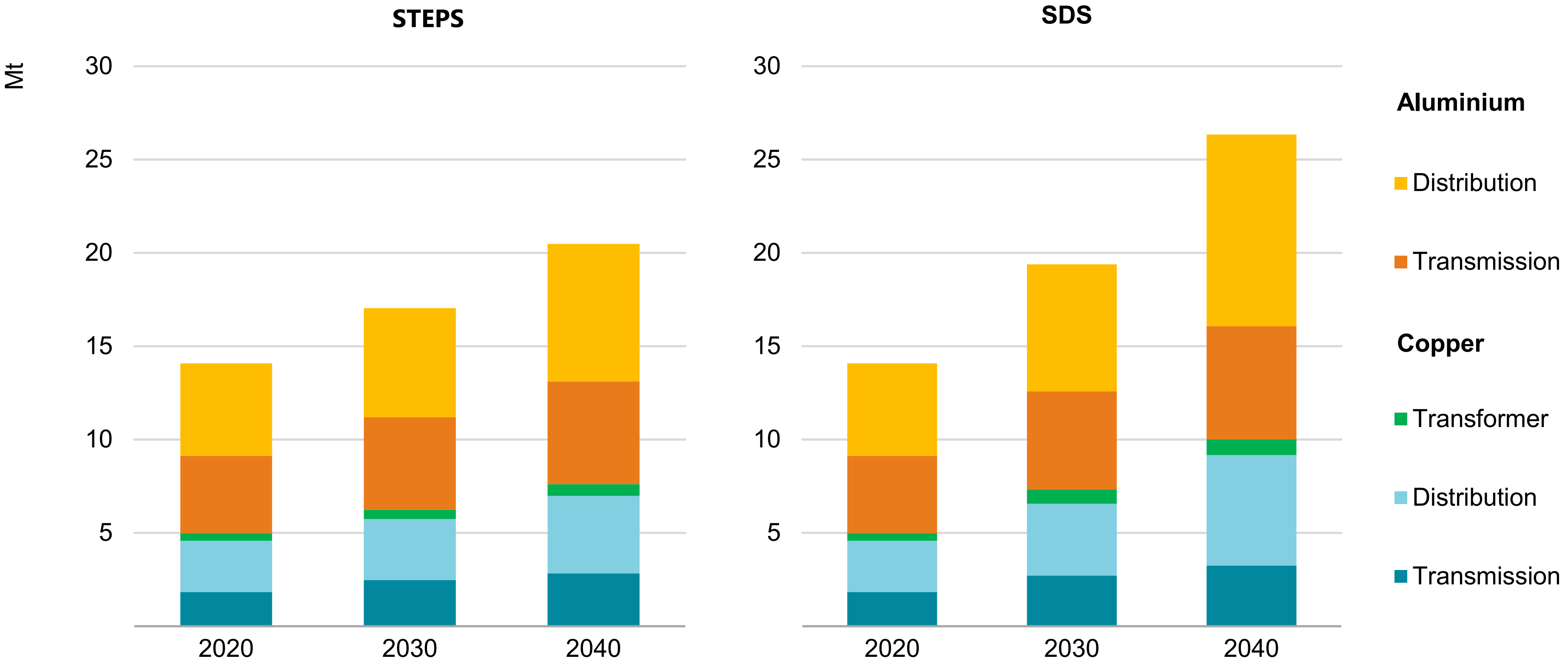
With over 70 million km of transmission and distribution lines worldwide, electricity networks are the backbone of today's power systems. Distribution systems currently account for over 90% of total line length, and play an increasing role in supporting the integration of residential solar PV and onshore wind capacity, in addition to their traditional role of delivering electricity to regional end users. Likewise, transmission systems, which are instrumental in connecting large hydro, thermal and nuclear power fleets with load centres, have new tasks to fulfil. For example, they now integrate large amounts of solar PV and wind capacity (in particular offshore wind), strengthen interconnection between countries and increase the resiliency of power systems. These new tasks are supported by the rise of high-voltage direct current (HVDC) technologies. HVDC systems have been used since the 1950s, but over two-third of total installed HVDC transmission capacity has been added in the past 10 years. Today, HVDC systems represent around 7% of newly installed transmission systems and their share is expected to rise further given the considerable technological progress made over the past decade.

