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Synergy of green energy technologies through critical materials circularity

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ABSTRACT

Synergies between technology flows is essential to balance the consumption of their related critical materials and promote a sustainable green economy transition. Using dynamics modelling, a comprehensive analysis of silicon flows applied in green energy technologies such as photovoltaic (PV) solar panels and lithium-ion batteries (LiBs) is provided. The results show that appropriate allocation of the circular flows of different silicon grades can become an effective global solution for saving material, energy and water as well as mitigating greenhouse gas (GHG) emissions. About 15 % of required global silicon could be provided by secondary production from end-of-life green energy technologies by 2030. Recovering metallurgical, solar and electronic grades of silicon from global end-of-life PVs compared to its primary production will lead to savings of 3.5 billion GJ of energy, 3.1 million m^3 of water and over 65 Mt CO_2 eq of GHG emissions globally by 2030. Also, synergies between material flows from PVs waste to advance LiBs production aims to save around 38 M GJ of energy and 0.01 million m^3 of water and mitigate 4 Mt CO_2 eq of GHG emissions through secondary production practices by 2030. The findings outline a systematic solution for environmental sustainability of recycling by suggesting optimized integrated material flows of recovery of 50 % metallurgical, 25 % solar and 25 % electric grades of silicon from global end-of-life PVs.

1. Introduction

Providing reliable and resilient clean energy is essential to a green transition and social development along with preventing anthropogenic climate change. Capture of solar energy by technologies such as photovoltaic (PV) panels and use of lithium-ion batteries (LiBs) for energy storage have accelerated considerably in the last decade as part of decarbonization measures to limit the global average temperature increase below 2 °C above pre-industrial levels [1,2]. Worldwide, this has led to around 850 GW (GW) of cumulative installed solar PV capacity as of 2021, according to the International Renewable Energy Agency (IRENA) [3]. A fast growth (>25 %) in the annual deployment of PVs is expected by 2030 to meet the targets of the green transition [4,5]. Additionally, it is estimated that the demand for LiBs used in electric vehicles (EVs) will increase from 215 GWh in 2020 to 1525 GWh by 2030 [6].

Consequently, the development of PV technologies such as monocrystalline and polycrystalline silicon solar panels, which dominates around 90 % of the global PVs market, has resulted in the increased consumption of critical materials like silicon (Si) [7]. It is worth noting that although silicon's crustal abundance is ~295,000 ppm [8], high-purity silica (>99.95 % purity) is relatively rare in nature, therefore it is considered to be a critical material [7]. Each crystalline silicon (c-Si) PV comprises 2–4 kg of solar-grade silicon (SoG-Si) and when the 20–30 year lifetime of PVs are considered, there is an increasingly significant amount of related PV waste - 8 million tonnes (Mt) by 2030 and 78 Mt by 2050 [9] – that requires treatment. Conversely, it is estimated around 1.3 Mt of silicon will be required to supply the demands of energy technologies like PVs and LiBs for the global energy transition by 2030 [10]. Furthermore, it is notable that the quality of raw quartz sand available to industry is also reducing as global resources become exhausted. In light of these challenges, an understanding of Si materials circularity offers a significant opportunity to support its supply for the energy sector [11].

As PVs and LiBs are among the most economically competitive green energy technologies for decarbonization [12,13], there is still a need to provide a systematic solution that offers a sustainable supply chain for key component materials like silicon. Literature shows that several PV module recycling technologies are under development. The regional differences in research and technology development foci including patents are provided by IEA [14]. Several studies have investigated

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Nomenclature

S	The global stock of silicon ore (tonne)
M	Annual production rate of silicon from mining (tonne)
MG	Annual processing of metallurgical grade silicon (tonne)
t	Time (year)
SMG	The global stock of metallurgical grade silicon (tonne)
G	Processing of produced high purity grades of silicon (tonne)
N	The global stock of silicon used in product (tonne)
D	Demand for global silicon required for product (tonne)
Pr	Annual demand of silicon grade (tonne)
C	Projected population of a country (person)
F	Projected GDP of a country (Euro)
Q	Silicon intensity coefficient applied in green energy technologies (percent)
R	The global stock of available silicon for the recycling stage (tonne)
T	The collection rate of silicon from used product (percent)
Re	The silicon recycling rate from product (percent)
Sec	The stock of recyclable silicon (tonne)
J	The amount of recovered silicon (tonne)
E	The cumulative amount of energy consumption (gigajoule)
AE	The annual amount of energy consumed in country (gigajoule)
AW	The annual amount of direct and indirect water consumed in global silicon flows (cubic meter)
W	The cumulative amount of direct and indirect water consumed in global silicon flows (cubic meter)
CG	The cumulative related emissions of silicon flows (unit of pollution)
AG	The annual related emissions of silicon flows (unit of pollution)
EG	The global environmental impact of recovering silicon grades (unit of pollution)

