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RESEARCH

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Impacts of key technologies on the sustainable development goals to reach net zero greenhouse gas emissions in Sweden

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Abstract

Background The target of the Swedish climate policy framework is to reach net-zero emissions of greenhouse gases by 2045, implying large transformations of the current industry, energy and transport sector. Electric vehicles, wind and solar power, biomass, carbon capture and storage, climate-neutral concrete and green hydrogen are considered key technologies in the Swedish climate transition. There is, however, a growing need to identify how such technologies impact the broader scope of sustainable development. The purpose of this study is to determine the positive and negative effects of the large-scale implementation of key technologies on the Sustainable Development Goals (SDGs). Additionally, the aim of this study is to allocate the effects as domestic or international spillovers. The study is based on expert opinions elicited from workshops in which the effects of each key technology on the SDGs were addressed. The workshop results were qualitatively analyzed to construct causal relationships and compared against published literature to gain empirical support.

Results This study identified impacts for 11 out of the 17 SDGs. More than half of the impacts in Sweden were positive, whereas most negative impacts were identified as international spillovers. Positive impacts in Sweden are foremost linked to economic growth and job creation as well as sustainable industrialization and innovation. Internationally, negative spillover impacts mainly stem from mineral extraction, with consequences for human health, environmental degradation, local democracy and corruption.

Conclusions The multifaceted linkages between climate mitigation efforts and the UN 2030 Agenda for Sustainable Development are highlighted in this study, illustrating a need for policy coherence. Large-scale implementation of key technologies will result in more positive than negative impacts in the domestic context, reinforcing the Swedish implementation of the SDGs. However, the opposite is true for international spillovers, where the Swedish climate transition might hamper the fulfillment of specific SDGs in other countries. To achieve a sustainable climate transition, a holistic view incorporating all the SDGs and the core principle of "Leaving No One Behind" needs to be employed. The next steps could include stakeholders in policy and industry to identify actions and initiate collaborative approaches to strengthen positive and minimize negative impacts from climate mitigation efforts on the SDGs.

Keywords Sustainable development goals, Climate change mitigation, SDG impact assessment tool, Climate-neutral technologies, Climate policy, Sustainability

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Background

Climate policy and the sustainable development goals

The Paris Agreement stipulates that compared with preindustrial levels, global warming needs to be maintained well below 2 °C, preferably to 1.5 °C [1]. Its fulfillment rests upon the ambitions expressed in the so-called Nationally Determined Contributions (NDCs), in which countries detail their expected mitigation efforts. According to the Intergovernmental Panel on Climate Change (IPCC) [2], the pledges made thus far are insufficient to keep global warming from exceeding 1.5 °C during the 21st century. National mitigation pathways in compliance with the Paris Agreement need to ensure that cumulative emissions of greenhouse gases (GHGs) are reduced at a greater pace or that substantial negative emissions are achieved by 2050 [3]. This is undoubtedly a great challenge for the global community and even more so when the broader context of sustainable development is acknowledged. The climate transition needs to be just, inclusive and consider socioeconomic, cultural and environmental perspectives. Thus, finding coherence between the Paris Agreement and the United Nations (UN) 2030 Agenda for Sustainable Development [4] is central to governments and policymakers at all levels of society [5].

Launched in 2015, the UN 2030 Agenda for Sustainable Development includes 17 Sustainable Development Goals (SDGs) to be reached by 2030, which are based on the core principle of "Leaving No One Behind". As expressed by the UN, the SDGs are integrated and indivisible and balance three dimensions of sustainable development: economic, social and environmental [4]. While conceptually not new—sustainable development has since its inception in the 1987 Brundtland Report [6] linked social and economic development to the limitations of nature—the holistic approach in the 2030 Agenda and the SDG framework stand out compared with previous UN treaties. The notion that the SDGs interconnect, relate and depend on each other was further emphasized by Nilsson et al. [7], who reported that successful implementation of the 2030 Agenda needs to consider interactions between the SDGs. These results challenge the current modus operandi characterized by organizational silos and intradisciplinarity. Embracing the approach of the SDG framework offers an extension of 'sustainable development' as a concept, expanded from three pillars of environmental, social and economic sustainability into 17 perspectives or dimensions. As such, the SDGs merit further attention, not only for their use as political goals but also as a framework to evaluate the holistic qualities of climate mitigation and adaptation efforts.

Although the topics of climate change and sustainable development were initially addressed by separate circles in research and policy [8], linking these topics has gained increasing attention. This is particularly true throughout the IPCC process, where climate mitigation and sustainable development are described as having a two-way relationship that is cross-cutting, complex and not always mutually beneficial [9, 10]. Similarly, the 2030 Agenda calls for urgent action to combat climate change by putting forward SDG 13 (climate action) and emphasizing its intrinsic link to the other 16 goals. The mitigation of GHGs could have positive effects, also known as synergies, on other sustainability dimensions but, if not carefully considered, could also have negative effects, also known as trade-offs. For example, in a recent study, Pörtner et al. [11] reviewed the intertwined nature of climate change and biodiversity loss and exemplified climate actions that will have negative effects on biodiversity. Hence, as nations across the world introduce climate policies and actors across sectors engage in climate action, there is a growing need to develop new knowledge and practices related to identifying and avoiding unintended consequences for the broader scope of sustainability.

Numerous studies have been carried out to quantitatively or qualitatively assess the potential effects of climate and energy policy on the SDGs e.g. [12–16]. Integrated assessment models (IAMs) were initially developed to project the economic costs of climate policy but have proven eligible in the broader scope of linking climate scenarios and mitigation pathways to the SDGs [17]. Using IAMs, Moreno et al. found that for the European Union (EU) and its member states, ambitious net-zero emission pathways would further improve health and agricultural productivity but pose risks to poverty, hunger, and economic growth [17]. Von Stechow et al. [18] analyzed synergies and trade-offs on the basis of a set of predefined energy-related indicators derived from IAMs. The results showed that climate policies with relatively low flexibility of mitigation options tend to induce fewer synergies and more trade-offs on the SDGs and that keeping energy demand low achieved the best overall performance. Other studies have drawn inspiration from Nilsson's score-based SDG system [7]; for example, McCollum et al. reported that positive interactions among energy-related SDG targets outweigh negative interactions [19]. In its latest assessment report, the IPCC extensively mapped synergies and trade-offs between sectoral mitigation options and the SDGs in a qualitative approach [9]. On the basis of literature reviews, the IPCC reported that aligning the Paris Agreement with the 2030 Agenda will produce more synergies than trade-offs to society. They also found a large set of synergies between mitigation options and the SDGs but also significant trade-offs concerning poverty, hunger and, in some cases, risks to marine and land-based ecosystems. Furthermore, the assessments identified several cases where mitigation options showed both synergies and trade-offs for the same SDG, particularly those relevant to land use changes. As emphasized in the IPCC report, synergies and trade-offs will depend on the scale of implementation and the geographical context in which mitigation options are implemented.

In 2017, the Swedish parliament agreed upon a climate policy framework in line with the Paris Agreement. The framework stipulates that by 2045, Sweden should have net-zero emissions of GHGs [20]. Even though the climate policy framework was subsequently adopted for the 2030 Agenda, it does not explicitly acknowledge linkages between the net-zero target and the SDGs. The Swedish Climate Policy Council, which evaluates how well the government's overall policy is aligned with the net-zero target, has expressed a need to align climate policy with other societal goals and vice versa to enforce synergies and avoid trade-offs [21]. Efforts to describe interactions between climate policy and the SDGs would thus provide valuable input to policymaking. The significance would be even greater if synergies and trade-offs were allocated to an appropriate geographical context, i.e., as domestic impacts and international spillovers. In essence, domestic impacts are of concern to national policy and regulation, whereas spillover impacts point to stakeholder engagement in global supply chains and international policy intervention. The aim of this study is to identify and qualitatively describe the potential impacts on the SDGs from the large-scale implementation of key technologies crucial for the climate transition in the Swedish industry, transport and electricity sectors. The impacts are categorized as positive, negative or ambiguous and described in terms of whether they arise domestically or as international spillovers. In this study, wind power, solar photovoltaics (solar PV), biomass, green hydrogen, climate-neutral cement, carbon capture and storage (CCS) and electric vehicle batteries (EVBs) are analyzed. These key technologies were selected because of their potential for upscaling and to reduce current and avoid future GHG emissions in Sweden. The underlying rationale is to address the holistic quality and complexity inherent in the SDG framework to deliver usable knowledge as input to policy and strategic decision-making.

Technological change in the Swedish climate transition

By 2045 at the latest, Sweden is expected to have net-zero GHG emissions and thereafter pursue negative emissions. According to the Swedish climate policy framework, net-zero emissions of GHGs translate to at least an 85% reduction in emissions compared with 1990 levels. The remaining emission reductions can be achieved through supplementary measures, including bioenergy with carbon capture and storage (BECCS), increased carbon sequestration in forestland and land, and verified emission reductions carried out outside the Swedish borders [20].

To achieve the net-zero target by 2045, the application of transformative technologies that curb GHG emissions is needed across several sectors in Sweden. The two single largest contributing sectors to Swedish territorial GHG emissions are industry and transport. The industry sector emits approximately 35% of the Swedish territorial GHG emissions, which in 2022 corresponded to 15.3 Mt of carbon dioxide equivalents. The transport sector emits approximately 30%, corresponding to 13.6 Mt of carbon dioxide equivalents in 2022 [22]. Direct electrification of transport and indirect electrification (via green hydrogen) in industry represent central strategies for climate mitigation. This in turn requires transformations in the electricity sector to meet the significant increase in demand for electricity from renewable sources. In addition to electrification, increased use of biomass as a replacement for fossil fuels as well as the application of CCS are needed to reach the net-zero target.