Many of the features that characterise a clean energy system – the growing role of electricity in final consumption, rising contributions from renewables in electricity supply and the greater need for flexibility – all necessitate significant expansion of electricity grids. The projected requirement for new transmission and distribution lines worldwide in the STEPS is 80% greater over the next decade than the expansion seen in the last ten years. The importance of electricity grids is even greater in the case of faster energy transitions. In the SDS, the annual pace of grid expansion needs to more than double in the period to 2040. Around 50% of the increase in transmission lines and 35% of the increase in distribution network lines are attributable to the increase in renewables.

In addition to additional lines, there is scope to refurbish grids to strengthen the resiliency of electricity systems to climate change and extreme weather events. Refurbishment of electricity grids is also strongly linked to digitalisation, given the rising need for smart and flexible grids. Investment in digitalisation and grid flexibility helps increase reliability and can reduce the cost of generating, transmitting and distributing electricity. In the SDS, some 55% of the expansion to 2030 in advanced economies such as the European Union and the United States are attributable to refurbishment and digitalisation.

Growing need for grid expansion underpins a doubling of annual demand for copper and aluminium by 2040 in the SDS

Demand for copper and aluminium for electricity grids by scenario



Note: Includes demand for grid expansion and replacement.

The choice of material in electricity networks is mainly driven by the type of power line, but is also influenced by cost and technical considerations

The huge expansion of electricity grids requires a large amount of minerals and metals. Copper and aluminium are the two main materials in wires and cables, with some also being used in transformers. It is estimated that some 150 Mt of copper and 210 Mt of aluminium are “locked in” the electricity grids operating today.

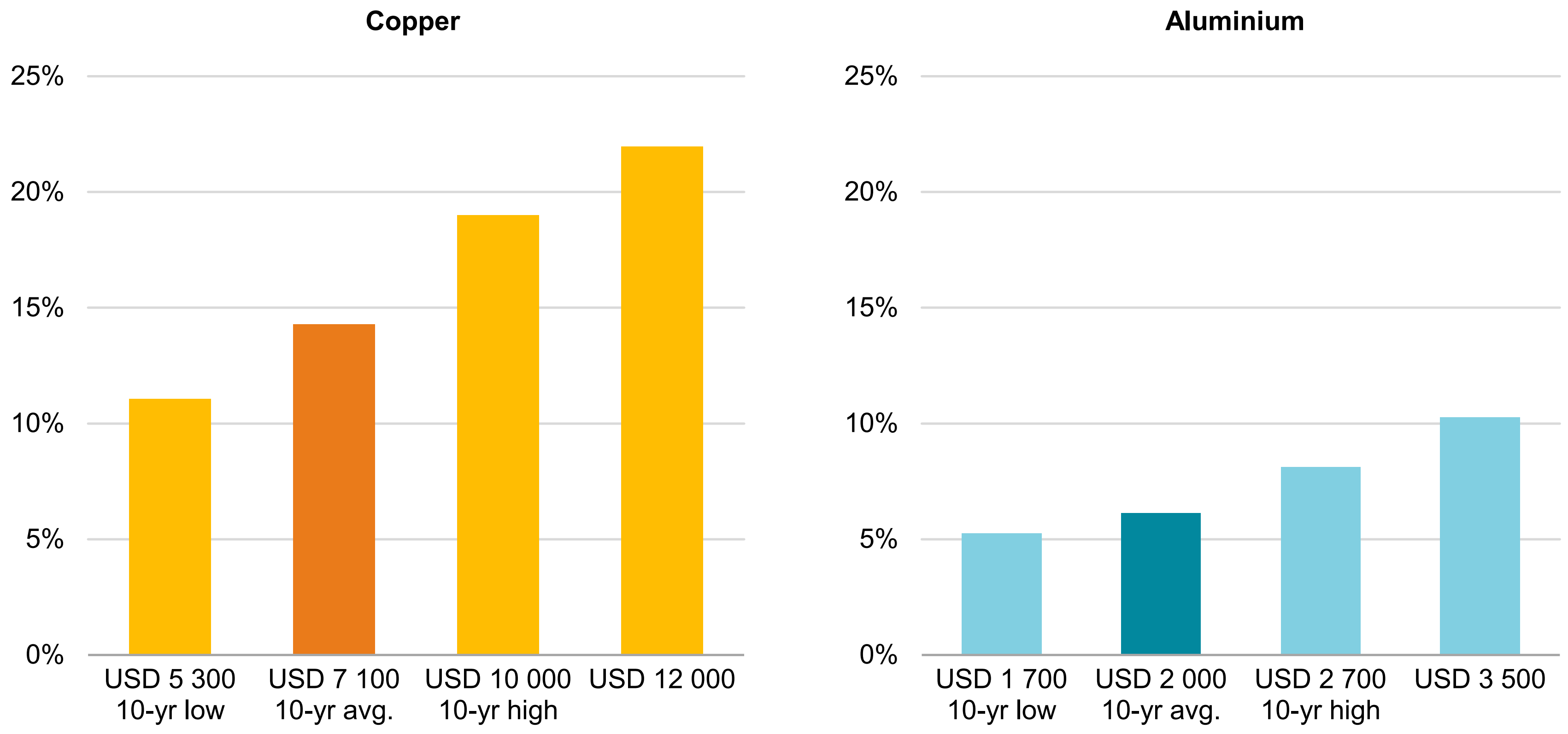
Copper has long been the preferred choice for electricity grids due to its inherent performance advantages. Its electrical conductivity is the second best among various metals after silver and 60% higher than aluminium. Its thermal conductivity, an often-overlooked attribute when designing and operating a grid, is also some 60% higher than aluminium. However, it also has drawbacks. Copper is over three times heavier by weight than aluminium and is more costly – average prices for copper over the past 10 years were USD 7 100 per tonne (in 2019 dollars) whereas those for aluminium averaged at around USD 2 000 per tonne.