Greeks

α	Coefficient of mining silicon
β	Coefficient of processing rate of metallurgical silicon
δ	Coefficient of silicon grade
μ	Share of silicon grade
θ	Recycling efficiency of product
ρ	Recovery efficiency of product
ν	Energy required per one tonne of silicon flow
ω	The intensity of water source
λ	The annual rate of emission

Subscripts

i	Industrial silicon and ferrosilicon
j	Mining country
k	Solar and electric grades
p	Product
n	Country
q	Stage of supply chain
m	Energy source
l	Water source
h	Emission
d	Environmental impact

Abbreviations

BC	Black carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 eq	Carbon dioxide equivalent
c-Si	Crystalline silicon
CZ	Intermediate Czochralski
EG-Si	Electric-grade of silicon
EPRS	European Parliamentary Research Service
EVs	Electric vehicles
EoL	End-of-life
GDP	Gross domestic product
GHG	Greenhouse gas
IRENA	International Renewable Energy Agency
kWp	The amount of energy a panel can produce at its peak performance
LiBs	Lithium-ion batteries
LiBs-Si	Silicon grade used in lithium-ion batteries
LCA	Life cycle assessment
LMR-NMC-Gr-Si	Cathode ($0.5Li_2MnO_3$•$0.5LiNi_{0.44}Co_{0.25}Mn_{0.31}O_2$ [LMR-NMC]) and a graphite-silicon blend anode
MG-Si	Metallurgical-grade silicon
NO_x	Nitrogen oxides
N_2O	Nitrous oxide
PM2.5	Particulate matter with sizes smaller than 2.5 μm
PM10	Airborne particulate matter with sizes smaller than 10 μm
POC	Particulate organic carbon
PV	Photovoltaic
Si	Silicon
SoG-Si	Solar-grade silicon
SO_x	Sulfur oxides
UNCOMTRADE	United Nations Commodity Trade Database
USGS	United States Geological Survey
VOC	Volatile organic compounds

silicon recovery from PVs waste at laboratory scale by chemical-based methods, e.g., recycling of polycrystalline silicon in US [15], South Korea [16–18], and Japan [19]; recycling of monocrystalline silicon in US [20], and South Korea [21,22]; recycling of both polycrystalline and monocrystalline silicon in Poland [23,24], and Japan [25]. Nevertheless, none of these chemical-based methodologies have been upscaled into industrial production. In addition, combination of thermal and chemical methods has been used for recycling of polycrystalline and monocrystalline silicon on a lab scale in Taiwan [26], South Korea [27–29] and EU [30] but also on a pilot scale within the EU [31,32].

2. Literature review

A detailed review of the environmental impacts of c-Si photovoltaic panels from literature is provided in Table 1. The table compares various aspects of the previous studies including information on the objective of the study, method used, type of PV, and the supply chain scope, as well as the key environmental indicators like energy consumption, water use and emissions. Main stages of the supply chain include mining, processing, manufacturing and recycling. A recent study [33] showed a significant environmental improvement in the mono c-Si PV system production, mainly at the wafer stage, for which the impacts have been reduced by up to 50 % in carbon emissions and 42 % in acid gas emissions. Maani et al. [34] highlighted that PV panel recycling can be integral to the recovery of considerable amounts of materials and add to installed solar panels economic benefits.

Several researchers have addressed the issues connected with environmental impacts of silicon flows, however, environmental impact assessments of silicon's life cycle are limited to certain supply chain stages and regions, e.g. recycling in Thailand [54], Korea [37] and China

Table 1
Summary of investigation on the environmental impact of crystalline silicon photovoltaic panels.

