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NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Report on assessment of impacts on key non-renewable resource chains: case study on global demand, supply and trade-offs for selected metals and minerals in global mitigation pathways

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Executive Summary

Non-renewable raw materials, such as different metals and minerals, are required in clean energy technologies, and thus in the transition towards global climate change mitigation targets. The demand for these materials is expected to increase in the future due to growing energy and industrial products demands, replacement of the old infrastructures and, especially, due to increased metal intensities of clean energy technologies. However, in the climate change mitigation scenarios the supply and demand of these materials are usually neglected. Based on our literature analysis, none of the recent scenario assessments looking at metal and mineral demands in the clean energy transition has made any assessments on Negative Emission Technologies and Practices, which was our primary focus in this deliverable. The quantitative climate and energy scenarios were modelled with the TIMES-VTT Integrated Assessment Model. The formulating of reference scenario was based on Nationally Determined Contributions (NDCs), which was reported in the IIASA database for the IPCC Working Group 3 of the 6th Assessment Report (IPCC 2022). In addition to NDC scenario, we formulated two more ambitious mitigation scenarios to reach 1.5-2 °C temperature limit of global warming by 2100 with immediate actions.

The results showed that the clean energy transition may be constrained by a supply of cobalt and neodymium, which are important metals in batteries and wind power installations. In addition, copper and silver are used high amounts in energy technologies but also in other sectors, and the supply of these metals could also limit long-term investments in clean energy technologies. If these boundary conditions are considered, the demand of NETPs could increase even further as the renewable energy implementation may be constrained and therefore, we potentially need to compensate greenhouse gas emissions with NETPs even more to reach the 1.5-2 °C mitigation target. On the other hand, in bioenergy with CCS (e.g., BECCS) other global boundary conditions, like land and water use, will limit its sustainable implementation.

During the next steps in NEGEM, global and regional climate and energy scenarios will be modelled in WP8 with especial focus on sustainable potentials of biomass for bioenergy. In addition, we will update our data and assessments related to negative emissions practices, like afforestration and reforestration as well as consider ocean based negative emissions technologies in the database of TIMES-VTT.

Table of contents

List of figures

Introduction

A key target of the NEGEM project is to assess the realistic potential of Negative Emission Technologies and Practices (NETPs) and their contribution to climate neutrality, as a supplementary strategy to emissions mitigation. Work Package 3 of the project assesses impacts, side-effects and trade-offs of large-scale NETPs deployment on the environmental state of the planet and its regions, and on selected supply and resource chains. Accounting for these impacts in a thorough way can constrain the realistic potential of the large-scale deployment of NETPs, and it is therefore seen as a justified part of the project.

Non-renewable raw materials, such as different metals and minerals, are required in clean energy technologies, and thus the transition towards global climate change mitigation targets. Demand for these materials is expected to increase in the future due to the growing demand for energy and industrial products, replacement of the old infrastructures and, especially, due to increased metal intensities of clean energy technologies. However, in the climate change mitigation scenarios the supply and demand of these materials are usually neglected (see for example IPCC 2022, IEA 2021a). Noteworthy, the demand for non-renewable raw materials interesting for the NEGEM project is not only driven by deployment of negative emission technologies (NETs), such as direct air capture of carbon dioxide (CO_2) with carbon storage (e.g., DACCS) or bioenergy production with carbon capture and storage (e.g., BECCS). Instead, we need to consider metal demands of other mitigation technologies, such as photovoltaics (PV), wind power, or electric vehicles (EV), which need to be accounted for in thorough overall assessments. In the recently published Working Group 3 (WG3) contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) it was recognised that reliance on certain metals and minerals, like cobalt (Co), copper (Cu), lithium (Li) and rare-earth elements, has raised questions about possible constraints to a low-carbon energy system transition (IPCC 2022, p. 6-31). Environmental and social concerns have also been raised about mining for these materials. As an example, major share of the global cobalt is mined in the Democratic Republic of Kongo, where also severe human rights issues in mining operations have been reported.

Technologies required for low-carbon energy pathways are often dependent on raw materials with limited supply in the long-term. This motivates us to assess if the raw material needed by the global energy system transition can become a constraint for the deployment of these technologies. Especially, during the last years, an increasing number of reports and peer review articles have been looking at metal demands in clean energy transition with a quantitative scenario analysis (IEA 2021b, The World Bank 2020, The World Bank 2017, Carrara et al. 2020, Watari et al. 2019). However, none of these reports considers mineral demands in the NETPs. On the other hand, the impacts that large-scale deployment of NETP technologies can bring are of interest in the framework of the NEGEM project. In this deliverable, the impacts on the global demand and supply of metals and minerals critical to climate change mitigation, including NETPs, is studied using the global TIMES-VTT Integrated Assessment Model. The analysis is based on our earlier studies on global mitigation scenarios (Lehtilä & Koljonen 2018, Grandell et al. 2016, Koljonen & Lehtilä 2012). In this study, we have updated the TIMES-VTT database with the most recent literature and data on metal intensities of clean energy technologies and NETPs.

To be able to conduct systematic assessments of overall impacts of low-carbon energy pathways on non-renewable raw material supply chains throughout this century with the methods used in this study, the following steps are needed:

(i) screening of the recent estimates on resource needs of technologies for energy system transformation based on literature, including key renewable energy, energy end-use, and negative emission technologies,
(ii) definition of the stringency of mitigation targets of global greenhouse gas (GHG) emissions reductions to assess the pace of global energy system transition,
(iii) calibration and update of the global TIMES-VTT Integrated Assessment Model with new data, and analysis of the results provided by the scenario model runs.

Building on the above-mentioned steps, the aim of this study is to evaluate the future need of selected raw materials focusing on metals and minerals in clean energy transition pathways. The raw materials under interest are selected based on literature and our earlier studies (Grandell et al. 2016) in order to explore interesting characteristics from the angle of the NEGEM project, including impacts of NETPs. As there is increasing literature on the demands of selected metals and minerals for the clean energy transition, the added value of this study is especially seen in its effort to explore the impacts brought by NETPs as a novel element for the assessments, as many of the earlier studies have primarily focused on electrification of the energy system with renewable energy technologies. As an outcome, indications of most critical resources, as updates to previous studies, are received. Also, the results give high-level indications on NETs most critical from resource sufficiency point of view and identify gaps in data for material use of technologies to be addressed in forthcoming studies. Negative emission practices are out of scope of this report, but the TIMES-VTT the scenario assessments also include afforestration and reforestration options in GHG mitigation, which will be studied in the forthcoming WP8 work of NEGEM.

1 Scope of the study

Climate change mitigation to limit the global temperature increase to 1.5-2 °C compared with the pre-industrial levels requires replacement of the energy infrastructures for energy production, transmission and end use. As an example, fossil fuel fired energy production, combustion engines in transport, and GHG emitting industries need to be replaced or refurbished with low or zero emission technologies. In addition, large investments are needed for electricity, hydrogen, CO_2 and other transmission infrastructures. It is also recognised that clean energy technologies require more materials when compared to the fossil-fuel based counterparts (The World Bank 2020, IEA 2021b). The scope of this study is to evaluate the need of selected minerals and metals in selected low carbon energy technologies and NETs to find potential bottlenecks in technology implementation based on the estimated reserves and resources of the selected elements[1]. The selection of minerals and metals as well as technologies are based on literature and our earlier studies, which are described in the Chapter 2, Chapter 3 and Appendix A.

The following technologies are selected for the evaluation; wind power, solar photovoltaics, concentrating solar power, geothermal, hydropower, biomass- and solid- and gaseous fossil fuel-based combustion, biofuels, nuclear power, BECCS, DACCS, PyCCS (pyrogenic carbon capture and storage), electric vehicle batteries and motors and electrolysers. Due to limited information, the direct metal demands of DACCS and PyCCS were not included in the modelling.

TIMES-VTT Integrated Assessment Model (IAM) is used to model the clean energy systems and demands of clean energy technologies to reach the mitigation goals of Paris Agreement (PA), which is compared

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[1] Mineral resources are defined as natural concentrations of minerals that are, or may become, of potential economic interest due to their inherent properties. Mineral reserve refers to the economically (and legally) mineable part of mineral resource. There are several standards and other characterizations to define reserves and resources, which can be proven, probable, indicated, discovered, undiscovered, etc.

with a reference scenario simulating NDC policies. For the scenario definitions, we have used the IPCC AR6 WG3 scenarios (IPCC 2022) which have been reported in the IIASA AR6 database[2]. The NDC emissions trajectory for Europe is assumed the minimum level of mitigation for Europe in all scenarios. The focus of the assessment is on medium term up to 2030 and long term up to 2050, but the scenarios are modelled up to 2100.

The methodology of our analysis is described in more detail in Chapter 2. Chapter 3 evaluates mineral demands of NETs. In Chapter 4, scenario definitions and results with TIMES-VTT model are shown. Chapter 5 presents key findings and policy relevant messages and in Chapter 6 conclusions are drawn.

2 Overview of data formulation on metals and minerals and modelling approach

2.1 Data formulation

The metal and mineral intensity data is typically expressed by the amount of metals and minerals needed to build a gigawatt of capacity, in tonnes per gigawatt (t/GW). The metal and mineral (later referred to as "minerals") intensity data used in this study is based on mineral intensity estimates collected from several publicly available studies.

As the mineral intensity data is collected from multiple sources that have used different methods and assumptions to obtain the data, inconsistencies are likely to occur. Therefore, the mineral intensity data applied in this study should only be taken as indicative. If a range of estimates has been given in the literature source, the midpoint value for mineral intensity has been applied. In addition to the mineral demand of the assessed technologies, the shares of potential sub-technologies, mineral intensity improvements and plant lifetimes have been taken into account in the scenario modelling. Mineral intensities of clean energy transition technologies, shares of potential sub-technologies and considerations on mineral intensity improvements can be found in Appendix A.

The Table 1 below describes the summary of the selected technologies in our analysis and the reference sources for their mineral intensities. Various recent peer review and grey literature sources were used to assess the mineral intensity values of negative emissions technologies, which was the primary focus in the analysis. However, besides carbon capture and storage (CCS), no sufficient mineral intensity data on negative emission technologies was found so that it could have been included in the scenario analysis of this study. The identified estimation for mineral intensity in CCS was for CCS to capture emissions from fossil-based combustion. In this study, CCS data is also applied to capture CO_2 emissions from biomass-based combustion and from pyrogenic carbon capture and storage (PyCCS)[3].

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[2] AR6 Scenario Explorer and Database hosted by IIASA. Available AR6 Scenario Explorer and Database hosted by IIASA

[3] In PyCCS biomass is pyrolysed in high temperature to produce biochar, which is used to enhance the carbon sequestration capacity of soils. The synthesis gas produced in pyrolysis is collected and used as fuel. Biogenic carbon can therefore be captured as biochar in soils and by BECCS when combusting it.

Table 1 Covered technologies and reference sources for their mineral intensities.

Technology	Reference
Wind power	Carrara et al. 2020, IEA 2021b
Solar photovoltaics (PV)	Carrara et al. 2020, IEA 2021b
CSP	Watari et al. 2019
Geothermal	Moss et al. 2011
Hydropower	Ashby 2013
Biomass-based combustion and biofuels	Ashby 2013, Moss et al. 2011
Solid and gaseous fossil fuel combustion	Ashby 2013, Moss et al. 2013
Nuclear power	Moss et al. 2011
Bioenergy with Carbon Capture and Storage (BECCS)	Moss et al. 2011
Direct Air Capture Carbon Storage (DACCS)	No sufficient mineral intensity data applicable for the study
EV batteries	Assumptions based on Volkswagen (2021)
EV motors	Assumptions based on IEA (2021b) and Månberger & Stenqvist (2018)
Electrolysers	IEA 2021b

Besides using virgin natural resources for metals and minerals we can also use recycled materials after their expected lifetime. In the scenario assessments we have also made rough estimates for recycling of selected metals in selected technologies, which will reduce the demand for virgin natural resources. However, there exists very little information on future potentials for recycling and therefore these estimates include large uncertainties. Besides recycling, other metals can substitute some metals in certain applications but this information is even more lacking and therefore not considered. However, the technology data includes also estimates for metal intensity development in the future, which naturally also includes large uncertainties.