In the industry sector, the production of steel and concrete contributes approximately 45% of industrial GHG emissions in Sweden [22]. Both of these industries require the application of transformative technologies to achieve deep emission reductions by 2045 [23, 24]. The iron and steel industry is currently the largest emitting industrial sector in Sweden, contributing one-third of the total industrial GHG emissions, or approximately 10–12% of the total territorial emissions [22]. Currently, two-thirds of the total Swedish steel is produced through a blast furnace process, where carbon and coke are used for the reduction of iron ore. The last third is produced through a scrap-based process using electric arc furnaces (EAFs). The reduction in iron ore in blast furnaces is the dominant source of GHG emissions from Swedish steel production. With respect to the ability of the Swedish steel industry to achieve significant GHG emission reductions, the main mitigation strategy is to replace the blast furnace process with hydrogen direct reduction (H-DR) and EAFs, with the potential to reduce GHG emissions from ironmaking by 90% [23, 25]. Since 2016, the main Swedish steel producer, SSAB, which accounts for more than 90% of the GHG emissions from Swedish steel production [23], together with the mining company LKAB and the energy company Vattenfall, have been supported by the government to run the Hydrogen Breakthrough Iron-Making Technology (HYBRIT) project [23, 25]. This project aims to produce fossil-free steel through H-DR, with a planned market introduction in 2026 [26], and largely eliminates GHG emissions from steel production by 2030 [27].

The concrete industry is responsible for approximately 15% of total industrial GHG emissions in Sweden, which is equivalent to approximately 5% of total territorial GHG emissions [22]. The majority of GHG emissions from the concrete industry, approximately 65%, can be attributed to the production of cement, specifically the calcination process where limestone is converted to cement clinker at high temperatures. Current main mitigation options to reduce GHG emissions from the Swedish concrete industry include replacing fossil fuels with waste-based fuels or biofuels, using alternative binders, and using less cement by optimizing concrete recipes, as well as increasing the reuse of concrete [24]. However, to achieve emission reductions in line with the climate target, the application of CCS is necessary, even when available abatement options are used to full potential [24, 28]. The Swedish cement industry has set the target of producing climate-neutral cement by 2030 [24, 29].

Swedish territorial GHG emissions from the transport sector are dominated by road transport, with passenger vehicles being responsible for approximately 60% of total emissions [22]. A substantial reduction in these emissions is needed for Sweden to meet the climate target by 2045. Large-scale adoption of new technologies will be crucial, particularly for electric vehicles (EVs), as well as for the replacement of fossil fuels with biofuels in existing internal combustion engine vehicles (ICEVs). Compared with ICEVs, EVs have high energy efficiency, zero tailpipe emissions, and lower life cycle GHG emissions when charged with low-carbon electricity [2], which is the case for the near-carbon-free Swedish electricity system [30]. The EV market in Sweden has already shown rapid growth—between 2020 and 2022, it almost tripled, with 33% of all newly registered passenger vehicles being EVs in 2022 [31].

Electrification of the transport sector and, particularly, electrification of the Swedish steel industry, will substantially increase demand for electricity. Today, the Swedish electricity system is almost carbon neutral and has low GHG emissions [30]. In 2022, Sweden produced a total of 170 TWh, 41% of which was generated from hydropower, 29% from nuclear power, 19% from wind power, 10% from thermal power, and 1% from solar PV [32]. For the Swedish iron and steel industry, it is estimated that the technological shift from blast furnaces to H-DR will increase electricity consumption annually from 7 to 22 TWh at current production volumes [25], which is in agreement with a scenario produced by Toktarova et al. [23]. However, assuming that Swedish steel production volumes would increase, both through increased production volumes in current plants and through new establishments following new demand for green steel, electricity consumption by 2045 could increase by 20 to 100 TWh, according to the Swedish Energy Agency [33]. The electrification of road-based transport, following the large-scale introduction of EVs, is expected to increase demand for electricity by an additional 30 TWh by 2045 [33]. In addition, the establishment of production facilities for EVBs in Sweden is likely to further increase electricity demand. In the short to medium term, new electricity demand is expected to be supplied mainly by wind power and solar PV because of their relatively low costs and rapid expansion possibilities [34, 35]. During the past ten years, the expansion of wind power has been rapid in Sweden, with installed capacity almost quadrupling from approximately 3 600 MW in 2012 to 14 300 MW in 2022 [36].

Methods

Description of the key technologies

To realize the Swedish climate transition, several key technologies in the electricity sector, the iron and steel industry, the transport sector and the concrete industry need to be scaled up. Figure 1 gives an overview of the key technologies in these sectors assessed in this study and their linkages to achieve decarbonization. Wind power and solar PV produce the renewable electricity required for electrification in the transport sector and green hydrogen production in the iron and steel industry. Biomass contributes to negative GHG emissions in the electricity sector when BECCS is applied, as well as to GHG emission reductions by replacing fossil fuels with biofuels in ICEVs in the transport sector and in the production of climate-neutral concrete.

The key technologies were assessed in terms of their production, use and end-of-life stages in a simplified lifecycle approach. Assessments of the production stage focused on the input of raw materials, particularly the critical minerals and metals necessary in the production of relevant key technologies, as presented in Table 1. The precise details of where and how the critical minerals will be sourced in the future are outside the scope of the study, but current main sourcing countries were used as proxies. The critical raw materials needed in climate-neutral concrete as well as the required biomass were assumed to be extracted domestically.

As noted by the International Energy Agency (IEA), minerals play a critical role in the development of the clean energy technologies needed for the climate transition [37]. A large-scale expansion of these technologies will dramatically increase demand during the coming decades. This is particularly true for EVBs, electrolyzers for green hydrogen, solar PV and wind power. Minerals assessed as highly critical by the IEA [37] for each of the key technologies were selected, namely, copper, aluminum, rare earth elements (REEs), zinc, cobalt, nickel, lithium and platinum group metals (PGMs) (see Table 1). These minerals are also included in the European Commission's 2023 list of critical raw materials [38].

A large share of these will be imported either directly or embedded in imports of the key technologies. Copper is

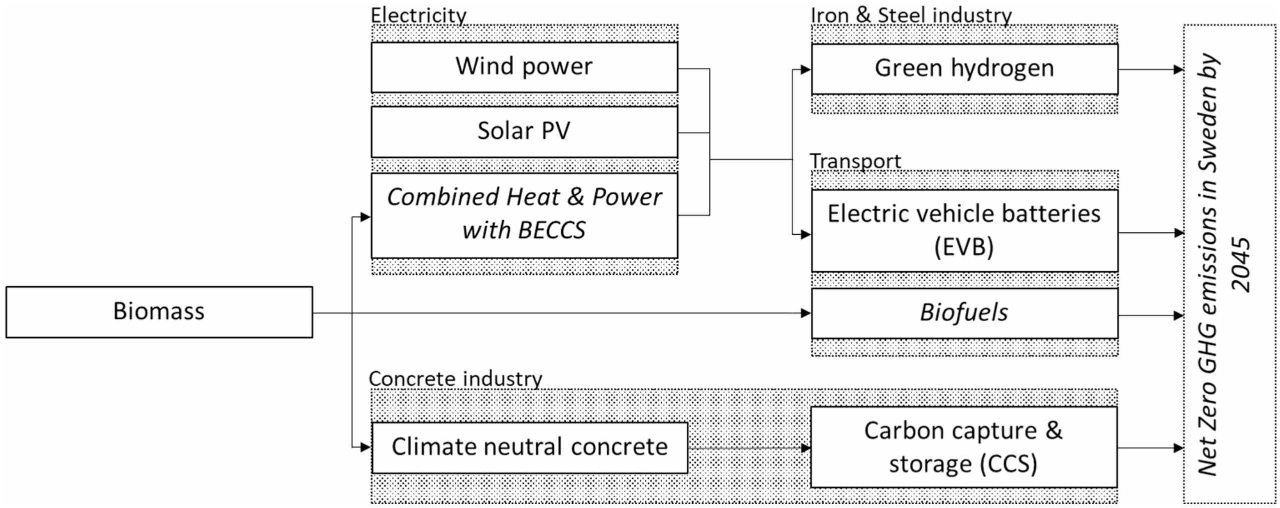

Fig. 1 Conceptual overview of the key technologies assessed and their sequential interconnections in contributing to mitigation in line with the target of net-zero GHG emissions in Sweden by 2045

the only of the included minerals that is currently mined in Sweden; however, imports are still assumed to be necessary to meet demand until 2045. There are known sources of lithium in the Swedish bedrock, and cobalt and REEs have been found in several locations, but none of these are currently mined [39]. However, the possibility that the large-scale deployment of key technologies could lead to intensified extraction in current Swedish mines and/or the opening of new mines was considered in the assessments.

In the use phase, a large-scale implementation of the key technologies was assumed, as outlined above and according to the scenarios summarized in Table 1. Specifically, EVBs in the user phase were studied for their application in EVs as replacements for ICEVs. The assessment considered export potential for domestically produced EVBs and green steel on the basis of ongoing industrial ventures. Biomass and climate-neutral concrete were assumed to be produced and used domestically. Electrolyzers, wind turbines and solar PV modules were assumed to be imported. The end-of-life assessments focused on reuse and recycling possibilities and the potential impacts on waste generation. For assumptions regarding end-of-life options for each key component, see Table 1.

SDG impact assessments

The qualitative and holistic assessments of potential impacts from large-scale implementation of the key technologies on the SDGs were conducted in three subsequent steps: (i) initial assessments based on interdisciplinary expert workshops using the SDG Impact Assessment Tool [41], (ii) a qualitative analysis and structuring of workshop outputs to construct causal relationships and (iii) a literature search to establish empirical support for, or discard, suggested SDG impacts, as shown in Fig. 2. The process aimed to move from expert workshop discussions where potential SDG impacts were identified to a prioritized set of SDG impacts backed by plausible rationales and empirically traceable accounts as the end goal.

The initial assessments were carried out in seven thematic workshops arranged per key technology during the period of 2018 to 2020. In total, 20 researchers in energy technology and energy systems, sustainable transport and mobility and environmental engineering, two representatives from car manufacturing and two representatives from a large construction firm contributed their specific knowledge of the Swedish climate transition. In addition, the authors of the current article facilitated the workshops and contributed as experts on the SDG Impact Assessment Tool.