Reference	Objective of study	Method	Type of PV	Supply chain scope				Environmental Impact			Geographical scope
				Mining	Processing	Manufacturing	Recycling	Energy	Water	Emissions	
[35]	Life cycle assessment of metallurgical silicon grade production to panel fabrication	Life cycle assessment (LCA)	Monocrystalline silicon (1.2 kWp)		✓	✓		✓		✓	Local: Brazil
[36]	Life-cycle energy and environmental performance of PV systems	LCA and net energy analysis	Polycrystalline and monocrystalline silicon	✓	✓	✓		✓		✓	Regional: Europe, China, USA
[37]	Evaluation of the environmental impact of c-Si PV	LCA and scenario analysis	Polycrystalline and monocrystalline silicon			✓	✓	✓		✓	Local: Korea
[38]	Comparison of CO_2 emissions of solar PV productions	LCA	c-Si PV	✓	✓	✓		✓		✓	Regional: China, Europe, USA
[39]	Assessing the environmental impact of PV system components (PV modules, inverters, batteries, and steel foundation)	LCA: cradle-to-use approach and scenario analysis	Polycrystalline silicon			✓		✓		✓	Global
[40]	Environmental impact of PV system	LCA and sensitivity analysis	Polycrystalline silicon			✓		✓		✓	Local: China
[41]	Environmental impact of domestic and international trade of raw materials for PV manufacturing	Scenario analysis	Polycrystalline silicon			✓				✓	Local: China
[42]	Water Footprint of European Rooftop Photovoltaic Electricity	LCA	Monocrystalline silicon			✓	✓		✓		Regional: Europe
[43]	Environmental impact of PV system	LCA: cradle-to-gate approach	Polycrystalline silicon			✓		✓		✓	Local: China
[44]	Environmental impact of PV system	LCA: cradle-to-gate approach	Monocrystalline silicon			✓		✓		✓	Local: China
[45]	Environmental impacts of recycling c-Si PV	LCA: "gate to gate" approach	c-Si PV				✓	✓		✓	Global
[46]	Environmental impacts of grid-connected power generation in silicon solar modules manufacturing	LCA	c-Si PV			✓		✓		✓	Local: China
[47]	Assessing the life cycle impact of silicon PV energy generation	LCA	c-Si PV (1.5 kW)			✓		✓		✓	Local: Nigeria
[48]	Environmental assessment of recycling multi-crystalline silicon	LCA	Polycrystalline silicon				✓			✓	Local: China

(*continued on next page*)

Table 1 (*continued*)

Reference	Objective of study	Method	Type of PV	Supply chain scope				Environmental Impact			Geographical scope
				Mining	Processing	Manufacturing	Recycling	Energy	Water	Emissions	
	photovoltaic panels										
[49]	Environmental assessment of green products	LCA	Monocrystalline silicon			✓		✓	✓	✓	Regional: EU
[50]	LCA of the most commercially adopted solar PV technologies	ReCiPe life cycle impact assessment	Polycrystalline and monocrystalline silicon	✓	✓	✓		✓	✓	✓	Regional: European and OECD countries
[51]	Assessing environmental footprint of PV technologies	Geospatial analysis	Polycrystalline and monocrystalline silicon			✓				✓	Global
[52]	Assessing environmental performance of PV systems	Introducing an intractive tool (ENVI-PV): combining geospatial analysis and LCA	Polycrystalline and monocrystalline silicon			✓				✓	Global
[53]	Comparative LCA of c-Si PVs	LCA	Polycrystalline silicon (60-cell)	✓	✓	✓		✓		✓	Local: Singapore

[55]. Nevertheless, these previous studies have not determined the environmental drawbacks and benefits of recovering different silicon grades in recycling cf. primary production. Furthermore, no holistic view to use recycled energy raw materials in the production of advanced LiBs based on a systems approach at a global scale is provided. This approach is needed to address the EU requirement for recycled content in new LiBs production from January 2027 [56]. By consideration of three primary grades of silicon including metallurgical-grade (MG-Si), SoG-Si, and electric-grade of silicon (EG-Si), this work provides a comprehensive assessment that involves the recovery of silicon from PV waste and subsequent use of recycled silicon not only for the manufacture of new PVs but also novel Li-batteries [57] i.e. Si-based anode LiBs e.g., LMR-NMC-Gr-Si (cathode ($0.5Li_2MnO_3 \bullet 0.5LiNi_{0.44}Co_{0.25}Mn_{0.31}O_2$ [LMR-NMC]) and a graphite-silicon blend anode) [58–61]. Moreover, a detailed quantitative assessment of environmentally sustainable ways to recover silicon is outlined to ascertain energy and water consumption as well as emission reduction throughout the different processes.