2.2 Mineral selection

Several studies have evaluated the demand of metals and minerals in the clean energy transition. The studies differ in the methods, targeted minerals and in the technologies covered. A recent study by IEA (2021b) evaluates the demand of minerals required for a range of low-carbon technologies (solar PV, onshore and offshore wind, concentrating solar power, hydropower, geothermal, biomass-based power, nuclear power, electricity networks, electric vehicles, battery storage, electrolysers and fuel cells). IEA (2021b) finds that the total mineral demand for clean energy technologies can be six times more in 2040 when compared to today’s demand, if global net-zero target would be reached by 2050. The World Bank (2020) has evaluated the future demands of various minerals for a range of technologies (e.g., solar PV, wind, CSP, geothermal, energy storage). The study foresees that the annual demands in 2050 for graphite, lithium and cobalt needed in energy storage technologies will be nearly up to 500% from 2018 production levels. The level of uncertainty in the future demands of these minerals is high because they are featured only in a small number of technologies and hence their demands are dependent on technological changes. The World Bank (2020) defines aluminium, copper, molybdenum, chromium, lead, nickel and manganese as cross-cutting minerals that are used across a variety of energy generation and storage technologies. Therefore, the demands of these minerals are expected to increase no matter which technologies or sub-technologies end up being deployed in the future.

Gielen (2021) summarises that many assessments related to critical minerals in the energy transition define cobalt, copper, nickel, lithium, and rare earth elements, more specifically neodymium and dysprosium, as minerals that should be considered as critical. However, Gielen (2021) also points out that one or few of the following minerals have been defined as critical in the studies assessed making the definition of criticality somewhat fluid: aluminium, chromium, gallium, germanium, graphite, indium, iron, lanthanum, lead, manganese, molybdenum, platinum, rhenium, ruthenium, scandium, silver, vanadium, tantalum, titanium, yttrium and zinc. Watari et al. (2019) also summarised studies from recent years that examined the mineral availability for the low-carbon energy transition. According to Watari et al. (2019), the studies found long-term availability of one or few of the following minerals as potential bottlenecks for decarbonization of the energy and transport sectors; cadmium, chromium, cobalt, copper, dysprosium, gallium, germanium, indium, lanthanum, lithium, manganese, neodymium, nickel, platinum, ruthenium, selenium, silver, tellurium, tin or zinc. In the Working Group 3 (WG3) contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) it was recognised that reliance on certain metals and minerals, like cobalt, copper, lithium and rare-earth elements, has raised questions about possible constraints to a low-carbon energy system transition (IPCC 2022, p. 6-31).

Based on the recent literature and on our earlier studies (Grandell et al. 2016), the following eight minerals were selected to be included in this study: silver, cobalt, copper, dysprosium, lithium, manganese, neodymium and nickel.

2.3 TIMES-VTT model description and scenario formulation

The TIMES-VTT model is a global multi-region model based on the ETSAP TIMES modelling framework. The model itself is a derivative of the global ETSAP TIAM model (TIMES Integrated Assessment Model, see Loulou 2008, Loulou & Labriet 2008). The methodology can be characterized as bottom-up, technology rich partial equilibrium modelling, and the model is usually run in a perfect foresight mode. The model covers all sectors, focusing on energy and emissions, with all Kyoto gases included (Figure 1).

The model is driven by a set of demands for energy services in all sectors: agriculture, residential, commercial, industry and transport. The construction of the exogenous demands for energy services may be done by using the results from general equilibrium models, which can provide a set of coherent drivers for each region and for the world as a whole, such as population, households, GDP, and sectors outputs.

The decoupling factors between the drivers and the demands for useful energy services account for phenomena such as saturation and suppressed markets and are in part empirically based. Most of these final demands have economic growth as their key driver. However, the demands for all other commodities in the system are endogenously determined by the model according to their supply-demand equilibrium, which must always satisfy various resource and sustainability constraints.

For supporting global integrated assessment modelling of climate change, the TIMES framework incorporates also an integrated climate module, with a three-reservoir carbon cycle for CO_2 concentrations and single-box decay models for the atmospheric CH_4 and N_2O concentrations, and the corresponding functions for radiative forcing. The forcing functions for CO_2, CH_4 and N_2O follow the non-linear formulations presented in the IPCC Fifth Assessment Report (Myhre et al. 2013) but are linearized around user-defined points. If necessary, by using an iterative approach the accuracy of the linearization can be improved to an arbitrary level. Additional forcing induced by other natural and anthropogenic causes is taken into account by means of exogenous projections. The changes in the global mean temperature are simulated for two layers, surface, and deep ocean (Loulou et al. 2016). When modelled, the emissions of F-gases (HFCs, PFCs and SF6) can also be taken into account in the climate model by converting them into equivalent CO_2 emissions. Although both the carbon cycle and the concentrations of CH_4 and N_2O are represented by quite simple models, the radiative forcing from anthropogenic GHG emissions is reasonably well approximated by the TIMES climate module and is calibrated to reproduce historical levels.

The model has been used earlier to study global, regional and national mitigation pathways to reach 1.5-2 °C mitigation targets and also for impact assessments of national, Nordic and EU level climate and energy policies. TIMES-VTT model has been the core tool in formulating and analysing the impacts of Finland's climate and energy strategies and policies, including climate neutrality target by 2035 (Lehtilä et al. 2021, Koljonen et al. 2021). Detailed description of the TIMES methodology can be found in the documentation (Loulou et al. 2016). Below, the modelling of metal demands is briefly described.

For the current work, we formulate long-term scenarios until 2100, using some of the key characteristics of mitigation pathways reported in the IPCC AR6 WG3 (2022). The pathways follow the current UNFCCC Nationally Determined Contributions (NDCs) until 2030 and immediate action towards limiting warming to 1.5-2 °C.

In the future, both the economic growth and more stringent environmental constraints are important drivers for increasing the use of various metals and minerals for the decarbonisation technologies, particularly in the transport and power sectors. The increasing use of critical metals is closely associated with the electrification of the energy systems and transition away from combustible fossil fuels. Conversely, however, many negative emission technologies and practices are among those important climate change mitigation options that have more moderate metal requirements and may thus be

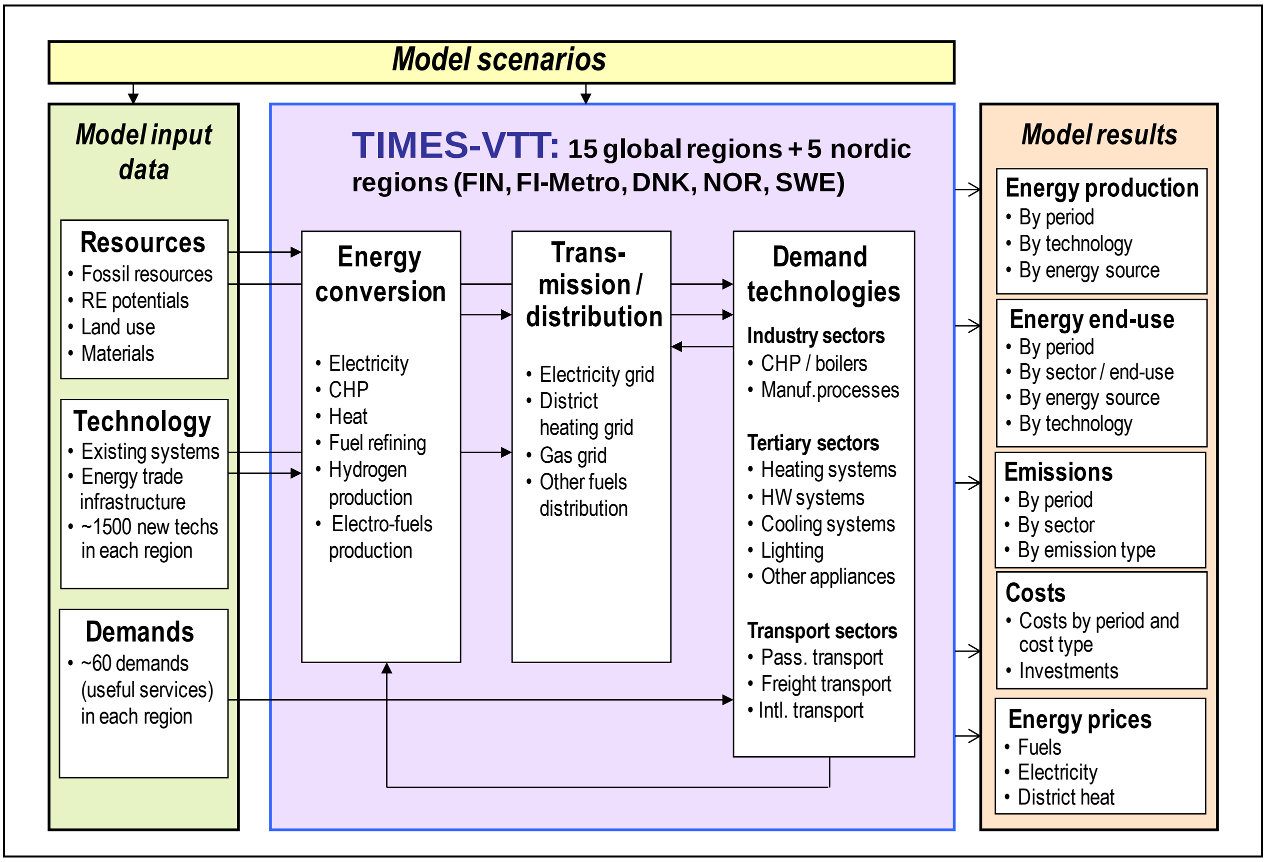

Figure 1. Components of the TIMES-VTT energy system model and simplified flowchart for one region.

Table 2 Summary characteristics of the metals selected for consideration and assumed net EoL (end of lifetime) recycling rates (net of losses). R/E: Resources per extraction indicates the number of years the resources can cover the consumption based on the resources and the current consumption numbers of the commodity.

Metal		Unit	Reserves	Identified Resources	Current Extraction	R/E Years	Current Demand	EoL Recycling, net		
								2020	2050	2100
Argentum (silver)	**Ag**	kt	530	600	25	31	33	52%	63%	80%
Cobalt	**Co**	Mt	7.6	25	0.14	179	0.14	37%	52%	80%
Copper	**Cu**	Mt	880	2100	21	100	29	50%	62%	80%
Dysprosium	**Dy**	kt	..	1500	2	500	2	7%	18%	50%
Lithium	**Li**	Mt	22	89	0.08	1143	0.1	6%	15%	43%
Manganese	**Mn**	Mt	1500	17000	20	850	21	23%	41%	75%
Neodymium	**Nd**	kt	..	11200	29	386	31	8%	20%	50%
Nickel	**Mi**	Mt	95	300	2.3	130	2.4	62%	71%	85%

needed not only for achieving deep reductions in net GHG emissions (IPCC 2022) but also for better coping with the constraints on sustainable use of mineral resources.

For the modelling experiment, we selected eight metals to be included in the TIMES-VTT model for assessing the impact of clean energy transition on the demand for the primary extraction of these metals and resource sufficiency. The selection of metals was based on recent literature described in Chapter 2, and on our earlier studies (Grandell et al. 2016). For each of these metals, we identified all the main energy technologies where the metals are needed, and estimated the consumption in terms of unit of installed capacity, as described in Chapter 3 and in Appendix A. After the technical lifetime of each of these technologies, the materials are assumed to be released for scrapping, and can be recycled into new products within an assumed average of five years' delay from scrapping to a building new installation. The model thereby produces the annual flows representing the amounts of metals stored in the new installations, and the annual recycling flows after the end of their product lifetimes (EoL).