This underpins different material choices according to the type of power line. Copper is widely used for underground and subsea cables where weight is not a major concern and superior technical properties (e.g. corrosion resistance, tensile strength) are required. By contrast, aluminium is commonly used for overhead lines given its weight advantage. In some instances, aluminium is also used for underground and subsea cables.

We estimate that some 5 Mt of copper and 9 Mt of aluminium were used in 2020 to build electricity grids, of which over 55% is attributable to distribution grids. We conducted bottom-up assessments of projected line additions and replacements by type (overhead, underground and subsea), voltage level and respective material choice. These show annual copper demand for electricity grids growing from 5 Mt in 2020 to 7.5 Mt by 2040 in the STEPS, and more than double that to almost 10 Mt in the SDS. Aluminium demand increases at a similar annual pace, from 9 Mt in 2020 to 13 Mt in the STEPS and 16 Mt in the SDS by 2040. Overhead lines account for a larger share of future expansion by line length, but underground and subsea cables require higher mineral content per unit length. The scope for significant demand growth, coupled with a higher share of raw materials in total cost, raises questions over how companies can reduce material intensity in their grids in order to lower material cost.

Costs for copper and aluminium currently represent around 20% of total grid investment; higher prices could have a major impact on the adequacy of grid investment

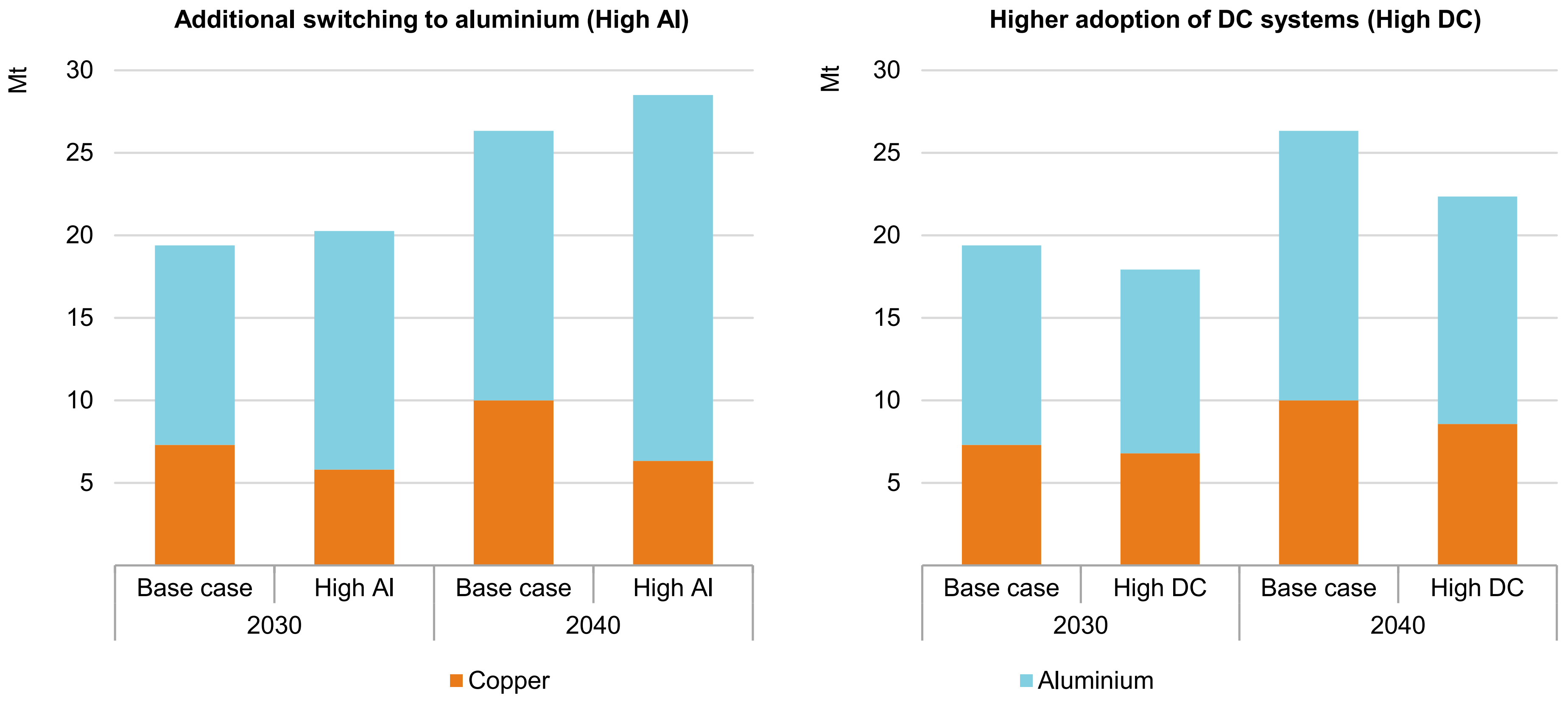
Share of copper and aluminium costs in new grid investment under different price assumptions



Notes: The shares have been calculated according to total electricity grid investment in 2019, with raw material prices adjusted. Darker bars indicate average costs between 2010 and 2019; costs are in USD per tonne.

Additional switching to aluminium for underground cables and the wider uptake of DC systems can alter the material requirements considerably

Copper and aluminium demand for electricity networks in the SDS under alternative cases



IEA. All rights reserved.

Increased use of aluminium could reduce copper demand by one-third, while wider adoption of DC systems could reduce aluminium and copper demand by 15%