The experts were given the task of identifying and describing the potential impacts on the SDGs from large-scale implementation of the key technologies in Sweden. As the basis for the assessments, the experts were instructed on the framings and scenarios presented in Table 1. When the assessments were being conducted, the experts were divided into groups of no more than five per key technology and followed the methodology given by the SDG Impact Assessment Tool. The tool provides users with succinct information on the SDGs, including all corresponding targets, and offers a simple approach to categorize SDG impacts as 'positive', 'no impact', 'negative' or 'more knowledge needed' (see Supplementary Information). Each key technology was assessed by reviewing the SDGs and their targets to identify and categorize their impacts. For each SDG impact, motivation clarifying arguments and reasoning were formulated

Table 1 Framing and relevant assumptions for the key technologies used in the assessments

Key component	Biomass	CCS	Climate neutral concrete	EVB	Green hydrogen	Solar PV	Wind power
Application	Electricity generation, biofuel in transport and concrete industry	BECCS andcarbon removal in concrete industry	Building and construction material	Electrification of transport	Raw material and energy input to iron and steel industry	Electricity generation	Electricity generation
Scenario	Expanded use of biomass in electricity generation, replacement of fossil fuels with biofuels in transport and concrete production	Expanded use of biomass in electricity generation, capture and storage of GHG emissions from concrete production	Replacement of conventional concrete with climate neutral in the building and construction sector	Replacement of fossil fuels with electrification in the transport sector through large-scale use of EVs	Replacement of fossil fuels with domestic green hydrogen production and Lined Rock Cavern (LRC) storage in the iron and steel industry	Expansion of solar PV to meet increased demand for electricity from renewable sources in industry and transport	Expansion of wind power to meet increased demand for electricity from renewable sources in industry and transport
Global value chain	No	No	No	Extraction of minerals and export potential for domestically produced EVBs	Extraction of minerals for electrolyzers and export potential for domestically produced green steel	Extraction of minerals for PV modules	Extraction of minerals for wind turbines
Critical raw materials and minerals (main sourcing countries > 10% of global mining [% of global mining])	Residual and cultivated forestry biomass (domestic)	N/A	Limestone (domestic)	Aluminum[a] (Australia [26%], China [24%], Guinea [23%]); Cobalt (Congo-Kinshasa [68%]), Copper[b] (Chile [24%], Congo-Kinshasa [10%], Peru [10%]); Lithium (Australia [47%], Chile [39%], China [15%])	Nickel (Indonesia [48%], Philippines [10%]); PGMs[c] (South Africa [55%], Russia [27%])	Aluminum[a] (Australia [26%], China [24%], Guinea [23%]); Copper[b] (Chile [24%], Congo-Kinshasa [10%], Peru [10%])	Aluminum[a] (Australia [26%], China [24%], Guinea [23%]); Copper[b] (Chile [24%], Congo-Kinshasa [10%], Peru [10%]); REEs (China [70%], United States [14%]); Zinc (China [32%], Peru [11%], Australia [10%])
End-of-life options	Not relevant	Not relevant	Possible to reuse	Limited reuse and recycling possibilities	Not relevant	Limited recycling possibilities	Limited recycling possibilities

Data covering the source countries and percentage of global mining are taken from the Mineral Commodity Summaries 2023 [40]

[a] The data reflect the mining of bauxite

[b] The data reflect mine production (not refinery)

[c] The data include both platinum and palladium combined

by consensus within the expert groups. In addition, the experts assigned their level of confidence for each SDG impact, ranging from speculative to very high. A ‘very high‘ level of confidence corresponds to self-evident arguments. For example, an argument such as “replacing fossil fuels with EVBs will decrease NOx emissions” is self-evident since EVB in its user phase does not produce exhausts. Additionally, workshop participants were tasked with describing whether the identified impacts would appear domestically or be considered international spillover effects arising outside of Sweden.

The workshop outputs were, at a later stage, further analyzed by the authors of the current article, aiming to construct causal relationships as an *a priori* justification or validation of suggested SDG impacts. These were structured as follows:

$$[\mathrm{cause}]\ ->\ [\mathrm{effect}]\ ->\ [\mathrm{SDG\ impact}]\,.$$

As an example, linking the large-scale implementation of EVBs to a suggested positive impact on SDG 3 (human health) would correspond to [replacement of fossil fuels with EVBs] -> [decreased NOx emissions] -> [improved human health]. SDG impacts where no such relationship could be constructed were discarded.

In some cases, a cause could give rise to effects both in support and in conflict with the same aspect of an SDG. For example, the large-scale deployment of EVBs decreases the use of fossil fuels while increasing the

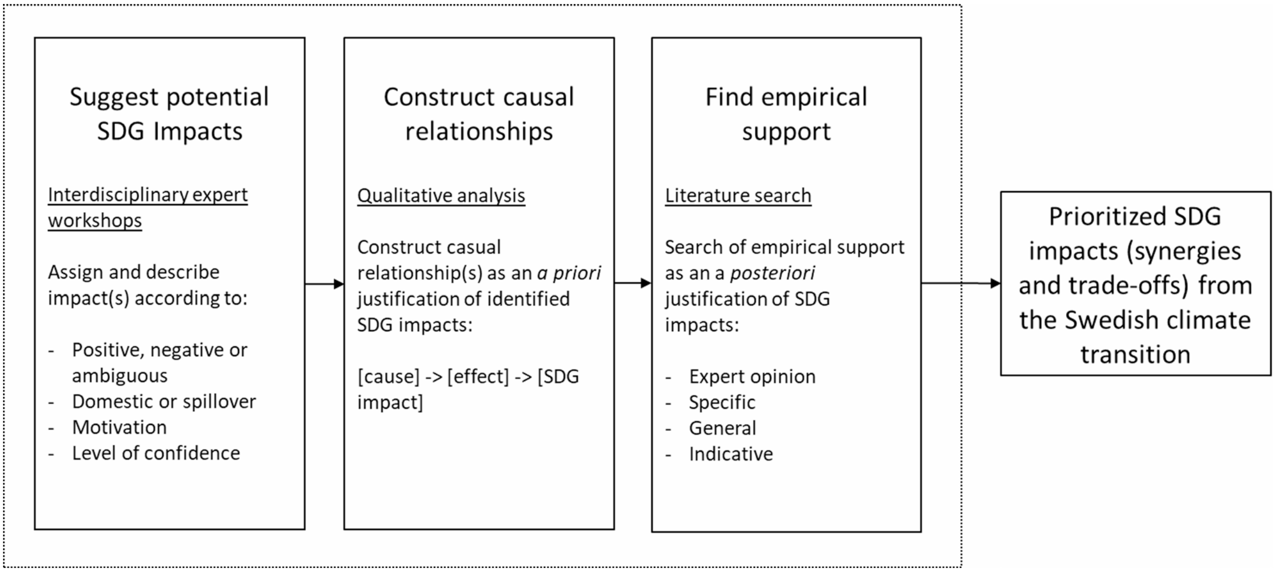

Fig. 2 Stepwise procedure of the SDG impact assessments, moving from expert input in workshops by constructing causal relationships and finding published observations to a prioritized subset of SDG impacts. The invited experts were engaged in the first step, "Suggest potential SDG Impacts", whereas the authors of the current article were involved in all the steps

Table 2 Empirical support categories and their descriptions. Geographical context refers to domestic impacts or international spillovers

Empirical support	Description
Expert opinion	Causal relationships assigned with very high level of expert confidence
Specific	Literature specific to [cause] -> [effect] and the geographical context
General	Literature specific to either [effect] or [cause] and supporting the geographical context
Indicative	Literature relevant to either [cause] or [effect] in any geographical context
None	No occurrences of literature in support of causal relationship

extraction of minerals necessary to produce EVBs. Thus, the impact on the material footprint, an aspect of SDG 12 (responsible consumption and production), is both positive and negative. Such bidirectional impacts were categorized as ambiguous.

To reach a final set of prioritized SDG impacts, a literature search was conducted with the aim of increasing confidence by finding empirical support as an *a posteriori* justification of suggested impacts and corresponding causal relationships. Searches were performed from August 2021 to May 2023 in the Web of Science database, and the Google search engine was used to find reports and web pages from governmental agencies and authorities. The search keywords were based on causal relationships, i.e., explicit words or synonyms used in [cause], [effect] and [SDG impact]. The literature search was performed for SDG impacts with an assigned level of confidence lower than 'very high' and was performed nonexhaustively; i.e., the most relevant articles were included in the analysis of empirical support. Empirical support for the identified SDG impacts was categorized into five levels, as described in Table 2. Causal relationships where no empirical support could be found, denoted as 'None' in Table 2, were deemed speculative and excluded from the set of prioritized impacts. Furthermore, causal relationships that were falsified by peer-reviewed literature were also excluded from the set of prioritized impacts.

SDG impacts justified by both a causal relationship and empirical support were selected as prioritized. The prioritized impacts were further checked for double allocation between key technologies. The guiding principle involved allocating impacts to key technologies in the sectors in which they would appear, as shown in Fig. 1. As an example, the large-scale expansion of wind power in Sweden would primarily have positive effects on SDG 13 (climate action) because of the replacement of fossil fuels in the transport sector and iron and steel industry and hence be allocated to EVB and green hydrogen and not wind power itself.