For the recycling, one cannot assume 100% EoL recycling rates, but considerably lower assumptions were used, starting from assumed present rates and increasing over time, as shown in Table 2. Like in the refining of primary metals, there are also losses in the recycling process, and the rates represent the net fractions recycled.

3 Mineral demand of NETs

3.1 Overview of recent studies

Based on our literature analysis, the mineral demand for negative emission technologies (NETs) is not included in the studies that evaluate the mineral demand in clean energy transition (e.g., IEA 2021b, The World Bank 2020, The World Bank 2017, Carrara et al. 2020, Watari et al. 2019). Some studies have included carbon capture and storage in their analyses (e.g., Moss et al. 2011, The World Bank 2020 and The World Bank 2017, Watari et al. 2019), however, the focus has been on CCS from conventional generation and e.g., bioenergy with carbon capture and storage (BECCS) is not introduced in the studies.

The World Bank (2020) claims that due to the lack of large-scale operating CCS plants, estimating the future mineral demand of CCS is difficult, however the following minerals have been identified as key minerals related to CCS technology: chromium, cobalt, copper, manganese, molybdenum, and nickel. The scenario-assessment of World Bank (2020) finds that when CCS is applied, the demand of manganese increases when compared to decarbonisation scenarios without CCS. However, the number of studies analysing the mineral demand of CCS is low, and e.g., Gielen (2021) finds that the impacts of carbon capture and storage on the mineral demand of decarbonisation of energy and transport sectors have not been studied in detail. It should also be noted that in studies where CCS is covered, the analyses use Moss et al. (2011) as a reference for the mineral intensities (e.g., Watari et al. 2019, The World Bank 2020 and The World Bank 2017). Related to other NETs, such as DACC, Realmonte et al. (2019) calls out for an assessment, where the mineral demand, among other factors such a process-scale data for DACC is covered in detail.

3.2 Bioenergy with Carbon Capture and Storage (BECCS)

Chromium, cobalt, copper, manganese, molybdenum, and nickel have been identified as key minerals in the CCS technology and The World Bank (2020) finds the demand of manganese to increase in decarbonisation scenarios where CCS is applied. The minerals in CCS can be used in different manners: in capturing the CO_2, in the steel alloys needed to construct the CCS plant or in the transportation pipes needed to transport the CO_2 from the source site to the storage or utilization site (The World Bank 2020). The length of the transportation pipelines has been identified as an essential factor for the mineral demand of CCS.

Moss et al. (2011) points out that as CCS infrastructure is expected to be at utility scale, the use of expensive metals in most cases is hindered. In addition, in terms of volume, the study estimates that the greatest use of materials in CCS will be related to the steel used in the capture plant, transportation sites and related changes in the generation system of the power plant.

Based on the literature, the only identified estimation for mineral intensity in CCS can be found in Moss et al. (2011). Although the referred study is over a decade old, it has been applied as a source material in evaluating the mineral demand of CCS in several recent studies such as The World Bank (2020), The World Bank (2017) and Watari et al. (2019). In Moss et al. (2011), CCS is applied in fossil fuel combustion to capture carbon dioxide emissions. In this study, CCS is applied to capture carbon dioxide emitted also from biomass and biogas fired combustion as well as in PyCCS. The mineral intensity assumptions for CCS are presented in Table 3. The unit is tonne per GW of power generation capacity of the plant where CCS is applied.

Table 3 Mineral demand in CCS, which is used for BECCS. Source: Moss et al. (2011)

Material	**t/GW**
Vanadium (V)	100
Niobium (Nb)	100
Nickel (Ni)	1 145
Manganese (Mn)	3 761
Cobalt (Co)	8
Copper (Cu)	692
Molybdenum (Mo)	8
Chromium (Cr)	326

3.3 Direct Air Capture Carbon Storage (DACCS)

Realmonte et al. (2019) evaluated the energy and material demand of large-scale deployment of direct air carbon capture (DACC). The study covered two DACC solutions that the study found most promising for large-scale deployment from technical and economic perspective. The first DACC technology uses hydroxide solutions such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) that are currently obtained as a side-product of chlorine production process. Another DACC technology analysed in the study utilizes amine sorbents that can be synthesised e.g., from ammonia and ethylene oxide. However, the precise nature of the future amine sorbents is subject to high uncertainty. Realmonte et al. (2019) does not take into account the mineral demand of DACC facilities; the study calls out for a full life-cycle assessment of DACC where, among other factors, the process-scale data and material demand for e.g., cement and steel in DACCS equipment would be covered.

Various scientific and grey literature sources were explored, and no sufficient mineral intensity data was found for DACCS so that it to be included in the scenario analysis for mineral demands. However, DACCS is included in scenario modelling to reach the PA climate targets (see Chapter 4.2.3).

4 TIMES-VTT scenario descriptions and key results

The demand for the following minerals is modelled in this study with bottom-up TIMES-VTT energy system model: cobalt, copper, dysprosium, lithium, manganese, neodymium, nickel and silver. The selection of the minerals taken under closer look is based on IEA (2021b) and the other literature described in Chapter 2 and on VTT's earlier studies (Grandell et al. 2016). The selected minerals could define possible bottlenecks in clean energy transition and needed investments on energy sector and/or greenhouse gas mitigation. The modelled demands are compared with reserves and resources of these metals. The data on reserves and resources are based on public data (most are based on USGS 2022).

4.1 Scenario descriptions

The reference scenario is based on updated Nationally determined contributions (NDCs) under the Paris Agreement, which were published at the COP26 in October 2021 (United Nations 2021). In the interim NDC registry[4] as of 12 October 2021, the NDCs covered 94.1% of the total global emissions in 2019, which are estimated at 52.4 Gt CO_2 eq. without LULUCF. However, the NDCs are not comparable between each other as they vary in content, background assumptions, scope and coverage, etc. In addition, they do not include information, which would be needed for scenario modelling. As an example, the NDCs typically include gross GHG or CO_2 emission reduction targets for 2030 as well as net carbon neutrality target by 2050 or some other specified year (e.g., including LULUCF) but no complete information on either gross or net GHG targets by 2030 and beyond.

In the IPCC AR6 report (2022), NDCs were analysed and mitigation pathways with NDCs until 2030 and below 2 °C thereafter were reported. The IPCC report did not include either a complete scenario data on NDCs, which would have been needed for our TIMES-VTT assessments. Therefore, we have used one scenario dataset published in the IIASA AR6 database as a reference and benchmark scenario. This NDC reference scenario is compared with two mitigation scenarios with immediate actions, i.e., one with 2 °C mitigation target by 2100 and the other with 1.5 °C mitigation target with an overshoot.

The scenarios modelled are long-term scenarios for the global energy system until 2100. For the scenario formulation we have used the key characteristics of mitigation pathways reported in the IPCC AR6 WG3 (2022). The pathways follow current UNFCCC Nationally Determined Contributions (NDCs) until 2030 and immediate action towards limiting warming to 1.5-2 °C, as follows:

- **NDC-1400:** The global and European GHG emissions reductions trajectory is taken from the EN_INDCi2030_1400f scenario results of the REMIND-MAgPIE 2.1-4.2 model in the IIASA

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[4] United Nations NDC registry can be found in https://unfccc.int/NDCREG

database (IIASA 2022). This scenario describes the impact of Nationally Determined Contributions on the annual GHG emission trajectories, on the global scale and by region.

- **Pol-2C:** The minimum European GHG emissions reduction trajectory is as above, and the global temperature change is limited to 2°C by 2100.
- **Pol-1.5C:** The minimum European GHG emissions reduction trajectory is as above, and the global temperature change is limited to 1.5°C by 2100.

In total, we thus examine three scenarios, one with NDC-determined emission trajectories and two global climate policy scenarios based on targets for maximum global temperature change. In the NDC scenario, the total global GHG emissions are about 25 Gt(CO_2 eq.) in 2050 and about 11 Gt(CO_2 eq.) in 2100. The scenario is characterized as a category C4 scenario, which limits warming to 2°C (with a probability of 50% or greater). The NDC reaches also 2 °C mitigation target by 2100 but unlike the other 2 °C mitigation pathway, the GHG reduction is delayed until 2030 and therefore the mitigation pathway is steeper after 2030.

Overshooting the temperature targets before 2100 is allowed in the global climate policy scenarios, but with a high penalty cost simulating the associated damage (about 10% of global GDP per degree). Consequently, no overshooting actually happens with the looser 2C target due to the damage exceeding the compliance cost.

According to the model results, the EN_INDCi2030_1400f scenario leads to a 2.0 °C temperature increase by 2100, and according to the scenario documentation it should be so with a higher than 50% probability. Therefore, we may well assume that the two other scenarios may also be categorized as reaching their temperature targets with the same level of probability.

In all the scenarios, numerous NETs are assumed available for emissions reduction, including afforestation schemes, various BECCS technologies in the energy conversion sector (several power plant technologies, CHP, many fuel refining technologies, hydrogen production), PyCCS, and a couple of DACCS technology variants (Keith et al. 2018, Liu et al. 2020, DEA 2021). As a side-benefit, using the biochar from PyCCS as a soil improvement is assumed to increase soil fertility and thus bring about also considerable reductions in the N_2O emissions from agricultural lands. Although most papers on the subject seem to agree on a potential emissions reduction, good numerical estimates appear to be scarce in the literature, and the modeling assumptions thus include high uncertainties. We assume N_2O emission reductions adding 25% on top of the negative emissions obtained by the permanent carbon stored in soil, in terms of CO_2 equivalent emissions (Gaunt & Lehmann 2008).

4.2 Energy systems and greenhouse gas emissions

4.2.1 Global primary energy supply (TPES)

The global primary energy supply (TPES) has been increasing steadily throughout the 2000s, with an increase of over 40% between 2000 and 2019 (IEA 2021c). If similar growth rates prevailed in the future, the total energy supply would increase five to six-fold by 2100 from 2020. However, it is clear that such growth cannot continue, but many studies have been projecting the total primary energy consumption may be roughly doubling from the present levels by 2100, although the range of different projections is quite large (e.g., IIASA 2022). While electrification and the expanding use of renewable electricity generation tend to reduce growth in primary energy (IRENA 2022, Murphy et al. 2020, Nadel 2019), the transition to post-fossil economy may also cause increasing efficiency losses in some parts of the energy system, notably in storage systems, hydrogen and power-to-X conversion systems, and due to applying CCS, PyCCS or DACCS for climate change mitigation. All these various effects are reflected in our modeling results.

In the current scenario experiment the growth in total energy supply remains quite moderate until 2050 (14–16% from 2020), but the growth becomes higher in the latter half of the century, the TPES reaching about 1100 EJ in 2100. While some additional growth is consistent with the increasing efficiency losses due to decarbonizing the energy systems, to some extent that may be caused by underestimation of technology advances beyond 2050 (technology parameters are often estimated only up to 2050), and the driver elasticities for some energy service demands. The trajectory thus suggests that these issues should be looked at in some more detail and the model improved where necessary.

Among the most important energy sources, solar energy becomes the dominant source for primary energy in the latter half of the century, as one can expect. On the global scale, solar would leave wind behind already before 2040, even though also wind power continues to expand significantly.