This novel study consists of a holistic assessment of the quantitative impact of synergizing green energy technologies on the mass flows of silicon and assessing their side effect and dynamic changes over time (2010–2030). Compared to previous publications, this research offers a detailed analysis of the subsequent stages of the silicon life cycle including two green energy technologies: solar PV and lithium-ion battery. In addition, the work attempts to determine the benefits of possible circularity options within the supply chain that include environmental impact reduction and improved resource efficiency.

The findings indicate that a systematic recycling and integration of recycled material flows—specifically EoL PV materials into advanced LiBs production—could help to achieve a more sustainable green energy transition. Overall, this approach provides an insight into the fundamental question: To what extent does the circularity of a critical material - silica - aim to synergize green energy technologies as a sustainable solution?

3. Materials and methods

The approach proposed in this study includes the following: (i) The quantitative assessment involves a holistic perspective of the silicon life cycle and green technologies including solar PVs and lithium-ion batteries; (ii) regional and global material flow analysis is used to quantify mass flows through the life cycle; (iii) an LCA method is used to obtain the environmental impact linked with material flows; (iv) system dynamics modeling is used to observe the dynamic causality of resources and environmental criteria influenced by changing economic and market conditions, throughout the silicon supply chain.

The methodology includes eight main steps: The first step involves studying previous literature and reports to understand the supply chain of silicon, including its factors, variables, subsystems, and dynamics. The second step focuses on identifying environmental problems associated with influential variables. The third step determines an appropriate approach to address the identified problems. Moving on to the fourth step, the system boundaries for the assessment are defined, and a comprehensive evaluation framework is selected. This allows for the creation of a conceptual model that includes mechanisms, balancing loops, and reinforcing loops affecting the subsystems of the silicon supply chain. A causal loop diagram is used to illustrate variables using the system dynamics approach. The fifth step involves collecting data from 1990 to 2021 and formulating a dynamic hypothesis. Based on the conceptual model, a stock and flow diagram is developed. The model is then verified and validated in the sixth step, emphasizing that modeling is a recursive process rather than a sequential one. In the seventh step, the integration of renewable energy technologies is simulated and evaluated using various scenarios. Finally, the environmental impact of processes is investigated across all scenarios.

The structure of the developed dynamic model consists of mathematical equations and input data. The material flow model is linked with energy and water resources required for production of silicon in all stages of supply chain from mining to recycling. Both material flows and energy and water resources characterized by solar PVs and LiBs production interact the demand for silicon. The assessment of GHG emissions and other pollution follows the cradle-to-cradle approach.

Using system dynamics modeling [62] as a first step, the silicon global mass flows are quantified through all supply chain stages. The silicon required for PVs and LiBs technologies from mining to recycling including exports and imports were simulated. The geographical distribution of flows has been used across GDP per capita along with the silicon utilization factor for green energy technologies. The environmental assessment of each flow through all supply chain stages has been carried out addressing energy consumption, water use, air emissions and related pollution. Fig. 1 shows the conceptual model of silicon flows