Results

The SDG impact assessments for the key technologies resulted in a total of 95 prioritized SDG impacts. These impacts were categorized as 44 positive, 44 negative and seven ambiguous. Although equal numbers of positive and negative impacts were identified, the distribution of these impacts into domestic and international spillovers differed (Fig. 3). The assessments revealed more positive than negative impacts in Sweden, whereas the opposite

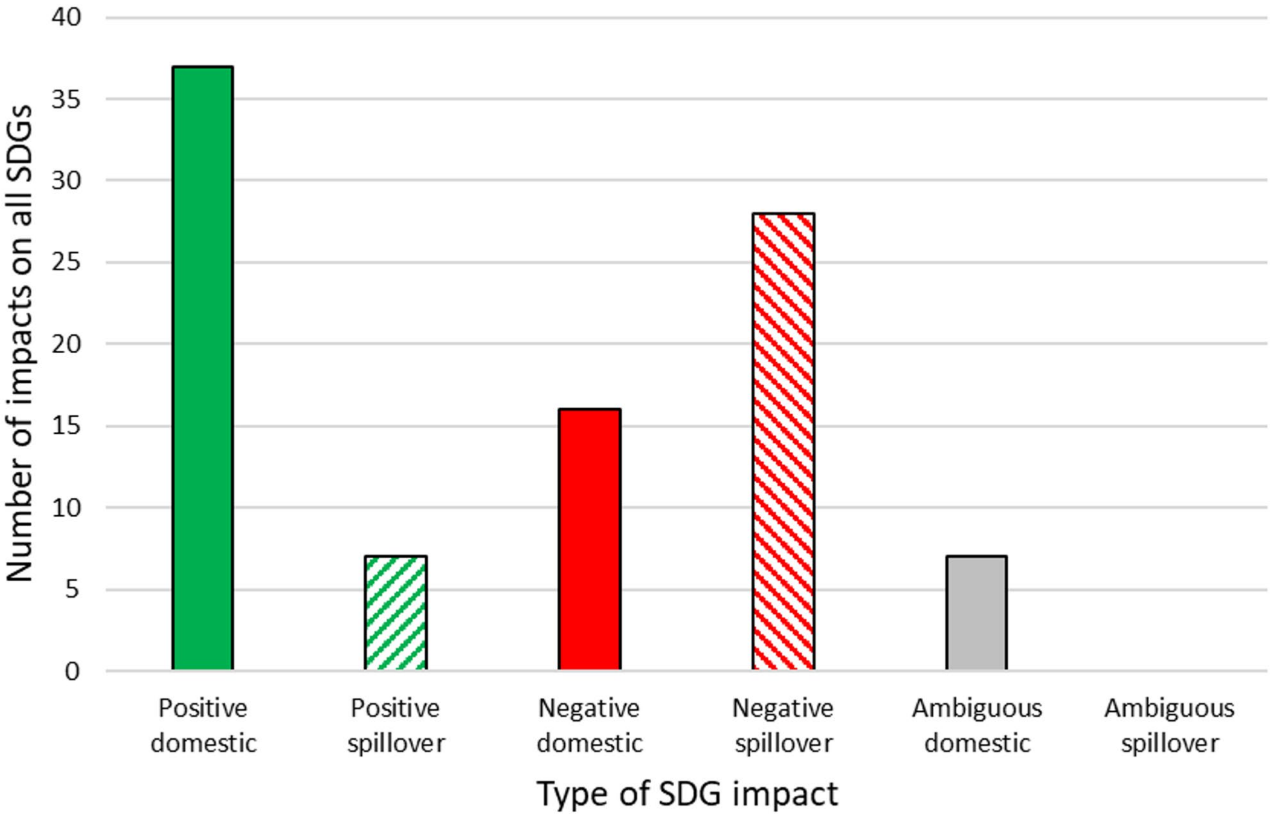

Fig. 3 Number of prioritized SDG impacts according to the type of impact

was evident for impacts abroad. No ambiguous spillover impacts were identified.

The distribution of impacts over the SDGs, as well as the breakdown into different impact categories, is shown in Fig. 4. Compared with the other key technologies, the key technologies EVB, green hydrogen, solar PV and wind power clearly have similar impact profiles. This is driven by the use and import of critical minerals for these technologies. From Fig. 4, it is also evident that all technologies have exclusively positive impacts on SDG 9 (industry, innovation, and infrastructure), while no impacts were identified for issues concerning poverty, hunger, education, gender equality, inequality and partnerships.

Biomass

There were five positive, four negative and two ambiguous impacts on the SDGs identified from the expanded use of biomass in the energy and transport sectors (Table 3). The combustion of biomass increases hazardous air pollution in local and regional surroundings, negatively impacting respiratory and, possibly, cardiovascular health, posing a risk to SDG 3 (good health and well-being) and SDG 11 (sustainable cities and communities) through the degradation of urban air quality.

The use of biomass to mitigate GHG emissions in the industry, energy, and transport sectors could have both positive and negative effects on different aspects of SDG 7 (affordable and clean energy). Expanded use of biomass will increase the share of renewable energy in total final energy consumption, thus contributing positively to SDG 7. Moreover, increased demand for biomass could increase energy prices, as biofuels are typically more expensive than fossil fuels, with a potential negative impact on the affordability perspective of SDG 7 [42, 43]. This is particularly true for the transport sector through the blending of ethanol and biodiesel in fossil fuels.

Replacement of fossil energy with bioenergy enables the decoupling of economic growth (GDP) from GHG emissions in the industry, energy and transport sectors, with positive impacts on SDG 8 (decent work and economic growth) and SDG 13 (climate action). Decreased use of fossil fuels also has positive effects on SDG 8 and SDG 12 (responsible consumption and production) through a reduced material footprint per GDP. On the other hand, increased domestic consumption of biomass will increase the Swedish material footprint per GDP, which might hamper ambitions to improve resource efficiency in consumption and production, with negative impacts on SDG 8 and SDG 12. Thus, the impact on the material footprint per GDP is assessed as ambiguous. A

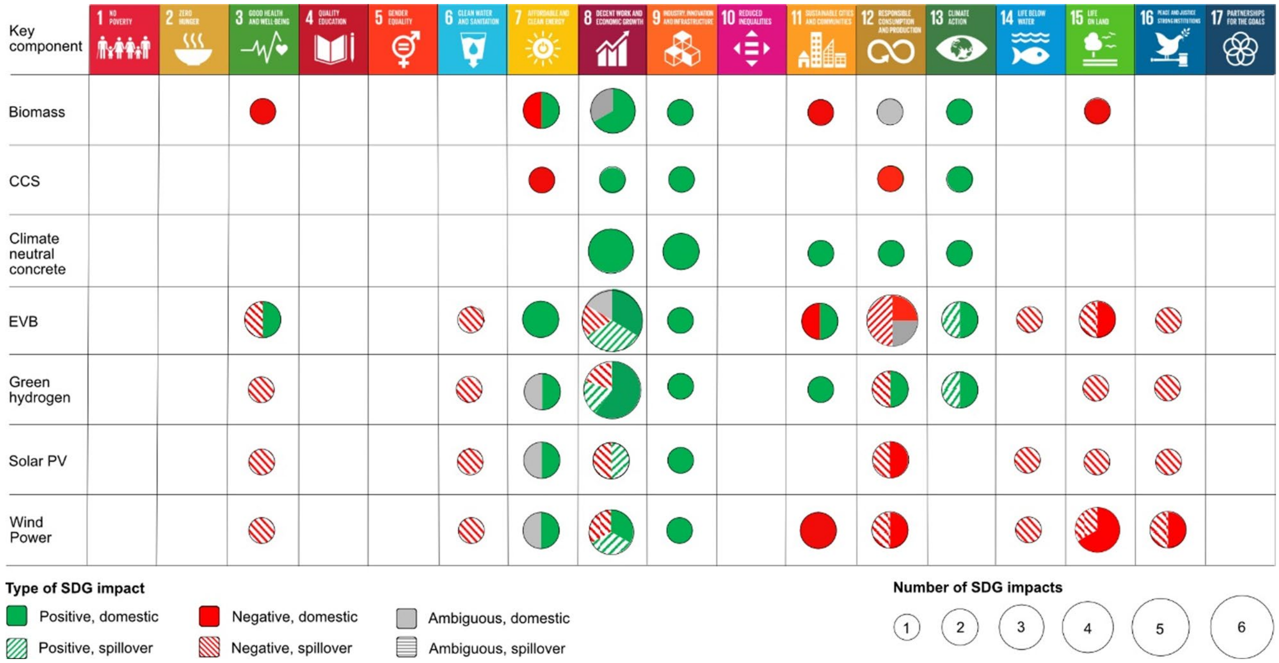

Fig. 4 Number of prioritized SDG impacts for the seven key technologies over the SDGs, shown as pie chart distributions of different impact types. The legend at the bottom left shows the colors and patterns of the types of impact. The legend at the bottom right shows the correspondence between the number of prioritized impacts and the pie chart size

Table 3 Prioritized SDG impacts from biomass

SDG	Impact	Spillover	Causal relationship	Empirical support
3	-	No	Combustion of biomass in the energy and transport sectors -> Increased NOx and PM emissions -> Increased illness and mortality from hazardous air pollution	Expert opinion
7	+	No	Use of biomass in the industry, energy, and transport sectors -> Increased use of renewable energy -> Increased share of renewable energy in total final energy consumption	Expert opinion
7	-	No	Use of biomass in the industry, energy, and transport sectors -> Increased demand for biomass -> Less affordable average energy prices	Specific
8	+	No	Replacement of fossil energy with bioenergy in the industry, energy, and transport sectors -> Mitigation of territorial GHG emissions -> Economic (GDP) decoupling from GHG emissions	Expert opinion
8	+/-	No	Use of biomass in the industry, energy, and transport sectors -> Decreased use of fossil fuels/Increased outtake of biomass resources -> Increased material footprint per GDP	Expert opinion
8	+	No	Use of biomass in the industry, energy, and transport sectors -> Increased economic activity in the agricultural, forestry and energy sectors -> Economic growth and job creation in the agricultural, forestry and energy sectors	Indicative
9	+	No	Replacement of fossil energy with bioenergy in the industry, energy, and transport sectors -> Reduced GHG emissions per unit of value added -> Upgrading and retrofitting of industries	Specific
11	-	No	Combustion of biomass in the energy and transport sectors -> Increased NOx and PM emissions -> Degradation of urban air quality	Expert opinion
12	+/-	No	Use of biomass in the industry, energy, and transport sectors -> Decreased use of fossil fuels/Increased outtake of biomass resources -> Impact on material footprint	Specific
13	+	No	Replacement of fossil energy with bioenergy in the industry and transport sectors -> Decreased use of fossil energy -> Mitigation of territorial GHG emissions	Expert opinion
15	-	No	Use of biomass in the industry, energy, and transport sectors -> Increased exploitation of biomass resources -> Habitat degradation, fragmentation, and loss	General

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given well-managed bioenergy production system, which uses materials that otherwise would go to waste, can mitigate the negative impact on SDG 12 through advances in the management of natural resources. Producing biogas, for instance, can decrease food waste or at least make the energy in food waste useful.

Economic growth and job creation are likely to increase and be sustained in the Swedish agricultural, forestry and energy sectors from the increased use of biomass, resulting in new opportunities for a wide range of associated actors [42] and positively impacting SDG 8. Biomass usage also has positive effects on SDG 9 (industry, innovation, and infrastructure), as it enables the upgrade and retrofit of industries through the replacement of fossil energy [23, 24].