As grids are modernised, expanded and digitalised, projected investment in electricity grids reaches USD 460 billion in 2030 in the STEPS and USD 620 billion in the SDS. However, shortfalls in grid revenues can put the adequacy of grid investment at risk.

Prices for minerals may add to this pressure given their considerable share in total investment costs. Using average prices over the past 10 years, copper and aluminium costs are estimated to represent around 14% and 6% of total grid investment respectively. At the highest prices observed over the past decade, these increase to almost 20% and 8% respectively, highlighting the major impacts that mineral prices can have on the ability of grid operators to undertake investment.

Increased use of aluminium in underground cables

Grid operators have long been working to reduce raw material costs. One option is to switch from copper to more affordable aluminium. When comparing the costs of the two materials, this seems to be an obvious option to improve the economics of grid investment. This is possible in cases where technical or regulatory boundaries allow, and has happened in recent years. Some drawbacks such as the lower electrical conductivity of aluminium can be compensated by the use of larger conductors, although technical or environmental requirements often do not allow such shifts.

If aluminium takes a higher share in underground and subsea cables than our base case assumptions – accounting for 50% for distribution lines and 30% for transmission lines by 2040 – this reduces copper demand in 2040 by 3.7 Mt (down by a third) while raising aluminium demand by 5.8 Mt (up by over a third).

Wider adoption of DC systems

Another option is to adopt HVDC systems more widely. At present electricity networks are largely operated via alternating current (AC) systems, which require a minimum of three wires to transmit electricity. However, HVDC systems use only two wires, which implies a direct saving on metal consumption of one-third compared to AC systems. HVDC systems are also capable of transporting more electricity (theoretically up to 3.5 times more) compared to AC systems, which could reduce copper and aluminium demand and also the need for grid expansion (which results in further savings).

In the case of a wider uptake of HVDC systems – accounting for 50% of new transmission lines and 30% of distribution lines by 2040 – would reduce combined demand for copper and aluminium in 2040 by 4 Mt (or 15%) in the SDS.