With respect to NETs, major uncertainties are related to the sustainable bioenergy supply potential in the longer term. Like in IAM models in general, in the TIMES-VTT model the use of limited resources are constrained to sustainable potentials estimated from literature. In particular, bioenergy supply is divided into a number of biomass categories (primary, secondary and tertiary biomass supply) with simplified supply-cost curves, and the sustainable potentials of primary biomass production by type have been estimated based on literature sources. On the global scale, the impacts of climate change on biomass yields are likely to be negative, even though CO_2 fertilization and soil improvements through PyCCS application might counter-balance some of those impacts. In addition, one can expect an increasing demand of biomass for material use and for various chemicals, and introduction of stricter sustainability criteria, all having adverse impacts on biomass energy use in the long term. Therefore, the Pol-1.5C scenario, where the reliance on bioenergy becomes relatively high, includes risks of failing to achieve the negative emissions by the relative large-scale utilization of bioenergy, including BECCS as well as PyCCS. This will be studied further in the forthcoming WP8 work by using the results of WP3 and the other WPs.

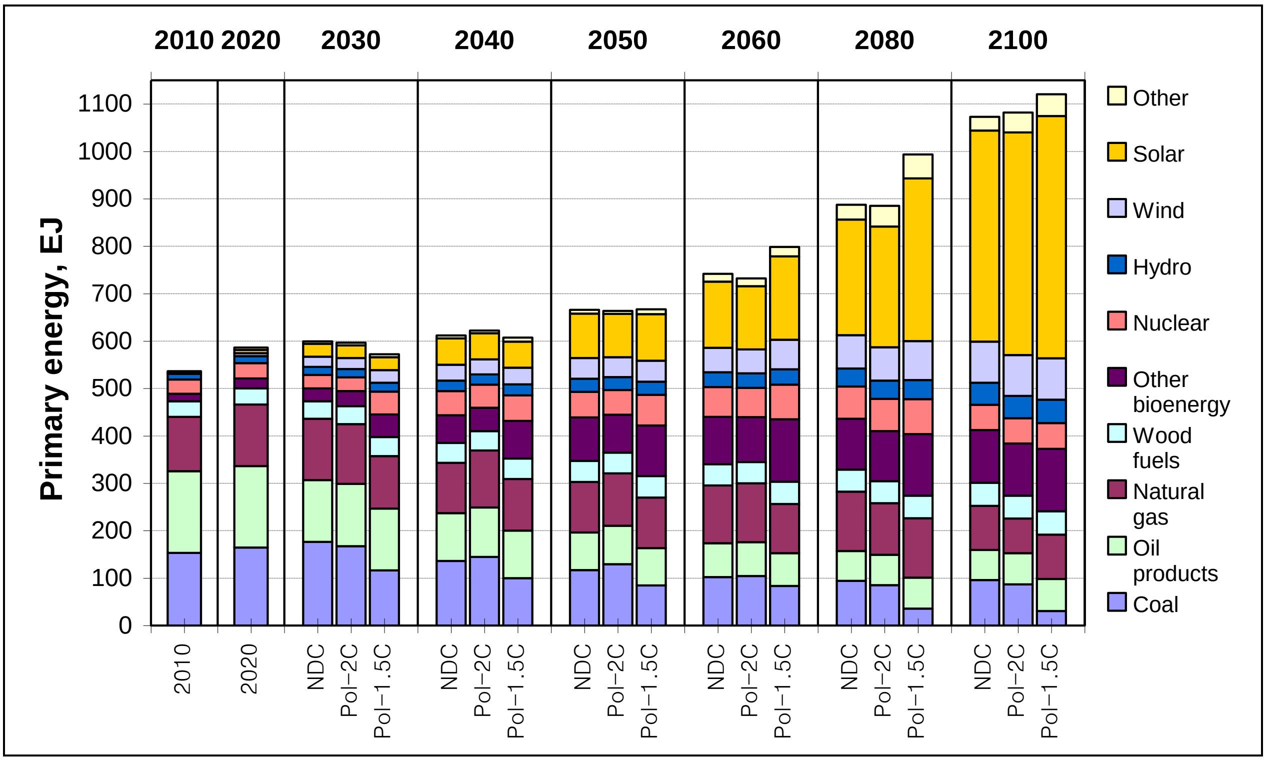

Figure 2. Development of global total primary energy supply (TPES) in the scenario variants, including non-energy uses.

4.2.2 Global electricity supply

The electrification of the global energy systems, as well as the expanding hydrogen economy, electrofuels and decarbonization systems, all increase electricity consumption, which may approach 200 PWh by 2100, according to the scenario results (Figure 3). The cost reductions of solar PV systems that have already taken place, and the projected further technical developments, can make solar power highly competitive on a large scale within the next few decades. The modeling results indicate that by 2040 solar power may pass wind power in the global electricity generation mix, and the trend would continue thereafter. Despite the additional flexibility required due to the variable nature of solar generation, the model results suggest that by 2100 about 70% of the global electricity generation would be solar based.

As expected, fossil fuel-based generation will be phased out almost completely by 2100, with natural gas fired power remaining on a somewhat notable level until 2080. Bioenergy-based power generation will not gain significant overall market share but will nonetheless be important in some regions and globally with respect to negative emissions achieved though BECCS power plants. Nuclear power might have a much larger potential than projected here, if the new small modular reactor technologies can improve its economy and will be legally feasible in different countries.

Until 2050, the global total electricity supply is actually slightly smaller than in the IEA NetZero by 2050 scenario (IEA 2021a). In the 1.5C scenario, the total supply is 62 PWh, while the figure in the IEA scenario is 71 PWh in 2050. Beyond 2050 the growth in electricity supply may appear large, but one should point out that it is of course nevertheless all reflected in the primary energy consumption shown in Figure 2.

4.2.3 Global greenhouse gas emissions and role of NETs

With respect to GHG emissions, the scenario results suggest that a quick transition away from fossil fuels may happen relatively slowly unless strict policies are implemented for accelerating that transition. Because such policies were not assumed in the analysis, but the overall targets were imposed on the

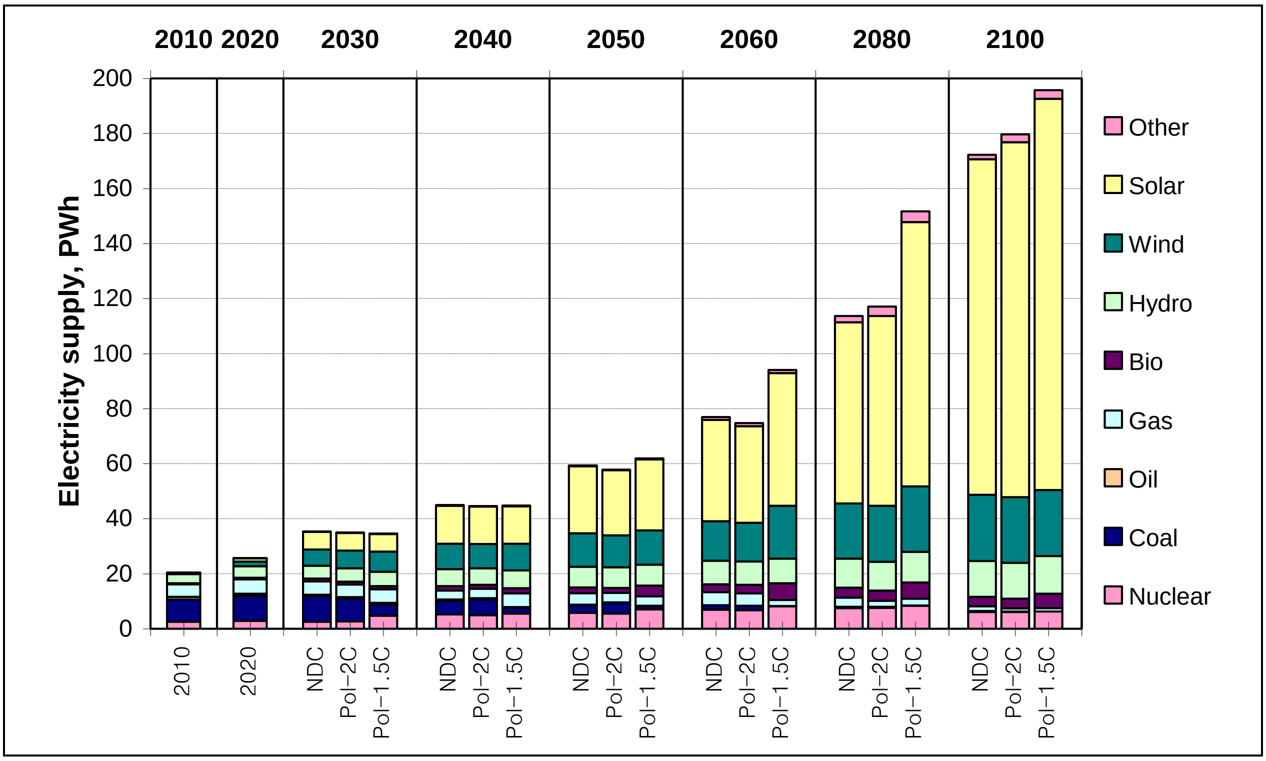

Figure 3. Development of global total net electricity supply in the scenario variants, excluding power plants own consumption.

total emissions or temperature limits, the results are thus representing indicative least-cost trajectories under relatively conservative assumptions on technology development in certain sectors, especially within energy-intensive industries and beyond 2050 in general. That is reflected by the considerable role of CCS in the results (Figure 4).

In the NDC-1400 scenario, the total net emissions develop exactly according to the global emission caps that were exogenously defined. In this case, the total CO_2 emissions approach zero only in 2100. The total GHG emissions remain above 10 Gt(CO_2 eq.)/a until 2100. The Pol-2C scenario follows closely similar emission paths, with slightly delayed reductions until 2050 compensated by somewhat larger reductions thereafter. The resulting temperature rise is in both cases 2°C in 2100 without intermediate overshooting. The role of negative emissions and CCS is in both cases already considerable, about 20 Gt/a during the last decades of the century. However, it is noteworthy that the projected costs of the DACCS options are high enough to prevent them from becoming competitive under either of these 2°C scenarios. In the 2°C scenario, the marginal emission price approaches 200 € (2020) per metric tonne (CO_2 eq.) only by 2100, which barely makes DACCS visible in the results for the last decade.

The Pol1.5C case depicts a much stricter climate policy case, where emissions have to be reduced much more rapidly to keep the temperature rise below 1.5°C in 2100. In this case, the damage cost imposed on overshooting also comes to play and reduces the peak overshooting to about 0.2°C in 2070. The role of negative emission practices (including any NETs involved) and CCS grows to a high level in this case, over 30 Gt/a during 2070–2080.

The results clearly indicate that moving from the 2°C target to the 1.5°C target leads to much more rapid emissions reductions and much higher mitigation costs. This effect is pronounced by the fact that in the scenarios relatively conservative assumptions were used about the development of new technologies that could replace fossil-based processes e.g., within energy-intensive industries. Therefore, larger CCS deployment remains the major economical option for achieving deeper emissions reductions, and on top of that, employing DACCS on a relatively large scale also becomes necessary (Figure 5).