Increased use of biomass could cause negative impacts on SDG 15 (life on land). As the demand for biomass increases, the harvesting of wood and logging residues (slash and stumps), as well as the cultivation of energy forests, is likely to increase [42–44]. Thus, the outtake of biomass has several negative environmental effects on, e.g., soil and water chemistry as well as biodiversity through the loss, degradation, and fragmentation of habitats [44, 45]. However, such negative impacts vary greatly depending on crops, forestry and farming methods, as well as geological and biological factors [46].

Table 4 Prioritized SDG impacts from carbon capture and storage

SDG	Impact	Spill-over effect	Causal relationship	Empirical support
7	-	No	Application of CCS in the industry and energy sectors -> Increased energy use per unit output -> Reduced energy efficiency of industrial processes and energy conversion	General
8	+	No	Application of CCS in the industry and energy sectors -> Mitigation of GHG emissions -> Economic (GDP) decoupling from GHG emissions	Expert opinion
9	+	No	Application of CCS in the industry and energy sectors -> Mitigation of GHG emissions -> Upgrade and retrofit of infrastructure and industries through reduced GHG emissions per unit of value added	Expert opinion
12	-	No	Application of CCS in biomass fueled thermal power plants -> Increased exploitation of biomass resources -> Increased material footprint	Expert opinion
13	+	No	Application of CCS in the industry and energy sectors -> Removal of GHG emissions -> Mitigation of territorial GHG emissions	Expert opinion

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given

Carbon capture and storage (CCS)

Three positive and two negative impacts on the SDGs were identified from the application of CCS in the industry and energy sectors (Table 4). CCS gives rise to energy penalties that, to varying degrees, reduce the overall energy efficiency of, e.g., concrete production and thermal power plants [47]. In addition, further energy losses occur at the system level because of the transport and storage of carbon dioxide. Hence, the large-scale implementation of CCS might have a negative effect on SDG 7 (affordable and clean energy) through decreased energy efficiency. CCS is, however, an important mitigation option to reach net-zero GHG emissions in concrete production and to enable negative GHG emissions when applied to biofueled thermal power plants. These two applications reduce territorial GHG emissions while upholding economic productivity and growth, thus positively impacting SDG 8 (decent work and economic growth) through economic decoupling of GHG emissions; SDG 9 (industry, innovation and infrastructure) through reduced GHG emissions per unit of value added in industry; and SDG 13 (climate action) as GHG emissions are removed in absolute terms.

CCS, when applied to biofueled power plants (BECCS), could lead to a negative effect on SDG 12 (sustainable consumption and production). BECCS enables negative GHG emissions, which could increase the demand for biomass used in electricity and heat production to achieve carbon offsets, thereby increasing the domestic material footprint. The significance and magnitude of this risk depends on the future market value of negative emissions, which will impact the demand for the biomass used for this purpose.

Climate-neutral concrete

Eight positive impacts on the SDGs were identified from replacing conventional concrete with climate-neutral concrete (Table 5). First, it mitigates territorial GHG emissions from the industry sector and associated embedded emissions in the supply chains of transport infrastructure and buildings. This enables economic activity and growth to be decoupled from GHG emissions. Climate-neutral concrete allows for the continued use of concrete in buildings and transport infrastructure while mitigating GHG emissions, which contributes to sustained economic growth and job creation (SDG 8). Second, climate-neutral concrete also has a positive effect on SDG 9 (industry, innovation, and infrastructure), as it mitigates GHG emissions from the industry sector and enables the retrofitting of the concrete industry, as well

Table 5 Prioritized SDG impacts from climate-neutral concrete

SDG	Impact	Spillover	Causal relationship	Empirical support
8	+	No	Replacing production of conventional concrete with climate neutral -> Mitigation of territorial GHG emissions -> Economic (GDP) decoupling from GHG emissions	Expert opinion
8	+	No	Replacing use of conventional concrete with climate neutral -> Continued use of concrete as a construction material -> Sustained economic growth and job creation in the buildings and transport infrastructure sectors	Expert opinion
8	+	No	Production of climate neutral concrete -> Substitution of gravel and sand with reused concrete in infrastructure -> Decreased material footprint per GDP	Expert opinion
9	+	No	Replacing production of conventional concrete with climate neutral -> Mitigation of GHG emissions from the industry sector -> Retrofit of industries	Specific
9	+	No	Replacing use of conventional concrete with climate neutral -> Reduced GHG emissions per unit of value added in transport infrastructure -> Upgrade of infrastructure through reduced embedded GHG emissions	Expert opinion
11	+	No	Replacing use of conventional concrete with climate neutral -> Reduced embedded GHG emissions in buildings and transport infrastructure -> Reduction of per capita environmental impact of cities	Expert opinion
12	+	No	Production of climate neutral concrete -> Substitution of gravel and sand with reused concrete in infrastructure -> Decreased material footprint	Expert opinion
13	+	No	Replacing production of conventional concrete with climate neutral -> Reduced GHG emissions from the industry sector -> Mitigation of territorial GHG emissions	Specific

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given

as infrastructure upgrades through reduced GHG emissions per unit of value added [24]. Through its mitigation potential, climate-neutral concrete also positively impacts SDG 13 (climate action).

Replacing conventional concrete with climate-neutral concrete, e.g., buildings and transport infrastructure, contributes positively to SDG 11 (sustainable cities and communities) through the reduction of embedded GHG emissions and thus the per capita environmental impact of cities. Furthermore, there is a potential to reuse waste concrete in new concrete production or as ballast in the construction of, e.g., transport infrastructure, decreasing the need for virgin raw materials as a positive effect on SDG 12 (sustainable consumption and production).

Electric vehicle batteries (EVBs)

There were 11 positive, 11 negative and two ambiguous impacts on the SDGs identified from replacing fossil fuels with EVBs in the transport sector (Table 6). Replacing ICEVs with EVs reduces the emissions of air pollutants from transport [48]. Air pollution, particularly nitrogen oxides (NOx), can negatively affect human health. Even at low levels, NOx may cause damage to the human respiratory system. The electrification of transport thus has a positive effect on SDG 3 (good health and well-being) and SDG 11 (sustainable cities and communities) through improved urban air quality. Although EVBs have zero tailpipe emissions of particulate matter (PM), the higher weight of electric vehicles gives rise to increased mobilization of road dust to the air, resulting in comparable total PM emissions from EVs and ICEVs [49].

As the electrification of transport accelerates, the demand for critical minerals used in EVBs such as aluminum, cobalt, copper and lithium will increase (Table 2). Mining of these minerals to support the electrification of transport in Sweden poses risks of several negative spillover effects. Mining is associated with emissions to air and water that increase the exposure of workers and residents to toxic elements, negatively impacting SDG 3. There are additional risks to SDG 6 (clean water and sanitation) from water pollution and aggravating water scarcity, particularly in the mining of lithium and copper. Artisanal mining and unregulated mining of cobalt have negative spillover effects on SDG 8 (decent work and economic growth) because of a lack of labor rights, the use of child labor and occupational accidents [37, 50]. Cobalt mining outside Sweden also has a negative spillover effect on SDG 16 (peace, justice and strong institutions) from increased corruption and a lack of participatory decision-making at local levels in countries with weak institutions [51]. Increased mining of aluminum, cobalt, copper and lithium is likely to further strengthen already existing harmful consequences for local biodiversity and habitats as well as terrestrial and inland freshwater ecosystems,

Table 6 Prioritized SDG impacts from electric vehicle batteries

SDG	Impact	Spillover	Causal relationship	Empirical support
3	+	No	Replacement of fossil fuels with EVBs -> Decreased NOx emissions -> Improved human health	Specific
3	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Health risks associated with mining	Specific
6	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Risks for pollution of drinking water and water scarcity	General
7	+	No	Replacement of fossil fuels with EVBs -> Decreased use of fossil energy -> Increased share of renewable energy in total final energy consumption	Specific
7	+	No	Replacement of fossil fuels with EVBs -> Increased energy efficiency -> Decreased primary energy per GDP	Expert opinion
8	+	No	Replacement of fossil fuels with EVBs -> Decreased use of fossil energy -> Economic (GDP) decoupling from GHG emissions	Expert opinion
8	+/-	No	Replacement of fossil fuels with EVBs -> Decreased domestic consumption of fossil fuels/Increased extraction of critical minerals -> Impact on material footprint per GDP	Expert opinion
8	+	No	Electrification of transport -> Increased demand for electric vehicles including components such as EVBs -> Economic growth and job creation in the transport, industry and energy sectors	Expert opinion
8	+	Yes	Electrification of transport -> Import of inputs to the transport and industry sectors -> Increased economic activity in export countries	Expert opinion
8	+	Yes	Domestic production of EVBs -> Export of low carbon footprint EVBs -> Economic (GDP) decoupling from GHG emissions in import countries	Expert opinion
8	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Risks for labor rights, child labor and safe and secure environments from mining	General
9	+	No	Electrification of transport -> Expansion of charging infrastructure -> Upgrade and retrofit of industry and infrastructure as well as encouraged innovation	Expert opinion
11	+	No	Replacement of fossil fuels with EVBs -> Decreased NOx emissions -> Improved urban air quality	Expert opinion
11	-	No	Domestic production of EVBs -> Establishment of new mines for extraction of critical minerals -> Risks to the protection and safeguard of natural and cultural heritage	Expert opinion
12	+/-	No	Replacement of fossil fuels with EVBs -> Decreased use of fossil energy/Increased extraction of critical minerals -> Impact on material footprint	Expert opinion
12	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Risks to sound management of chemicals and wastes including release to air, water and soil	General
12	-	No	Electrification of transport -> Increased deposit of exhausted EVBs -> Increased waste generation	Expert opinion
12	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Risks to the sustainable management and efficient use of natural resources	Specific
13	+	No	Replacement of fossil fuels with EVBs -> Reduced GHG emissions from the transport sector -> Mitigation of territorial GHG emissions	Expert opinion
13	+	Yes	Domestic production of EVBs -> Export of low carbon footprint EVBs -> Mitigation of GHG emissions in import countries	Expert opinion
14	-	Yes	Production of EVBs -> Increased extraction for critical minerals -> Risk for marine ecosystems from seabed and deep-sea mining	General
15	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Risks for biodiversity, habitats as well as terrestrial and inland freshwater ecosystems	Expert opinion
15	-	No	Domestic production of EVBs -> Establishment of new mines for extraction of critical minerals -> Risks to terrestrial and inland freshwater ecosystems	Expert opinion
16	-	Yes	Production of EVBs -> Increased extraction of critical minerals -> Risks for corruption and lack off participatory decision-making at local levels in countries with weak institutions	General

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given

resulting in negative spillover impacts on SDG 15 (life on land). To meet the increased demand, new mines or the intensified extraction in existing mines for, in particular, copper, cobalt and lithium could also occur in Sweden, with risks for a negative impact on SDG 15. In the long term, the need for critical minerals could trigger searches for new deposits of copper and cobalt on the ocean floor should conventional resources become scarce. Seabed and deep-sea mining poses great risks for marine ecosystems, thus leading to negative spillover effects on SDG 14 (life below water) [52, 53].