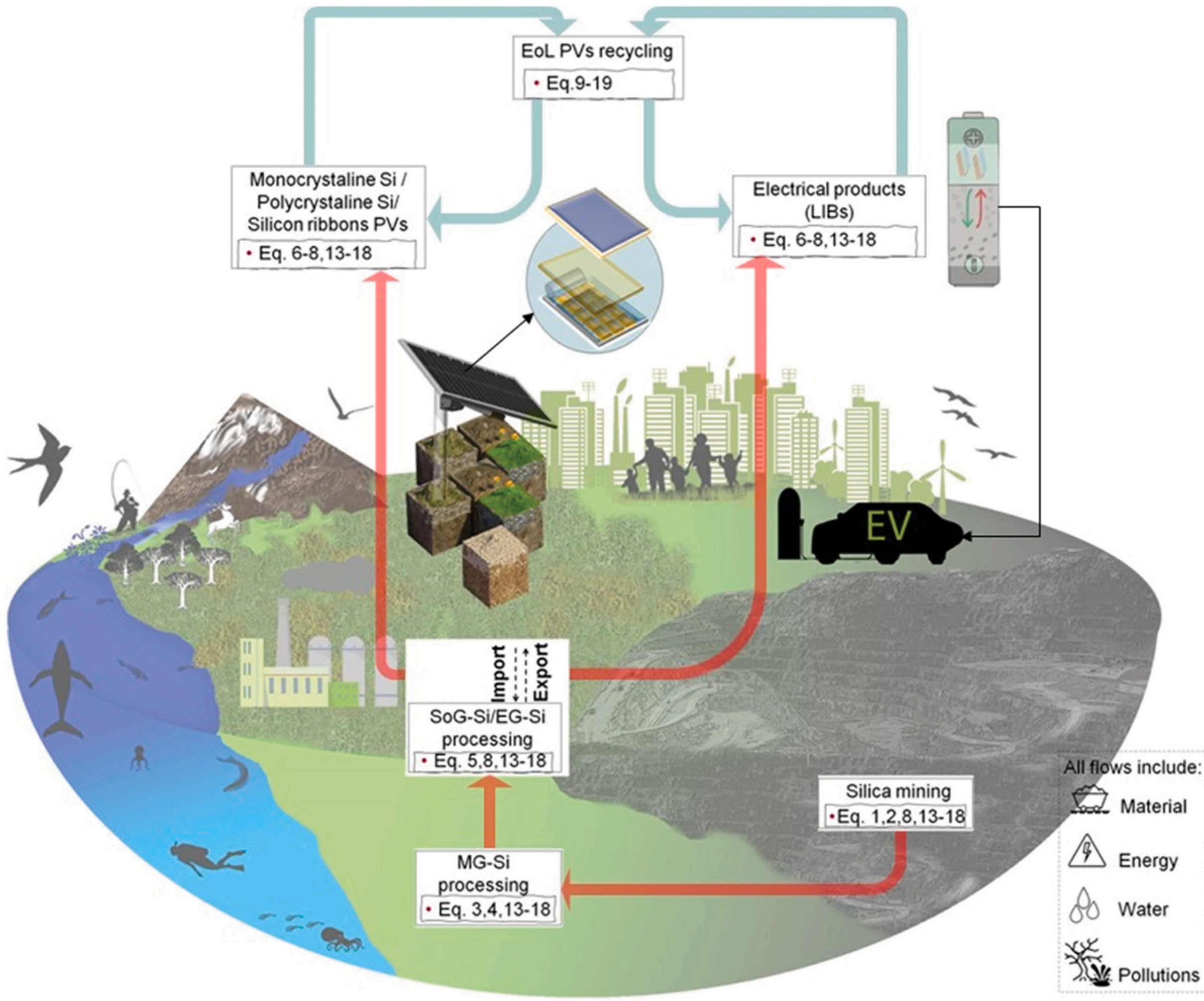

Fig. 1. Conceptual model of silicon flows in green energy technologies.

utilized in green energy technologies with relevant mathematical equations. This model quantifies the stocks and flows of silicon as well as their environmental impact and consists of 522 endogenous (i.e. they affect and are affected by other components), exogenous (i.e. they are not directly affected by the system components) variables and parameters.

The most critical parameters that influence the results are volatility of silicon markets caused by geopolitics and changes to c-Si PV technologies that require less Si. Due to the fast pace of technological development and growing uncertainties of silicon market the horizon of the analysis in this study is considered over a short-term period, until 2030, based on the best available technology. Although, there are several new technologies in pilot tests phase, however, there remain questions related to their industrial scale use. Therefore, it is assumed that such technologies will not be an influence in the near future.

3.1. Stock and flow of silicon

Usually, the source of the silicon is silica in various natural forms such as quartzite or quartz sand, which is refined to a high grade for use in green energy technologies via processing and purification to remove impurities. Silica in the quartz sand is reduced in an arc furnace to MG-Si followed by high purification (6N–9N) for SoG-Si and EG-Si. In particular, impurity tolerances must be no greater than 0.01 and 0.0001 parts per million by weight (ppmw) for SoG-Si and EG-Si, respectively [63]. Generally, this process is achieved through a (modified) Siemens process [64]. Then, polycrystalline silicon ingots are cast and sliced into wafers. Several methods [65,66] have also been investigated to fabricate polycrystalline silicon PV cell materials with increased photoelectric transfer efficiencies and lower production costs. In addition, monocrystalline PV cells require another recrystallization known as the intermediate Czochralski (CZ) step [67]. Finally after wafer slicing, PV cells are encapsulated between glass panes and assembled into frame.