In total, the NETs considered account for about 12 Gt(CO_2) during 2080–2100 in the 2C scenario, and even up to 22 Gt/a in the 1.5C scenario. Among the NETs, the biomass-based technology options BECCS

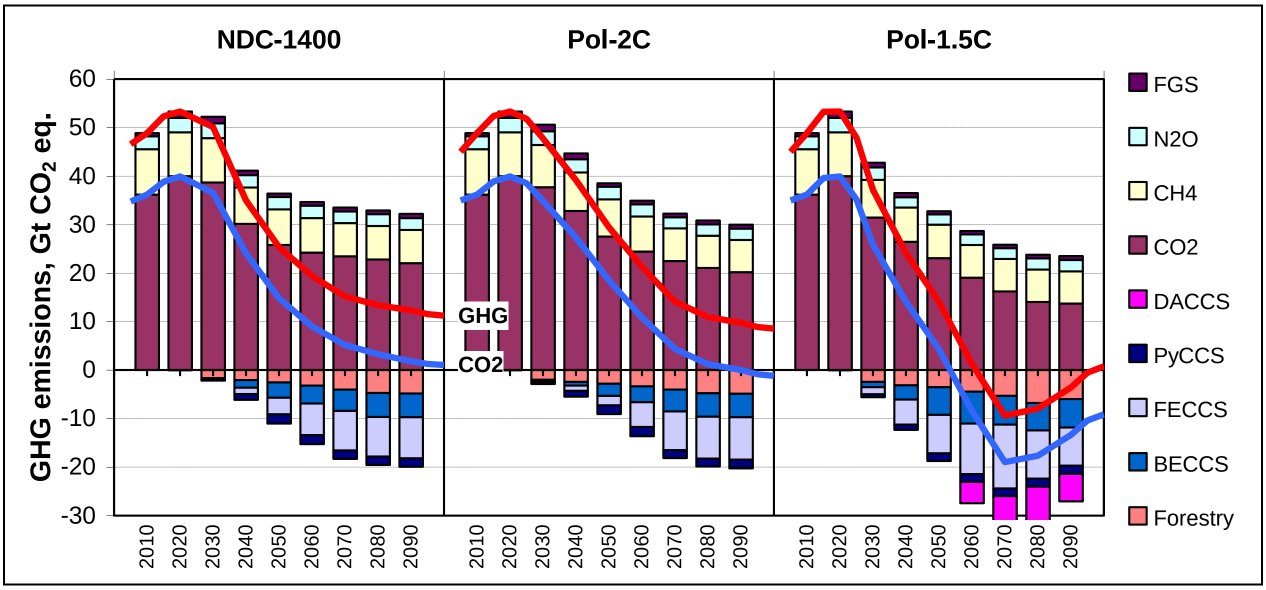

Figure 4. Development of greenhouse gas emissions (Kyoto gases) in the scenario variants. The red and blue lines represent the total net emissions of GHGs and CO_2, respectively, and the vertical bars show the gross emissions (positive) and removals (negative) either from flue gases or the atmosphere (BECCS = bioenergy with CCS, FECCS= fossil energy with CCS).

and PyCCS both become competitive in all three cases. The results indicate that PyCCS has improved comparative advantage when the competing energy uses of biomass remain at lower levels. This is shown by the larger deployment of PyCCS in the Pol-2C scenario compared to the Pol-1.5C scenario and is explained by the limited sustainable biomass potentials that make the value of the energy produced with BECCS high enough to be more widely preferred over PyCCS until 2060. But overall, PyCCS gets deployed roughly at the maximum scale assumed realistic in both cases after 2070, which amounts to about 1.7 Gt(CO_2)/a. As a side-benefit, according to the modeling assumptions, it also brings about significant reduction in the N_2O emissions from agricultural lands (at maximum, about 0.5 Gt(CO_2 eq.)/a).

Concerning BECCS applications, the total negative emissions amount to at most 6.6 Gt/a in the Pol-1.5C scenario. According to the Pol-2C scenario results, power plants (including CHP) would account for about 30–50% of the captured amount globally, while other energy conversion technologies cover the rest. However, in the 1.5C scenario, the power plant share increases to 60–70%. In both cases, the power plant share is at its lowest before 2050, and then increases over time. As mentioned above, DACCS appears only in the Pol-1.5C case, where it reaches deployment levels of 4–9 Gt/a during 2060–2100.

4.3 Demands of selected metals for selected technologies

The total cumulative net demand for the metals included in the energy systems modeling is presented in Table 4 for the 2C and 1.5C policy scenarios. The cumulative values represent only the modeled demands related to clean energy transition, and not all uses. Due to the similar ambition levels, the demands in the NDC scenario have been omitted but were close to those in the 2C scenario. According to the results, out of the selected metals considered, in terms of sufficiency the most critical appear to become cobalt, dysprosium and neodymium. The projected cumulative primary cobalt use would be 27–28 Mt, exceeding the identified resources. For dysprosium, the projected primary metal requirements correspond to 80% of the identified resources, and for neodymium they correspond to almost 60%. Moreover, even though the modeled cumulative consumption of copper remains below 40% of the identified resources, one should point out that copper has significant other uses that were left out of the

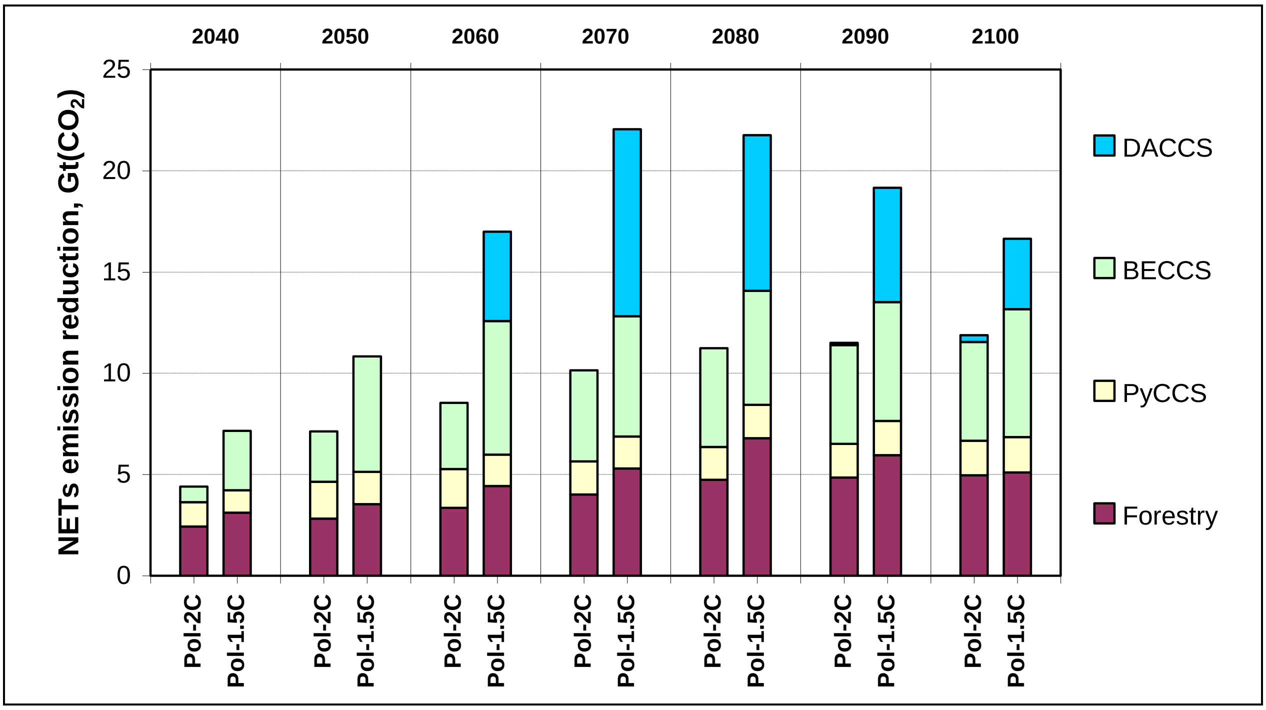

Figure 5. Contribution of NETs to the emission reductions in the experimental climate policy scenarios.

Table 4. Summary of the modelled cumulative net demand for primary production of metals.

		Identified	Modeled cumulative primary metal use by 2100			
Metal	**Unit**	**Resources**	**2C**	**%**	**1.5C**	**%**
Ag	kt	600	140	23%	160	27%
Co	kt	25000	27200	109%	28100	112%
Cu	Mt	2100	680	32%	720	34%
Dy	kt	1500	1160	77%	1190	79%
Li	kt	89000	37000	42%	38200	43%
Mn	Mt	17000	120	1%	130	1%
Nd	kt	11200	6300	56%	6400	57%
Ni	Mt	300	80	27%	80	27%

estimation, including electricity transmission networks that have been projected to create significant additional demand for copper, e.g., by the IEA (2021b). Some more detailed discussion is given below.

4.3.1 Cobalt

Cobalt (Co) has significant uses in lithium-ion and other types of batteries, the manufacture of magnetic, wear-resistant and high-strength alloys, for electroplating, and in chemical industries as catalysts and as drying agents for paints and inks.

Primary cobalt is obtained mainly as a by-product from the mining of nickel, silver, lead, copper and iron. According to USGS (2022), the current annual global mine production of cobalt is about 140,000 tonnes and the identified resources are 25 Mt. The modeled cumulative primary cobalt consumption due to energy technologies already exceeds that amount of 25 Mt, of which most would be attributable to batteries, primarily in electric vehicles but to some extent also in stationary battery systems. However, one should note that some sources estimate significant reduction in the cobalt requirements of new battery chemistry options by 2050. On the other hand, one should also point out that the consumption of metals in other than light duty cars may well be underestimated in the current modeling experiment.

4.3.2 Copper

Copper is used for various applications within all sectors of the economy. The current annual total copper demand is about 29 Mt, annual extraction is about 21 Mt and the identified terrestrial resources amount to 2100 Mt, translating into an R/E ratio of 100 years. About 26% is currently consumed by building construction, about 15% into infrastructure (including electricity transmission), about 13% into transportation vehicles, and the remaining 46% into various industrial and consumer equipment.

Table 5. Proportions of each metal consumed by main groups of energy technology.

	Ag	Co	Cu	Dy	Li	Mn	Nd	Ni
Cars		97.5%	57.1%	95.2%	98.2%	86.8%	91.9%	89.2%
Wind			2.9%	4.8%		6.6%	8.1%	4.3%
Solar	93.7%		39.0%					
PP CCS		0.1%	0.4%			5.8%		1.3%
Other power plants	6.3%	0.1%	0.4%			0.8%		4.7%
Fuel refining		0.2%						
Stationary batteries		2.2%	0.2%		1.8%			0.5%
Total	100%	100%	100%	100%	100%	100%	100%	100%

In the modeling experiment, the modeled cumulative net primary copper consumption (after recycling) was 680 Mt in the 2C scenario and 720 Mt in the 1.5C scenario. Most significant proportions of the modeled copper use are attributable to road vehicles, especially electric cars, and solar power systems, of which a large part would be genuinely additional consumption. Moreover, one should note that the expanding power generation with large amounts of distributed generation would require remarkable additional investments also into transmission networks requiring most likely much more copper than currently. The IEA has estimated that the annual copper consumption for transmission networks would increase to 10 Mt by 2040 (IEA 2021b). By extrapolating this projection to 2100, one may estimate the cumulative consumption at around 1400 Mt during 2020–2100, which would cause significant additional demand of primary copper even with high recycling rates.

On the basis of these results, the sufficiency of primary copper resources may indeed become somewhat critical during the current century, and substantial efforts to further improve the recycling rates would appear justified.

4.3.3 Dysprosium

Dysprosium (Dy) is mainly used for permanent neodymium magnets, which are used especially in wind power plants and electric motors (e.g., road vehicles). The current annual demand for dysprosium is about 2,000 metric tonnes, and the identified resources have been estimated at 1500 kt, which translates into a reasonably high R/E ratio of over 700 years. However, the demand is projected to increase quite rapidly, and the results suggest that by 2100 the cumulative primary metal use in the applications modeled might account for 80% of the identified resources.

Until recently, the recycling rates of most rare earth metals have been very low. According to a UNEP report (UNEP 2011), the end-of-life recycling rate of dysprosium was estimated at 1% or below. The low rates are mainly due to the low content of the metal in the recycled products, which may make the recycling process costly. In the modelling experiment, the results on primary metal requirements were obtained assuming steadily increasing recycling rates reaching 50% in 2100, the same level as for neodymium. Therefore, the results clearly indicate that dysprosium may be among the most critical metals in terms of resource sufficiency and need for enhanced recycling.