Replacing fossil fuels with EVBs will positively impact SDG 7 (clean and affordable energy) and SDG 13 (climate action) as the share of renewable energy in total energy consumption increases and as territorial GHG emissions are mitigated, respectively. This also positively impacts SDG 8 through the decoupling of GHG emissions from economic (GDP) growth in the transport sector. Additionally, compared with internal combustion engines, electric motors are significantly more energy efficient. Hence, the electrification of transport will have another positive effect on SDG 7 by increasing the energy efficiency of the transport sector, which decreases the energy intensity of GDP.

Following the electrification of transport, domestic car manufacturers will see a growing demand for electric vehicles on the Swedish market, which could provide economic growth and job creation if successfully met, as a positive impact on SDG 8. The electrification of transport could bring further opportunities for sustainable industrialization and new innovations and could supplement infrastructure along the whole production, distribution and use supply chain. A fundamental requirement is the realization of increased capacity for renewable electricity production and distribution, including the upgrading of electricity grids and the construction of charging stations. This could have a positive effect on SDG 9 (industry, innovation and infrastructure). Positive spillover impacts on SDG 8 could also be realized from Swedish imports of electric vehicles, EVBs and other components, since this would drive economic activity in other countries. If other countries, on the other hand, import EVBs produced in Sweden, it also has a positive spillover effect on SDG 8, since such EVBs are produced with relatively low carbon footprints and hence decouple economic growth from GHG emissions.

Decreased domestic consumption of fossil fuels in the transport sector reduces the material footprint, which positively impacts SDG 8, specifically the material footprint per GDP, and SDG 12 (sustainable consumption and production). At the same time, however, electrification of transport will increase the exploitation of critical minerals and thus increase the material footprint. Given that the actual net effect is uncertain, the related impacts on SDG 8 and SDG 12 are assessed as ambiguous. The electrification of transport will also increase the turnover of EVBs, but owing to the lack of established recycling and/or reuse options, waste generation from exhausted EVBs could increase, which negatively impacts SDG 12. For lithium, there is a specific risk of scarcity, which could have another negative impact on SDG 12 and the sustainable management and efficient use of natural resources [54]. Opening new mines in Sweden following increased demand for cobalt, copper and lithium could pose additional risks to SDG 11 and the protection and safeguarding of the natural and cultural heritage of the Sami people [55].

Green hydrogen

There were 10 positive, six negative and one ambiguous impact on the SDGs identified from replacing fossil fuels with green hydrogen (Table 7). The mining of PGMs and nickel, which is necessary in electrolyzers used to produce green hydrogen, is associated with health risks [56, 57]. Large-scale implementation of green hydrogen in the iron and steel industry can hence have a negative spillover effect on SDG 3 (good health and well-being) in countries that extract and process these minerals. Such mining can also generate a negative spillover effect on SDG 6 (clean water and sanitation) because of high water usage during extraction and processing, as well as freshwater pollution [51, 58]. Mining can also generate negative spillover effects on SDG 12 (sustainable consumption and production) from poor management of chemicals and wastes, as well as on SDG 15 (life on land), because of poor management of terrestrial and freshwater ecosystems and the resulting risks of habitat destruction and decrease in biodiversity. Both PGMs and nickel are predominantly mined in countries with weak institutions. This poses additional negative spillovers on SDG 8 (decent work and economic growth) and SDG 16 (peace, justice and strong institutions) through risks for the violation of labor rights and safe and secure working environments. and through risks of increased injustice, corruption and a lack of inclusive institutions, respectively [51, 59].

Using green hydrogen as an input and energy carrier in the iron and steel industry enables the flexible use of intermittent electricity and the replacement of fossil resources, which positively impacts SDG 7 (affordable and clean energy) through an increased share of renewable energy in the total final energy consumption of Sweden [34]. The electrification of the iron and steel industry will, however, significantly increase demand for electricity, a demand that in the short to medium term is most likely to be met by wind power. Even though green hydrogen can balance the intermittent electricity production from wind power, the actual net effect on consumer electricity prices from increased electricity demand is uncertain, which leads to an ambiguous impact on SDG 7 and affordability.

Green hydrogen enables the decarbonization of the Swedish iron and steel industry, clearly positively impacting SDG 13 (climate action) and contributing to a positive spillover effect on SDG 13 in countries importing green steel from Sweden. Replacing coal with electricity and green hydrogen in the iron and steel industry has additional positive effects on SDG 8 and SDG 12 through the decoupling of economic (GDP) growth from GHG emissions and through a decrease in the material footprint per GDP. Actors in the Swedish iron and steel industry could also benefit from a first mover advantage

Table 7 Prioritized SDG impacts from green hydrogen

SDG	Impact	Spillover	Causal relationship	Empirical support
3	-	Yes	Production of electrolyzers -> Increased extraction of critical minerals -> Health risks associated with mining	Specific
6	-	Yes	Production of electrolyzers-> Increased extraction of critical minerals -> Risks for pollution of drinking water and water scarcity	General
7	+	No	Replacement of fossil fuels with electrification in the iron and steel industry -> Decreased use of fossil energy -> Increased share of renewable energy in total final energy consumption	Specific
7	+/-	No	Electrification of the iron and steel industry with green hydrogen -> Increased flexibility of electricity use through green hydrogen storage/Increased demand for electricity -> Impact on average electricity prices	Expert opinion
8	+	No	Replacement of fossil fuels with electrification in the iron and steel industry -> Decreased use of fossil energy -> Economic (GDP) decoupling from GHG emissions	Expert opinion
8	+	No	Replacement of fossil fuels with electrification in the iron and steel industry -> Decreased use of fossil energy -> Decreased material footprint per GDP	Expert opinion
8	+	No	Electrification of the iron and steel industry with green hydrogen -> Increased economic activity in the industry and energy sectors -> Economic growth and job creation	Indicative
8	+	Yes	Domestic production of steel with green hydrogen -> Export of green steel -> Economic (GDP) decoupling from GHG emissions in import countries	Expert opinion
8	-	Yes	Production of electrolyzers -> Increased extraction of critical minerals -> Risks for labor rights and safe and secure environments	General
9	+	No	Electrification of the iron and steel industry with green hydrogen -> Reduced GHG emissions per unit of value added -> Upgrade and retrofit of industry and infrastructure	Expert opinion
11	+	No	Replacement of conventional steel with green -> Reduced embedded GHG emissions in buildings and transport infrastructure -> Reduction of per capita environmental impact of cities	Expert opinion
12	+	No	Replacement of fossil fuels with electrification in the iron and steel industry -> Decreased use of fossil raw materials -> Decreased material footprint	Expert opinion
12	-	Yes	Production of electrolyzers -> Increased extraction of critical minerals -> Risks to sound management of chemicals and wastes including release to air, water and soil	General
13	+	No	Replacement of fossil fuels with electrification in the iron and steel industry -> Decreased use of fossil energy -> Mitigation of territorial GHG emissions	Expert opinion
13	+	Yes	Domestic production of steel with green hydrogen -> Export of green steel -> Mitigation of GHG emissions in import countries	Expert opinion
15	-	Yes	Production of electrolyzers -> Increased extraction of critical minerals -> Risks for biodiversity, habitats as well as terrestrial and inland freshwater ecosystems	General
16	-	Yes	Production of electrolyzers -> Increased extraction of critical minerals -> Risks for corruption and lack off participatory decision-making at local levels in countries with weak institutions	General

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given

by producing premium green steel that could lead to growth opportunities and job creation, offering another positive effect on SDG 8. The export of green steel from Sweden, which replaces conventional steel in industrial production and manufacturing, could also have a positive spillover effect on SDG 8 and SDG 12 by decoupling economic growth from GHG emissions in import countries.

Replacing current coal-based processes with electrification and green hydrogen enables the mitigation of GHG emissions per unit of value added, which constitutes a retrofit of industries and thereby has a positive effect on SDG 9 (industry, innovation, and infrastructure). Replacing conventional steel with green steel in buildings and transport infrastructure also reduces embedded GHG emissions and thus the per capita environmental impact of cities, positively impacting SDG 11 (sustainable cities and communities).

Solar PV

Three positive, eight negative and one ambiguous impact on the SDGs were identified from the large-scale expansion of solar PV (Table 8). The expanded use of solar PV will increase the demand for aluminum and copper (Table 2). Mining of these minerals is associated with negative effects on human health [51, 60], particularly respiratory diseases and allergies, thereby generating a negative spillover effect on SDG 3 (good health and well-being). Such mining might also lead to acid mine drainage and metal and chemical pollution of land, surface and ground water that can impair the ecological status of terrestrial and freshwater ecosystems, threaten local biodiversity, degrade habitats and limit the availability of freshwater. Increased extraction of minerals for solar PV is thus likely to cause negative spillover effects on SDG 6 (clean water and sanitation), SDG 15 (life on land) and SDG 12 (sustainable consumption and

Table 8 Prioritized SDG impacts from solar PV

SDG	Impact	Spillover	Causal relationship	Empirical support
3	-	Yes	Production of PV modules -> Increased extraction of critical minerals -> Health risks associated with mining	General
6	-	Yes	Production of PV modules -> Increased extraction for critical minerals -> Risks for pollution of drinking water and water scarcity	Expert opinion
7	+	No	Expansion of solar PV -> Increased renewable electricity production -> Increased share of renewable energy in total final energy consumption	Expert opinion
7	+/-	No	Expansion of solar PV -> Increased supply of electricity/Increased share of intermittent electricity production -> Impact on average electricity prices	Expert opinion
8	+	Yes	Expansion of solar PV -> Import of solar PV modules -> Increased economic activity in export countries	Indicative
8	-	Yes	Production of PV modules -> Increased extraction of critical minerals -> Risk for labor rights and safe and secure environments	General
9	+	No	Expansion of solar PV -> Development of grid connected energy storage -> Upgrade of infrastructure and new innovations	Specific
12	-	Yes	Production of PV modules -> Increased extraction of critical minerals -> Risks to sound management of chemicals and wastes including release to air, water and soil	Specific
12	-	No	Expansion of solar PV -> Increased deposit of exhausted PV modules -> Increased waste generation	Expert opinion
14	-	Yes	Production of PV modules -> Increased extraction of critical minerals -> Risk for marine ecosystems from seabed and deep-sea mining	General
15	-	Yes	Production of PV modules -> Increased extraction of critical minerals -> Risks for biodiversity, habitats as well as terrestrial and inland freshwater ecosystems	General
16	-	Yes	Production of PV modules -> Increased extraction of critical minerals -> Risks for corruption and lack off participatory decision-making at local levels in countries with weak institutions	General

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given

production) through poor management of chemicals and wastes [60, 61]. The mining and processing of aluminum (bauxite) and copper in countries with weak institutions could have additional negative spillover effects on SDG 8 (decent work and economic growth) through violations of labor rights and safe and secure working environments and SDG 16 (peace, justice and strong institutions) as a consequence of increased injustice, corruption and a lack of inclusive institutions [51, 60]. Additionally, the increased demand for copper could trigger searches for new resource deposits on the ocean floor, which poses risks to damaging marine ecosystems as a negative spillover effect on SDG 14 (life below water) [52, 53].

The increased integration of solar PV in the Swedish energy system will increase the share of renewable energy in total energy consumption, thereby leading to a positive impact on SDG 7 (affordable and clean energy). The impact on consumer electricity prices, i.e., the affordability aspect of SDG 7, is ambiguous, as an increased supply of intermittent electricity might contribute to greater price fluctuations. The imports of solar PV modules to Sweden generate a positive spillover effect on SDG 8 in terms of increased economic growth, job creation and innovation in exporting countries. In Sweden, the large-scale expansion of solar PV could support the development of energy storage capabilities in electricity infrastructure, such as stationary batteries, thereby strengthening innovation, stimulating the development of sustainable infrastructure and positively impacting SDG 9 (industry, innovation, and infrastructure) [62].

Wind power

Four positive, 13 negative and one ambiguous impact on the SDGs were identified from the expansion of wind power (Table 9). The production of wind turbine components requires aluminum, copper, REEs, mainly neodymium and dysprosium, and zinc (Table 2). Mining these minerals may contaminate soil, freshwater and drinking water and cause local air pollution [63–66]. The large-scale expansion of wind power in Sweden thus poses a risk for negative spillover effects on SDG 3 (good health and well-being), SDG 6 (clean water and sanitation) and SDG 15 (life on land). Furthermore, there is an additional risk for a negative spillover impact on SDG 12 (responsible consumption and production), specifically the environmentally sound management of chemicals and wastes [65, 66]. Increased global demand for copper, REEs and zinc could trigger searches for new deposits on the ocean floor. Seabed and deep-sea mining poses great risks to marine ecosystems, with a negative spillover effect on SDG 14 (life below water) [52, 53]. There is a risk for a negative spillover impact on SDG 8 (decent work and economic growth), as mining of REEs in particular is associated with possible violations of labor rights

Table 9 Prioritized SDG impacts from wind power

SDG	Impact	Spillover	Causal relationship	Empirical support
3	-	Yes	Production of wind turbines -> Increased extraction of critical minerals -> Health risks associated with mining	Specific
6	-	Yes	Production of wind turbines -> Increased extraction of critical minerals -> Risks for pollution of drinking water and water scarcity	Specific
7	+	No	Expansion of wind power -> Increased renewable electricity production -> Increased share of renewable energy in total final energy consumption	Expert opinion
7	+/-	No	Expansion of wind power -> Increased supply of electricity/Increased share of intermittent electricity production -> Impact on average electricity prices	Expert opinion
8	+	No	Expansion of wind power -> Increased economic activity in the energy sector -> Economic growth and job creation	Expert opinion
8	+	Yes	Expansion of wind power -> Import of wind turbines -> Increased economic activity in export countries	Indicative
8	-	Yes	Production of wind turbines -> Increased extraction of critical minerals -> Risks for labor rights and safe and secure environments	Specific
9	+	No	Expansion of wind power -> Development of grid connected energy storage -> Upgrade of infrastructure and new innovations	Expert opinion
11	-	No	Expansion of wind power -> Increased land use for wind power parks -> Risks to local participatory democracy	Expert opinion
11	-	No	Expansion of wind power -> Increased extraction of critical minerals and land use for wind power parks -> Risks to the protection and safeguard of natural and cultural heritage	Expert opinion
12	-	Yes	Production of wind turbines -> Increased extraction of critical minerals -> Risks for sound management of chemicals and wastes including release to air, water, and soil	General
12	-	No	Expansion of wind power -> Increased deposit of turbine blades -> Increased waste generation	Specific
14	-	Yes	Production of wind turbines -> Increased extraction of critical minerals -> Risks for marine ecosystems from seabed and deep-sea mining	General
15	-	No	Production of wind turbines -> Increased extraction of critical minerals -> Risks for biodiversity, habitats as well as terrestrial and inland freshwater ecosystems	Specific
15	-	No	Expansion of wind power -> Increased land use for wind power parks -> Risks for habitat degradation, fragmentation, and loss	Expert opinion
15	-	Yes	Production of wind turbines-> Increased extraction of critical minerals -> Risks for biodiversity, habitats as well as terrestrial and inland freshwater ecosystems	General
16	-	Yes	Production of wind turbines-> Increased extraction of critical minerals -> Risks for corruption and lack off participatory decision-making at local levels in countries with weak institutions	Specific
16	-	No	Expansion of wind power -> Increased land use for wind power parks -> Risks for participatory decision-making on local levels	Expert opinion

The positive (+), negative (-) or ambiguous (+/-) impacts, spillovers, causal relationships and empirical support are given

and safe and secure working environments. Increased demand for REEs also poses a risk for corruption and a lack of participatory decision-making as a negative spillover effect on SDG 16 (peace, justice and strong institutions), as the mining of REEs is concentrated in countries with weak institutions [63, 67].

In addition, increased demand for REEs might lead to the opening of new mines in Sweden, which is associated with risks for a negative impact on SDG 15 because of habitat loss, pollution, and the leakage of hazardous chemicals [66, 68]. Opening new mines as well as new wind power establishments could also negatively impact SDG 11 (sustainable cities and communities) through risks for the protection and safeguarding of the natural and cultural heritage of the Sami people [55, 69]. The large-scale expansion of wind power will exploit areas at land and sea. This could lead to political and/or commercial conflicts between national, regional and local interests with additional risks for a negative impact on SDG 11. If established in sensitive areas, the expansion of wind power could also pose a risk to biodiversity and ecosystems through the loss or degradation of habitats, negatively impacting SDG 15.

The large-scale expansion of wind power increases the share of renewable energy in total final energy consumption, which positively affects SDG 7 (affordable and clean energy). However, the impact on consumer electricity prices, i.e., the affordability aspect of SDG 7, is ambiguous, as an increased supply of intermittent electricity might contribute to greater price fluctuations. Swedish energy companies and supplementing industries could benefit from the expansion of wind power, leading to economic growth and job creation and having a positive effect on SDG 8. The import of wind turbines could also generate a positive spillover effect on economic activity outside of Sweden [70]. Increased electricity generation from wind power may also create incentives to develop energy storage capabilities in electricity infrastructure, such as stationary batteries, thereby strengthening the innovation and development of sustainable infrastructure and positively affecting SDG 9 (industry, innovation, and infrastructure).

Discussion

The technological transformation required to reach net-zero GHG emissions in Sweden by 2045 is clearly sweeping, with far-reaching consequences across many sectors. As shown in this study, at least 11 out of the 17 SDGs will potentially be affected positively or negatively, domestically or abroad—thus highlighting a multifaceted linkage between climate mitigation efforts and the UN 2030 Agenda for Sustainable Development. In this study, it is also shown that the key technologies in this transformation have more positive impacts than negative impacts in Sweden, whereas the opposite is true for impacts abroad. International spillover effects have received increased attention in recent years as they obstruct the implementation of the SDGs in other countries. When SDG indices are analyzed, it is clear that there is a negative correlation between a nation's fulfillment of the SDGs and its negative spillover effects [71, 72]. Aligning Swedish climate policy with the SDGs and vice versa needs to consider spillover impacts in line with the core principle of Agenda 2030: "Leaving No One Behind".

McCollum et al. [19] noted that SDG interactions may not always be universally linked but rather context dependent and case specific. SDG impact assessments that differ in context and scope are, indeed, likely to show varying and perhaps even contrasting results. The qualitative SDG assessments presented by the IPCC [9] do, however, provide a global overview of synergies and trade-offs from the large-scale deployment of sectorial mitigation options. In a direct comparison, the results presented here for the studied key technologies show both agreement and differences with the assessments of the IPCC. The main similarities are that both studies identified no significant impacts linked to SDG 4 (quality education), SDG 5 (gender equality) or SDG 10 (reduced inequalities) and synergies with SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation and infrastructure). The IPCC identified several synergies with SDG 1 (no poverty) and SDG 2 (zero hunger), which were not identified in this study. The main reason is likely due to the difference in scope—the scenario studied by the IPCC was the climate transition on a global level, including the transition in low-income regions, thus making issues of poverty and hunger increasingly relevant to mitigation efforts. Furthermore, the IPCC identified synergies with SDG 3 (human health) when replacing fossil-fueled thermal power in electricity generation with solar PV and wind power, as it reduces air pollution. In Sweden, however, thermal power is typically free from fossil fuels and is viewed as an important mitigation strategy that will continue to expand. Therefore, it is unlikely that solar PV and wind power will replace thermal power and induce such synergies. Instead, biomass utilization in the Swedish power sector was assessed as having a negative effect on SDG 3 (Table 3). The IPCC identified trade-offs between solar PV and wind power with SDG 2 (zero hunger) as well as SDG 15 (life on land) because land use changes negatively affect agriculture and biodiversity, highlighting a common concern of climate mitigation [9]. A negative impact on SDG 2 is unlikely to be realized in Sweden because of current environmental regulations, which do not allow energy projects to be established on arable land. While a negative impact of wind power on SDG 15 was identified on the basis of land use changes, solar PV projects are much more flexible in their placements and are believed to primarily be placed on land, including rooftops, with low values for biodiversity.