4.3.4 Lithium

Currently the main uses of lithium (Li) are batteries (about 50%), ceramics and glass (about 25%) and various other industrial applications (about 25%). Total annual extraction amounts to about 80 kt/a, and the global identified resources are about 89 Mt (USGS 2022). With these estimates, the R/E ratio would be 1100 years, which appears quite high. However, in the scenarios modeled, the modeled cumulative primary metal use alone would increase to over 40% of the identified resources. Nonetheless, assuming that the demands excluded from the modeling would not increase significantly, the resource sufficiency may be considered adequate, bearing in mind that there are large other unaccounted resources of lithium e.g., in seawater. Recently, researchers have indeed developed promising new methods for the extraction of lithium from seawater.

4.3.5 Manganese

Manganese (Mn) is currently used in significant amounts e.g., in many steel and aluminium alloys, and in glass making. Although considered an interesting mineral with respect to clean energy transition, the modelling experiment did not indicate any resource sufficiency issues regarding manganese. The modelled cumulative primary metal use was only about 1% of the identified resources.

4.3.6 Neodymium

Like dysprosium, neodymium (Nd) is mainly used for permanent neodymium magnets, but also to smaller extent in metallurgical, ceramics and other industries. Therefore, unlike with dysprosium, one should bear in mind also the demand in those other sectors when considering resource sufficiency.

The total demand for neodymium is currently about 30 kt/a and the identified resources are estimated at 11,200 kt, giving a R/E ratio of about 400 years. However, the modeling suggests a rapidly increasing demand in electric motor and wind power applications, such that the modeled cumulative primary metal use would amount to nearly 60% of the identified resources, assuming EoL recycling rate increasing to 50% by 2100. The results thus suggest that sufficient recycling systems will be of high importance also for the sustainable use of neodymium.

4.3.7 Nickel

Nickel is used in significant amounts in stainless steel and other alloys for making them stronger and withstanding extreme temperatures and to avoid corrosion. Moreover, it has considerable uses in plating and battery chemistry applications.

The total identified resources of nickel are estimated at about 300 Mt, while the current primary extraction is about 2.3 Mt/a, giving a relatively low R/E ratio of 130 years. However, assuming that nickel recycling can still be enhanced from the current levels, the modeling experiment did not indicate significant criticality in the sufficiency of nickel, when also considering the extensive resources not counted in the identified resource base.

4.3.8 Silver

Silver is a precious metal, and it is used for jewelry, silverware, coins and bars. Industrial applications are, however, increasingly significant, including photography, electrical and electronic industries. Among energy technologies, solar power systems have gained a notable role in the total consumption of silver.

According to the USGS, the current global silver reserves are about 530,000 tonnes, while the annual mine production is about 24,000 (2021). That would mean exhaustion of the global reserves in 22 years assuming just the current level of mining. The total resources are larger, but according to an URR analysis (Sverdrup et al. 2014), the remaining recoverable silver resources are not significantly higher, but only about 1 million tonnes. That would translate into the exhaustion of the global silver resources within the current century, with peak primary production estimated to occur already by 2040.

The modeling results indicate that transition to carbon neutrality would create additional demand for silver about 200 kt by 2100, and slightly less under the 2°C scenario. Most of the additional demand comes from the installation of new PV systems, for which the model projects extremely high growth rates. One should also note that, as shown above, the specific silver consumption of PV systems is projected to reduce significantly by 2050, and these reducing specific metal requirements have been taken into account in the modeling.

Bearing in mind that most of the current silver demand is not related to energy technologies, and that main part of the demand can be assumed reasonably stable, the additional demand would inevitably cause accelerated exhaustion of the remaining silver resources and some additional pressure on maximizing the recycling rates.

4.4 Impact of NETs on the use of the selected metals

As explained in the previous chapters, we were able to model the requirements of the selected metals for most BECCS technology options, by using the data from literature on the direct material intensities for bioenergy and CCS power plants, as well as for FT processes. On the other hand, for afforestation, PyCCS and DACCS we could not find corresponding estimates. Nonetheless, the indirect impact of any DACCS operation on the use of those metals, through its electricity consumption, was of course automatically included in the modeling results. The results for the cumulative direct consumption values shown in Table 4 indicate that the deployment of BECCS even on a large scale does not impose significant burden on the sustainability of using metals, as the direct impacts were found proportionally quite small. Indirect impacts on material use due to the feedstock use may also be estimated rather small. However, concerning DACCS the indirect impacts are indeed significant. According to the results of the 1.5°C case, the cumulative global power consumption of the DACCS plants amounted to 7.5% in proportion to the cumulative global net power generation, and therefore, the indirect impact on the cumulative metals consumption may be estimated as being of that same proportion of the total power sector consumption. At their peak around 2070, the DACCS plants consumed about 15% of the global electricity in the 1.5°C case, which is quite remarkable.

Moreover, we did an interesting sensitivity analysis, where we removed DACCS from the technology options for climate change mitigation, such that it was not available for reducing the global net GHG emissions in the Pol-1.5°C scenario, while at the same time limiting the deployment of BECCS to the scale in the original results of the scenario. The motivation for this sensitivity analysis was to get better estimates for the impact of the DACCS option on the cumulative metal requirements under that stricter climate change mitigation scenario. According to the results, the cumulative metal requirements of the energy sector all increased by 3–60% by 2100 when the DACCS options were not available. In other words, the additional metals requirements in fact remained smaller by those differences when DACCS was assumed available. When DACCS was not available, the increases were largest in the cobalt and lithium uses, mainly due to the increased needs for stationary electricity storage systems, but also the added consumption of dysprosium, neodymium and nickel were significant, between 7% and 18%. These combined results on the indirect impacts suggest that DACCS may actually perform reasonably well with respect to sustainable material use, in comparative terms. However, a thorough and credible sustainability analysis would require more comprehensive data both on the direct and indirect material use, and land use impacts.

5 Key findings and policy relevant messages

Based on the study, long-term climate change mitigation efforts as outlined in recent assessments may be threatened by the availability of non-renewable metals and minerals, required by the key technologies needed globally. For the study, literature on material demand and metal intensities of low-carbon technologies and NETPs was explored, and the data availability allowed inclusion of impacts of BECCS, PyCCS, and DACCS to different extents as novel NETs elements in the scenario analyses. Importantly, the results demonstrate that raw material issues are not only driven by NETPs but strongly by material needs of clean energy transition more generally, including rollout of electric vehicles and different renewable energy technologies. Specifically, the overall results suggest that availability may become an issue with cobalt and dysprosium, which are used in batteries and wind power plants respectably. In addition, due to the demands of copper and silver in several energy and other applications, the supply of these metals might constrain the future investments on clean energy technologies and infrastructures. The resources per extraction (R/E) numbers shown in Table 2 indicate the potential constraints of these metal supplies. Hence, the raw material availability adds up an extra layer of constraints and uncertainties in addition to environmental, economic and social barriers for the large-scale NETP deployment studied in other Work Packages and tasks of the NEGEM project.

Findings of the study indicate a lack of data with mineral needs of several key NETs and there are also many open questions with the data that may have an impact on the demand of metals. As an example, we did not find any information of the metal needs for DACCS or BECCS. For the latter, we therefore used the data on CCS and bioenergy production. On the other hand, the estimate of cobalt demand with CCS is based on a relatively old study, and the length of CO_2 pipelines needed calls for more thorough assessments. These cases underline the need for further research to be able to create reliable low-carbon scenarios building on NETPs, as well as policy roadmaps and action plans connected to them.

6 Conclusions and further steps

In this report, we have made assessments of demands non-renewable metals and minerals in the clean energy transition. Our focus was on metal and mineral demands of NETs, e.g., BECCS, DACCS and PyCCS, which have not been considered in reported mitigation scenarios focusing on mineral demands (IEA, 2021, IRENA 2022, World Bank, 2020). However, it should be noted that in this study, we did not focus on negative emissions practices (NEPs), like afforestration and deforestration, and the data on NEPs are based on our earlier studies (Lehtilä & Koljonen 2018). Therefore, the next steps in TIMES-VTT scenario modelling in WP8 would look at NEPs in more detail based on recent literature, the results of other WPs in NEGEM and also based on collaboration with H2020 sister project LANDMARC (Land Use Based Mitigation for Resilient Climate Pathways)[5]. In TIMES-VTT modelling we have not included ocean based negative emissions technologies and practised in our modelling either. Thus, the next steps in WP8 and related TIMES-VTT modelling also include analysis on these technologies and practises, where we are also collaborating with another H2020 sister project OceanNETs (Ocean-based negative emissions technologies[6]).

The World Bank (2020) claims that due to the lack of large-scale operating CCS plants, estimating the future mineral demand of CCS is difficult. This then accounts for both BECCS and PyCCS. However, the following minerals have been identified as key minerals related to CCS technology: chromium, cobalt, copper, manganese, molybdenum, and nickel. Comparing with the other technologies, like electric vehicles, solar technologies and wind power, the mineral demand of CCS can be considered low, but this need further analysis before any final conclusions can be drawn. As an example, in our assessments cobalt and lithium demands of electric vehicles was about 98 % of full energy sector demands of these metals and silver demand of solar technologies was about 94 % respectively. It should also be noted that studies where CCS is covered use Moss et al. (2011) as a reference for the mineral intensities (e.g., Watari et al. 2019, The World Bank 2020 and The World Bank 2017). Related to NETs such as DACC, Realmonte et al. (2019) calls out for an assessment, where the mineral demand, among other factors such a process-scale data, of DACC facilities are covered in detail.

IAM scenario assessments with TIMES-VTT model will be elaborated further with more detailed focus on modelling realistic potentials of NETPs by using the results and findings of the other WPs. As highlighted in the report, this assessment did not focus on land-use practices, which increases the uncertainties of the assessments shown in this report. In case the modelled techno-economical potentials of land-use

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[5] Information on LANDMARC can be found from https://www.landmarc2020.eu/

[6] Information on OceanNETs can be found from https://www.oceannets.eu/

practices are too low in our results, the assessed demands of metals and minerals can be too high. On the other hand, in case our assessments are too optimistic for deforestration, reforestration and afforestration, more investments are needed for NETs and other clean energy technologies, which will again increase the metal demands.

The results for the cumulative direct consumption values of metals under consideration indicate that the deployment of BECCS even on a large scale does not impose significant additional use of metals, as the direct impacts were found proportionally quite small. In addition, indirect impacts on material use due to the feedstock use may also be estimated rather small. However, concerning DACCS the indirect impacts on metals use are indeed significant due to high increase in global power demand. On the other hand, our results also showed that limiting the BECCS investments and removing DACCS from the NET portfolio, increased the cumulative metal requirements of the energy sector. This is a good example about the level of uncertainties, when we are looking at integrated assessments with metals and minerals.

In this study, we did not conduct an in depth literature review on the metal supply, including the most recent estimates of reserves and resources of metals and minerals. In addition, we should make better analysis on expansion of current metal production capacities and development of metal reserves, which would better indicate the challenging dynamics of the supply side. As an example, opening a new mine could take decades after identified and explored reserves (or resources) are in production. Therefore, the data shown for the metal resources as well as the percentage of their cumulative use should be considered as indicative because there could be several constraints for opening new mines.

Considering the demands of virgin metals and minerals, many factors can influence the future material demands. There is very limited information on the metal demands of other than energy sectors, which should be taken into account in the scenario assessments and the analysis shown in this report. On the other hand, there is large potential for recycling of metals compared with the current levels, but we were not able to find much literature on that. Maybe the most important uncertainty is related to the long-term development of energy (and other) technologies as new technologies may consume smaller amounts of critical metals or these might be substituted with some other, less critical metals.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D1.4.	Comprehensive sustainability assessment of Bio-CCS NETPs	VTT	Report	Public	M12
D4.2	Bio-geophysics database	ICL	Other	Public	M15
D8.1	Stocktaking of scenarios with negative emission technologies and practices - Documentation of the vision making process and initial NEGEM vision	VTT	Report	Public	M8

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Appendix A - Mineral intensities of clean energy transition technologies

Wind power

The main components of wind turbines including the tower, nacelle and rotor are mainly made of steel. Steel is a mix of iron and different minor and base metals such as nickel, molybdenum, manganese and chromium. Concrete is also an essential material in wind energy as it is used in the foundations of a wind power plant. Aluminium is utilized in lightweight components such as the turbine tower and nacelle and it is also applied in cabling. Zinc is used in wind turbine coatings to protect them against corrosion. Polymers and composite materials are utilized in the blades, nacelle and hub covers. (Carrara et al. 2020, IEA 2021b)

The turbine type has an impact on the mineral intensity of the wind power plant. Wind power plants can be divided into two main categories: geared and direct-drive designs. The geared wind turbine designs use a gearbox to increase the low rotational speed of the turbine rotor to a higher speed to feed the electrical generator. In the direct-drive designs, the rotor is connected directly to the generator and therefore they turn with the same speed. Turbine designs with a gearbox have higher maintenance needs, and therefore they are used in onshore installations. On the contrary, direct-drive turbines have lower maintenance needs and are hence preferred in offshore applications. (The World Bank 2020)

Wind turbines with a gearbox can be spilt into designs that contain a permanent magnet (gearbox permanent-magnet synchronous generator, GB-PMSG) or a double-fed induction generator (gearbox double-fed induction generator, GB-DFIG). In direct-drive designs, a generator with permanent magnet (direct-drive permanent-magnet synchronous generator, DD-PMSG) or electrically excited generators (direct-drive electrically excited synchronous generator, DD-EESG) can be applied. Turbine designs with permanent magnets require larger amounts of rare earth minerals such as neodymium and dysprosium. Rare earth elements are also present in the turbine types which do not have permanent magnets since besides permanent magnets, rare earth elements are also used in attaching internal figures in the turbine tower (Carrara et al. 2020).

A future direct drive wind turbine option based on high-temperature super conductors (HTS) would reduce the need of rare earth elements and weight of the turbines (Månberger & Stenqvist 2018). However, as the HTS turbines are still under early research, they are not included in this study.

There are also differences between the required materials between onshore and offshore wind applications. For instance, copper and lead demands are higher in offshore applications due to larger cabling needs for electricity transmission. Also, the foundations of offshore turbines require more materials, primarily steel. (Carrara et al. 2020, The World Bank 2022)

The future raw material demand of wind turbines is dependent on which sub-technologies are most widely deployed. Currently the most widely deployed wind technology is the gearbox double-fed induction generator (GB-DFIG) design which is favourable for onshore applications (The World Bank 2020). In the future, the share of offshore wind installations is projected to increase, which is expected to increase the share of direct-drive applications (The World Bank 2020).

Difficulties in making long-term projections of the future mix of wind technologies has been expressed by many studies (Carrara et al. 2020, IEA 2021b). In this report, the assumptions of the market share projections for capacity additions are formulated based on IEA (2021b) and are presented in Table A1 and Table A2. In short, IEA (2021b) estimates that permanent magnet technologies will greatly increase their market share in the future as they enable lighter and more efficient designs as well as lower maintenance costs.

Table A1 Wind turbine market shares for capacity additions in onshore applications. Assumptions based on IEA (2021).

	GB-DFIG	GB-PMSG	DD-PMSG	DD-EESG
2020	72 %	5 %	18 %	5 %
2030	75 %	5 %	15 %	5 %
2040	70 %	10 %	15 %	5 %
2050	70 %	10 %	15 %	5 %

Table A2 Wind turbine market shares for capacity addition in offshore installations. Assumptions based on IEA (2021).

	GB-DFIG	GB-PMSG	DD-PMSG
2020	6 %	24 %	70 %
2030	0 %	16 %	84 %
2040	0 %	13 %	87 %
2050	0 %	13 %	87 %

The dataset used in this study on mineral usage per unit of installed capacity for wind power technologies is derived from Carrara et. al (2020) and is presented in Table A3. The Table summarises mineral intensity data for the four main wind turbine types introduced before: 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).

Changes in mineral intensities in wind turbines are expected to occur in the future. To estimate the future mineral intensities, Carrara et al. (2020) has divided the materials present in a wind turbine to structural materials (aluminium, chromium, copper, iron, manganese, molybdenum, nickel and zinc) and technology-specific materials (boron, dysprosium, neodymium, praseodymium and terbium). In the baseline scenario of the study, Carrara et al. (2020) estimates, that for the structural materials, the values in 2050 will correspond to 90% of the present mineral intensities given in the study. For the technology-specific materials, an estimated annual 2% reduction is applied. Therefore, for the technology-specific materials, the resulting mineral intensity is approximately half of the current value in 2050. These projections of the mineral intensity improvements in wind energy are also applied in this study.

Table A3 Mineral intensities (t/GW) for different wind turbine types. Source: Carrara et al. (2020).

t/GW	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG
Aluminium (Al)	700	500	1 600	1 400
Boron (B)	0	6	1	0
Chromium (Cr)	525	525	580	470
Copper (Cu)	5 000	3 000	950	1 400
Manganese (Mn)	790	790	800	780
Molybdenum (Mo)	109	109	119	99
Nickel (Ni)	340	240	440	430
Zinc (Zn)	5 500	5 500	5 500	5 500
Rare earths total	44	239	62	14
Dysprosium (Dy)	6	17	6	2
Neodymium (Nd)	28	180	51	12
Praseodymium (Pr)	9	35	4	0
Terbium (Tb)	1	7	1	0

Solar photovoltaics (PV)

A solar PV system composes of different components including modules, inverters, trackers, mounting structures and electrical components (IEA 2021b). The differences in mineral intensities in solar PV system are mainly based on the solar PV technology applied. The four most commonly applied solar PV technologies are crystalline silicon (c-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) technologies. Crystalline silicon modules can be divided into single-crystalline and multi-crystalline cells, however no distinction between these two are made in this study. As of today, crystalline silicon (c-Si) cells dominate the solar PV market and in 2020, c-Si cells supplied 95% of the global annual solar PV production (ISE 2022).

The three latter solar PV technologies (CdTe, CIGS and a-Si) are grouped to “thin film technologies”, which are made of thinner cells in comparison to crystalline silicon cells. The thin film technologies can reduce the material and manufacturing costs of the cells and increase the flexibility of their use (The World Bank, 2020). Also, the materials used in thin-film technologies can absorb light more efficiently in comparison to the silicon-based wafers (Carrara et al. 2020). In 2020, the thin-films technologies covered 5.0% of the annual solar PV production and the share of CdTe, CIGS and a-Si technologies in the total annual PV production were 4.0%, 0.9% and 0.1%, respectively (ISE 2022). Other emerging and innovative solar PV technologies are also under development. However, as it is unlikely that these technologies will dominate the solar PV market in the near-term future (Carrara et al. 2020) they are not included in this study.

Mineral intensity values of different solar PV technologies are presented in Table A4. In Carrara et al. (2020), the materials used in solar PV technologies are divided into two main groups; the non-cell general materials and materials that are used to manufacture the solar cells. The demand for non-cell general materials is common for all PV sub-technologies and include materials that are used in the structural and electric parts of the PV systems such as concrete, steel, plastic, glass, aluminium and copper. Copper and steel are used in the support structures, aluminium is used e.g., in module frames and copper is used e.g., in cabling and PV cell ribbons. Carrara et al. (2020) expects only minor innovations towards the mineral intensity of these components and therefore in 2050, the baseline scenario of Carrara et al. (2020) estimates, that the mineral intensity is 90% of the current mineral intensity value. In relation to the specific materials used in solar cells, Carrara et al. (2020) has conducted a more detailed intensity improvement assumptions presented in Table A5. The mineral intensity improvement assumptions from Carrara et al. (2020) for both structural and specific materials are applied in this study.

Table A4 Mineral intensities for solar PV technologies. Source: Carrara et al. (2020).

t/GW	c-Si	CdTe	CIGS	a-Si
Aluminium (Al)	7500	7500	7500	7500
Cadmium (Cd)		50		
Copper (Cu)	4600	4600	4622	4600
Gallium (Ga)			4	
Germanium (Ge)				48
Indium (In)			15	
Selenium (Se)			35	
Silicon (Si)	4000			150
Silver (Ag)	20			
Tellurium (Te)		52		

Table A5 Mineral intensity improvement assumptions by Carrara et al. (2020).

	t/GW	Present	2030	2050
All	Aluminium (Al)	7 500	7 200	6 800
	Copper (Cu)	4 600	4 500	4 200
c-Si	Silicon (Si)	4000	2750	2000
	Silver (Ag)	20	6	2
CdTe	Cadmium (Cd)	50	27	12
	Tellurium (Te)	52	27	15
CIGS	Copper (Cu)	22	15	10.5
	Indium (In)	15	10	6
	Gallium (Ga)	4	2.5	1.5
	Selenium (Se)	35	20	12
a-Si	Silicon (Si)	150	100	75
	Germanium (Ge)	48	27	15

Similar to wind power, the future mineral demand for solar PV technologies is dependent of the future mix of different solar PV sub-technologies. Due decreased costs and improved efficiencies IEA (2021) projects that c-Si technologies will continue to dominate the solar PV markets and the thin-film technologies will remain as a niche, although cost improvements and efficiency gains can also be expected there. IEA (2021) estimates that the use of thin-film technologies will focus on applications that require flexibility, such as building applications. In Carrara et al. (2020), the market share projections based on observed trends result in a similar outcome. The study estimates that c-Si technologies will continue to dominate the solar PV market and that the market share of thin-films will grow linearly until their market share reaches 10% in 2050. In the thin-film mix, the shares of CdTe, CIGS and a-Si are 4.5%, 4.5 % and 1%, respectively.

The assumptions of the market share projections for capacity additions in this study are formulated based on the current market share data from Fraunhofer Institute (ISE 2022) and projections of Carrara et al. (2020) and IEA (2021) and are presented in Table A6.

Table A6 PV market shares for capacity additions. Assumptions based on Fraunhofer Institute (ISE, 2022), Carrara et al. (2020) and IEA (2021).

	c-Si	CdTe	CIGS	a-Si
2020	95 %	4 %	0.9 %	0.1 %
2030	93.3 %	4.2 %	2.1 %	0.4 %
2040	91.6 %	4.3 %	3.3 %	0.7 %
2050	90 %	4.5 %	4.5 %	1 %

Concentrated solar power (CSP)

The main operating principle of concentrating solar power (CSP) is that the heat of the sun is concentrated to a central receiver with mirrors to heat water or another heat-exchange fluid to drive steam turbines. An important advantage of CSP in comparison to solar PV is that CSP can store energy by using molten salts to store heat for later release. CSP technology has geographic constraints, as it requires great direct normal irradiation for cost-effective operation. Two types of CSP technologies account for most of the installed and planned additions: parabolic troughs and central towers (The World Bank 2020, IEA 2021b).

Several studies have highlighted the role of silver in CSP technology (The World Bank 2017, Grandell et al. 2016, Moss et al. 2011). Silver is applied on the surface of the mirrors as it has the highest reflectivity of all elements, however its demand depends on the sub-technology applied (Grandell et al. 2016). Bulk materials such as aluminium and steel are needed for the support structures of the mirrors whereas copper is used e.g., in wiring (The World Bank 2020).

IEA (2021) estimates, that the central tower sub-technology will be the most widely used CSP technology in the future. Mineral demand values for CSP are obtained from a dataset compiled by Watari et al. (2019), which includes a mineral intensity assessment for the central tower technology. The mineral intensity data for CSP in presented in Table A7.

Table A7 Mineral intensity in CSP. Source: Watari et al. (2019).