On the basis of the results of the SDG assessments presented here, a set of overarching narratives encapsulating synergies and trade-offs between the Swedish climate transition and the SDGs emerges. In the domestic context, positive impacts are foremost linked to SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation and infrastructure). This is not surprising given the technological focus of this study. It is also well in line with political aspirations and the Swedish public debate that emphasizes the need for industrial transformation to reach net-zero emissions of GHGs as well as how the climate transition can provide growth and export opportunities to the Swedish industry. As is evident across all the key technologies assessed, the development and implementation of climate-neutral technologies have the potential to create jobs, growth markets, infrastructures, innovations and systemic know-how with export potential. Climate benefits from Swedish exports—sometimes referred to as a 'comparative carbon advantage' [73]—could be realized and are here assessed as potential positive spillover impacts on SDG 8 (decent work and economic growth) and SDG 13 (climate action) through the decoupling of economic growth and GHG emissions in countries that import Swedish EVBs and green steel.

The Swedish climate transition is, however, largely dependent on imports along supply chains to support technological transformations. The need for raw materials, particularly critical minerals, is expected to increase rapidly. The most clear-cut narrative derived from the SDG impact assessments is the shift from fossil resources to critical minerals. The growing dependency on critical minerals is acknowledged in policy—for example, the European Critical Raw Materials Act—emphasizing increased attention to the security of supply issues, including sustainable sourcing practices [74]. Among industrial businesses acting in global supply chains, there is growing awareness of broader sustainability implications from the upstream extraction of minerals. In response, several global initiatives, such as the Alliance for Responsible Mining, the Initiative for Responsible Mining Assurance, the Responsible Mining Foundation and the Responsible Minerals Initiative, work on different levels to provide information and encourage cooperation to combat social and environmental risks from mining. Sustainability efforts or corporate social responsibility (CSR) actions are, however, limited by the lack of transparency, data and corruption, which hamper trust among private actors, authorities and civic society [75, 76]. A large set of trade-offs originating from mineral extraction in countries with weak institutions, posing spillover risks to SDG 3 (human health and well-being), SDG 6 (clean water and sanitation), SDG 8 (decent work and economic growth), SDG 15 (life on land) and SDG 16 (peace, justice and strong institutions), were identified in this study. These risks, if not carefully considered in policy, business conduct and due diligence, could increase over time.

Another narrative concerns material use, recycling and circularity. As the deployment of transformative technologies unfolds, end-of-life aspects with potential risks to SDG 12 (responsible consumption and production) increase. Wind power, solar PV and EVBs all contain advanced composite materials and alloys to enhance durability, energy efficiency and energy density. While responsible for crucial properties for market performance and uptake, these advanced materials might cause concern for future recycling options. Although the risks associated with SDG 12 and waste generation were categorized as domestic in this study, effective solutions could involve actors upstream in value chains and, thus, be of concern to international policymaking and business cooperation. To avoid related waste problems, environmental degradation and mineral scarcity, new technologies and practices for recycling need to be developed in tandem with product development, incorporating future circular options in its design. Indeed, as noted by the IEA [37], in contrast to fossil fuels, the advantage of renewable energy technologies is the potential for material recovery and recycling, whereas oil, coal and natural gas require a continuous new supply. The increased circular flow of materials will decrease the need for virgin minerals and associated risks for sustainable development. Although some test facilities are planned, there are currently no fully established recycling options in Sweden for, e.g., wind turbine blades, solar PV modules or EVBs.

Recently, much of the public debate in Sweden, as in most of Europe, has focused on increasing energy and electricity prices, as well as aspects of participatory decision-making at local levels. A final narrative derived from the assessments is linked to SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 16 (peace, justice and strong institutions) and the impact of upscaling intermittent renewable energy on household economies as well as issues of local acceptance. There is growing concern that an increased share of household income will be spent on energy costs, bringing households already on the margin closer to energy poverty. Since the 1970s, the Swedish electricity mix has been fully reliant on hydro and nuclear power, which have provided relatively low and stable electricity prices. Even though Sweden has decommissioned six out of twelve nuclear reactors in the span of 25 years, the electricity jointly produced by hydro and nuclear power has remained roughly the same [77]. A large-scale expansion of wind power and solar PV will cause short-term fluctuations in power generation and, consequently, electricity prices. The long-term economic effect is, however, assessed as ambiguous, as actual electricity prices depend on demand and supply in European energy markets as well as governmental policies. Public concern for energy prices is one of several reasons for the increased opposition against the planning and permitting of new land-based wind power installations in a growing conflict between national and local interests. A resistance that was initially characterized by ’not in my backyard’ has expanded into a wider manifestation of ’not in anyone’s backyard‘, putting forward arguments against wind power as negatively impacting health, natural environments, and cultural heritage, as well as being ineffective, expensive, weather dependent and harmful to the climate [78, 79]. The lack of incentives to local communities to accept wind power establishments could prove to be a major obstacle for Sweden to achieve its climate target, as is evident in recent trends of municipal vetoes against planned wind power installations. Some of these issues could be influenced by the recent EU directive [80], which promotes energy from renewable sources, allowing member states to declare renewables acceleration areas. This instrument makes it possible to avoid duplication of environmental assessments and, according to the EU, simultaneously ensures a high level of environmental protection.

The SDG impacts identified in this study should be viewed as a first assessment of potential synergies and trade-offs between the technological transformations needed to reach zero net GHG emissions in Sweden and the SDGs. The scope of the study has several limitations, and some methodological considerations should be discussed.

First, the SDG impact assessments carried out in this study were based on input from a set of academic and practitioner experts who were challenged to address the complexity of the SDGs. When moving beyond their explicit expertise, the tendency to acknowledge emerging risks in favor of what is perceived as familiar [81] may introduce bias in the results. However, the approach to structure workshop outputs, construct causal relationships and establish empirical support resulted in the removal of empirically unsupported SDG impacts and contributed to minimizing such biases. Second, incomplete contextual information is a typical challenge in scenario-based SDG impact assessments [19]. Spatial and temporal context, as well as governance and sociocultural and technological conditions, are generally considered key factors in SDG interactions [7]. The temporal development of the key technologies and the specific context in which they are implemented and used were deemed to be out of scope for this study. For example, changes in Swedish policies to not expand hydro or nuclear power or needs for additional infrastructure such as electrical grid connections were not included. Hence, the key technologies, as well as the governance, sociocultural and socioeconomic aspects, were studied. Since these aspects might change, along with the development of how the key technologies will be designed, produced, adopted and disposed of in the future, the SDG impact assessments should potentially be updated to follow future developments. Third, the construction of causal relationships and the search for empirical support were designed to strengthen confidence in the results and seek confirmation when prioritizing SDG impacts. It should be noted, however, that the causal relationships were formulated a priori and the search for empirical support was nonexhaustive. As such, these relationships should not be mistaken for expressions of verified causality over all possible applications.

Conclusions

The conclusion of this study is that the large-scale implementation of key technologies in Sweden will have far-reaching consequences across several sectors, illustrating the need for policy coherence between the Paris Agreement and the 2030 Agenda for Sustainable Development. Reaching net-zero GHG emissions will result in more positive than negative impacts in the domestic context, reinforcing the Swedish implementation of the SDGs. However, the opposite is true for international spillovers, where the Swedish climate transition might hamper the fulfillment of specific SDGs in other countries, mainly those concerning human health, environmental degradation, local democracy and corruption.

Therefore, governance policies and strategies for business cooperation that align the Swedish climate transition with the UN 2030 Agenda are needed. As such, the SDG impacts identified in this study represent an opportunity for policymakers and business actors to explore options for a more sustainable climate transition. The SDG impact assessments presented serve as a starting point for such efforts. Although knowledge from academic and practitioner experts is summarized together with knowledge from the scientific literature into a set of prioritized SDG impacts, continued efforts from the scientific community are needed to deepen this knowledge.

A plausible next step would be to involve stakeholders and relevant expertise to jointly pinpoint needs for action in the policy sphere and discuss collaborative business approaches to strengthen potential synergies and minimize trade-offs. Furthermore, to mitigate sustainability challenges identified as spillover impacts or to reinforce feedback loops in recycling, actors across relevant supply chains of transformative technologies need to seek new ways of collaboration. Supply chain-specific SDG impact assessments could be carried out as starting points for such efforts, facilitated by neutral partners to induce trust and create a common view of where to focus joint action. The set of prioritized SDG impacts presented in this study could lay the groundwork for the construction of indicators as a measure to monitor the progress of a climate transition in line with the SDGs.

Although the focus of this study is on the specific context of the Swedish climate transition, some results might mirror the situation in other countries. Hence, the results might be a relevant starting point for similar studies in other parts of the world. Additionally, the results can be relevant at the subnational level. Several regions, cities, municipalities and local businesses in Sweden actively participate in climate transition and implement policies aimed at reducing GHG emissions. The SDG impact assessments could help regional and local policymakers and businesses align their efforts to reduce climate transition impacts on the SDGs.

Finally, the methodological approach applied in this study, i.e., to elicit expert judgments in a workshop format followed by the structuring and analysis of inputs, could inspire researchers and practitioners to collaborate more to develop new knowledge concerning complex sustainability issues.

Supplementary Information

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Supplementary Material 1.

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Author contributions

A.A., H.K. and K.M.E. wrote the main manuscript text, A.A. and K.M.E. prepared Figs. 1, 2 and 3 and A.A., H.K. and K.M.E. prepared all tables. All authors contributed to conceptualization, literature review, data analysis and review of the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

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Competing interests

The authors declare no competing interests.

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