Mineral	t/GW
Aluminium (Al)	72 967
Chromium (Cr)	3 700
Copper (Cu)	1 400
Magnesium (Mg)	2 600
Manganese (Mn)	5 700
Molybdenum (Mo)	56
Nickel (Ni)	1 800
Niobium (Nb)	140
Silver (Ag)	12
Vanadium (V)	2
Zinc (Zn)	1 400

Geothermal

Geothermal energy requires great amounts of high-quality steels to be able to tolerate high temperature and pressure. The steel alloys also need to be corrosion resistant. The demand of these minerals depends on the plant, as the demand is based on for instance on the number and depth of the wells. (The World Bank 2020)

To tolerate the difficult operating environment, the steel needed is high in chromium, molybdenum, nickel and titanium (IEA 2021b). The mineral demand for geothermal energy generation is evaluated by Moss et al. (2011) which has created average mineral demand for three geothermal plants: a 50 MW plant with 25 wells of 5 km in depth, a 10 MW plant with 5 wells of 1.5 km in depth and a 48.8 MW plant with 22 wells of 2.5 km in depth. The mineral intensity data for geothermal is presented in Table A8.

Table A8 Mineral intensity for geothermal plant. Source: Moss et al. (2011).

Mineral	t/GW
Copper (Cu)	3 605
Chromium (Cr)	64 405
Manganese (Mn)	4 325
Molybdenum (Mo)	7 209
Nickel (Ni)	120 155
Niobium (Nb)	128
Tantalum (Ta)	64
Titanium (Ti)	1 634

Hydropower

Hydropower has rather low mineral intensity when compared to other low-carbon power generation technologies, although hydropower requires extensive amounts of cement and concrete (IEA 2021b). No rare earth elements are needed in hydropower. Due to modest growth related to hydropower and relatively low mineral intensity, no significant mineral supply constraints for hydropower are expected (IEA 2021b). The mineral intensity data for hydropower is presented in Table A9.

Table A9 Mineral intensity for hydropower. Source: Ashby (2013).

Mineral	t/GW
Aluminium (Al)	3400
Chromium (Cr)	1500
Copper (Cu)	1050
Lead (Pb)	300
Magnesium (Mg)	100
Manganese (Mn)	200
Molybdenum (Mo)	250
Zinc (Zn)	400

Biomass-based combustion and biofuels

Mineral demand and the scale of equipment in biomass boilers are similar to those of fossil fuel combustion (e.g., coal and gas-fired power plants) boilers and hence no mineral and metal supply issues are expected for bioenergy production (IEA 2021b, Moss et al. 2011). The mineral intensity data biomass-based combustion is presented in Table A10. The unit is t/GW of power production capacity.

Table A10 Mineral intensity for biomass-based combustion. The unit is t/GW of power capacity. Source: Ashby (2013).

Mineral	t/GW
Aluminium (Al)	3900
Chromium (Cr)	2.4
Cobalt (Co)	1.8
Copper (Cu)	2270
Lead (Pb)	104
Nickel (Ni)	20
Titanium (Ti)	400
Zinc (Zn)	160

In relation to mineral demand in biofuels production, the mineral demand for catalysts needed for Fischer-Tropsch process to is brought up by Moss et al. (2011) and Grandell (2014). Catalysts used in biofuel production can be reused and regenerated. The most common catalysts used for F-T process are based on cobalt, iron and ruthenium. According to Grandell (2014), the cobalt-based catalyst is most common in commercial F-T plants. Moss et al. (2011) has evaluated the metal requirement for a Co-based F-T catalyst to be 6 kg of cobalt and 0.12 kg of ruthenium for one Mtoe of produced biofuel with the catalyst lifetime of 10 years (Table A11).

Table A11 Mineral intensity for F-T catalyst. The unit is kg per Mtoe of biofuel produced. Source: Moss et al. (2011).

Mineral	kg/Mtoe
Cobalt (Co)	6
Ruthenium (Ru)	0.12

Solid and gaseous fossil fuel combustion

Metals and scale of equipment in fossil fuel combustion are similar to biomass-based combustion (IEA 2021b, Moss et al. 2011). The mineral intensity data for coal and gas-fired conventional combustion is derived from Ashby (2013) and Moss et al. (2013), respectively. The mineral intensity data for coal and gas-fired conventional combustion can be seen in Table A12 and Table A13.

Table A12 Mineral intensity in coal-based combustion. The unit is t/GW of power capacity. Source: Ashby (2013).

Mineral	t/GW
Aluminium (Al)	3540
Chromium (Cr)	2765
Copper (Cu)	3320
Iron (Fe)	429600
Lead (Pb)	135
Manganese (Mn)	84
Molybdenum (Mo)	32
Nickel (Ni)	10
Silver (Ag)	4
Vanadium (V)	3
Zinc (Zn)	70

Table A13 Mineral intensity in gas-fired combustion. The unit is t/GW of power capacity. Source: Moss et al. (2013).

Mineral	t/GW
Aluminium (Al)	1 100
Chromium (Cr)	2.44
Cobalt (Co)	1.80
Copper (Cu)	1 100
Nickel (Ni)	15.75

Nuclear power

Mineral intensity data for nuclear power plants is compiled by Moss et al. (2011) for light water reactors, which is the dominant technology in the nuclear fleet. Light water reactors include both boiling water reactors and pressurised water reactors. Uranium is excluded from the analysis. IEA (2021) expects pressurised-water reactors to be the dominant choice for future expansions and hence does not foresee drastic reductions in the mineral intensity of nuclear power as the technology is mature. However, the mineral intensity data for small modular reactors or more advanced reactors can be different, but the data related to these technologies is scarce (IEA 2021b). The mineral intensity data for nuclear power plants is presented in Table A14.

Table A14 Mineral intensity in nuclear power plants. Source: Moss et al. (2011).

Mineral	t/GW
Cadmium (Cd)	0.5
Chromium (Cr)	426.7
Copper (Cu)	59.6
Hafnium (Hf)	0.48
Indium (In)	1.6
Lead (Pb)	4.3
Molybdenum (Mo)	70.8
Nickel (Ni)	255.5
Niobium (Nb)	2
Silver (Ag)	8.3
Tin (Sn)	4.6
Titaniun (Ti)	1.5
Tungsten (W)	5
Vanadium (V)	0.6
Yttrium (Y)	0.5
Zirconium (Zr)	30.5

EV batteries

Battery is an essential element of an electric vehicle. The energy consumption per kilometre in today's electric vehicles varies from 100 Wh/km to 300 Wh/km (Electric Vehicle Database 2022a) and the battery capacity spans from 17 kWh to 118 kWh with the average capacity of the battery being around 60 kWh (Electric Vehicle Database 2022b). The weight of the battery is 7-10 kg per kWh and the weight is expected to decline below 5 kg/kWh in the near future (Gielen 2021).

Battery cell is the smallest element of a lithium-ion battery that is used in electric vehicles and also as an energy storage. The battery cell contains an anode (most commonly graphite), a cathode (e.g., lithium, nickel, cobalt, manganese), current collector and an electrolyte between the anode and cathode. The battery cells are installed in battery modules and packs that form the battery. The battery chemistry is flexible to some extent and the cathode chemistry is often used to categorize the batteries. For example, NMC battery contains lithium, nickel, manganese and cobalt and NCA battery contains lithium, nickel, cobalt and aluminum. Besides battery chemistry, the shares of the minerals present in the anode can vary as well. (IEA 2021b, Gielen 2021)

Gielen (2021) introduced a typical battery pack composition adapted from Volkswagen (2021). The same reference is adapted in this study to estimate the mineral demand of a typical lithium-ion battery that can be used in electric vehicles and as an energy storage. The mineral intensity (kg/kWh) of a lithium-ion battery is presented in Table A15. We assume here that the battery capacity is 60 kWh.

Table A15 Mineral intensity for an li-ion battery. Adapted from Volkswagen (2021).

Mineral	kg/kWh
Aluminium (Al)	2.15
Cobalt (Co)	0.2
Copper (Cu)	0.4
Lithium (Li)	0.1
Manganese (Mn)	0.2
Nickel (Ni)	0.7

EV motors

As of today, permanent-magnet synchronous motor is one of the most common electric motor technologies and it is expected to remain the dominant electric motor technology in electric vehicles in the future (IEA 2021b). When compared to its counterparts, benefits of a permanent-magnet synchronous motor include higher efficiency and power density (IEA 2021b). As a drawback, permanent-magnet synchronous motors require rare earth elements. The most commonly used permanent magnet is neodymium–iron–boron (NdFeb) magnet and although the exact composition and proportions of rare earths can vary inside the magnet, it typically contains four different rare earth elements: neodymium, praseodymium, terbium and dysprosium (Alves Dias et al. 2020).

Månberger & Stenqvist (2018) has compiled permanent-magnet motor data on dysprosium, neodymium and copper intensities in terms of kg/kW. Månberger & Stenqvist (2018) assumes the motor size of a passenger vehicle to range from 50-90 kW depending on the car type and whether it is used in an urban or rural environment. In Månberger & Stenqvist (2018), the motor size for an urban EV is assumed to be 60 kW with lifetime of 15 years. Mineral intensity data on iron and boron is calculated based on IEA (2021) and assuming a 60-kW motor capacity. The data on mineral intensity for permanent-magnet motors in electric vehicles is compiled to Table A16.

Table A16 Mineral intensity in permanent-magnet motors in electric vehicles. The assumed motor size is 60 kW. Source: Månberger & Stenqvist (2018) and own calculations based on IEA (2021).

Mineral	kg/kW
Boron (B)	0.0063
Dysprosium (Dy)	0.000052
Copper (Cu)	0.2
Iron (Fe)	0.024
Neodymium (Nd)	0.0038

In addition to electric motors and Li-ion batteries, fuel cell electric vehicles (FCEV) also contain a hydrogen storage and a fuel cell. The energy source in FCEVs is hydrogen. Platinum is used as a catalyst in the fuel cells with an approximate demand of 0.65 t/GW (Grandell et al. 2016).

Electrolysers

Electrolysers enable to store intermittent solar and wind energy into hydrogen. There are three main types of electrolysers: alkaline electrolysers, proton exchange membrane (PEM) electrolysers and solid oxide electrolysis cells (SOECs). Today, alkaline electrolysis is the most mature and commercial technology and hence it is used as the electrolyser sub-technology type in this study. IEA (2021) has evaluated the mineral demand of alkaline electrolysers, and the data is presented in Table A17. The demand for cobalt catalyst is derived from Grandell et al. (2016).

Table A17 Mineral intensity in alkaline electrolysers. Source: IEA (2021).

Mineral	t/GW
Aluminium (Al)	500
Cobalt (Co)	10
Nickel (Ni)	1000
Zirconium (Zr)	100

Expected improvements in mineral intensities

Improvements in mineral intensities of the assessed technologies are likely to occur due to technological and material developments. To evaluate the rate of mineral intensity improvements, Carrara et al. (2020) has divided materials present in wind and solar PV technologies to structural and technology-specific materials, as explained in Chapters 1 and 2 of the Appendix. For structural materials, the intensity values of 2050 are expected to correspond to 90% of the present mineral intensities whereas the mineral intensity in the technology-specific materials is expected to decrease annually by 2%.

Månberger & Stenqvist (2018) used two alternative scenarios to evaluate mineral intensity improvements; the applied improvements in mineral intensity were either none or between an annual improvement of 2% and 5%. For the sake of simplicity, Watari et al. (2019) used a conservative estimation where the current mineral intensity values remain constant, although mineral intensity improvements are expected to take place in the future. In IEA (2021), the pace of mineral intensity improvements varies by scenario and technology from minimal improvement to modest improvement, with the modest improvement being around 10% improved mineral intensity in long-term. In addition, specific improvement rates were applied for some mineral in e.g., solar PV (silver, silicon) and wind turbines (rare earth elements).

In this study, mineral intensity assumptions for wind and solar PV are taken from Carrara et al. (2020). The mineral intensity for other technologies is assumed to decline linearly to 2050 when the mineral intensity value reaches 90% of the current value. However, some exceptions are applied. For electric vehicle batteries and motors, we expect a more rapid mineral intensity improvement and hence an annual decrease of 2% for all the involved minerals is applied until 2050.