Equation (1) calculates the global stock of silicon ore ($S(t)$) over the period "t_0-t", where"t_0" is the initial year and "t" is the final year. M_{ij} (t) presents annual production rate of silicon from mining by type "i" (with $i = 1,2$) including industrial silicon and ferrosilicon and by mining country "j" (with $j = 1,2, \ldots,28$) including Argentina, Australia, Bhutan, Bosnia and Herzegovina, Brazil, Canada, China, Egypt, France, Germany, Iceland, India, Kazakhstan, South Korea, Laos, Malaysia, Norway, Paraguay, Poland, Russia, Slovakia, South Africa, Spain, Turkey, Ukraine, Uzbekistan and United States (Equation (2)). MG_j (t) corresponds to annual processing of metallurgical grade silicon, which is calculated according to Equation (3). Historical data for the global mine production of ferrosilicon and silicon are available for the period between 1990 and 2021 from United States Geological Survey (USGS) data sources [68].

$$S(t) = \int_{t_0}^{t} \left(\sum_{j=1}^{28} \sum_{i=1}^{2} M_{ij}\ (t) - \sum_{j=1}^{28} MG_j\ (t) \right) dt + S(t_0) \tag{1}$$

$$M_{ij}(t) = \alpha_{ij} * S\ (t) \tag{2}$$

$$MG_j(t) = \beta_j * S(t) \tag{3}$$

where α_{ij} is a coefficient of mining silicon in type "i" by mining country "j" and β_j is a coefficient of processing rate of metallurgical silicon affected by stock of silicon ore in the year "t", $S_j(t)$.

Equation (4) calculates the global stock of metallurgical grade silicon (SMG(t)) in the time period "t_0-t" by a time integral of annual processing of metallurgical grade of silicon ($MG_j(t)$) in mining country "j" minus processing of produced high purity grades of silicon, $G_k(t)$ (with k = 1,2) including solar and electric grades (Equation (5)).

$$SMG(t) = \int_{t_0}^{t} \left(\sum_{j=1}^{28} MG_j(t) - \sum_{k=1}^{2} G_k(t) \right) dt + SMG(t_0) \tag{4}$$

$$G_k(t) = \delta_k * SMG(t) \tag{5}$$

where δ_k is a coefficient of silicon grade "k".

Equation (6) calculates the global stock of silicon used in product "p" ($N_p(t)$) (with p = 1,2,3,4) including polycrystalline, monocrystalline and ribbon silicon PV and electric products over the time period "t_0-t" by a time integral of $G_k(t)$ as annual rate of silicon grade "k" applying in global manufacturing minus annual demand of silicon grade "k" in global manufacturing of product "p", $Pr_{kp}(t)$ (Equation (7)).

$$N_p(t) = \int_{t_0}^{t} \left(G_k(t) - Pr_{kp}(t) \right) dt + N_p(t_0) \tag{6}$$

$$Pr_{kp}(t) = \mu_{kp} * D_p(t) \tag{7}$$

where $D_p(t)$ is demand of global silicon required for product "p" in the year "t" and μ_{kp} is a share of silicon grade "k" in product "p". The demand for silicon defines as the available amount of silicon in country "n" and its deficit for production sector which will be supplied by import.

The distribution factor of silicon consumption is determined with Equation (8) and adjusts the total demand to match the stock $N_p(t)$ at different time steps to 2030.

$$Si_n(t) = \frac{N_p(t)}{\sum_{n=1}^{N} (C_n(t) \times F_n(t) \times Q_n(t))} \tag{8}$$

where $Si_n(t)$ represents stock of silicon for country "n" in year "t"; $N_p(t)$ corresponds to the global stock of silicon used in product "p" in year "t"; $C_n(t)$ stands for projected population of a country "n" in year "t"; $F_n(t)$ represents projected GDP of country "n" in year "t"; $Q_n(t)$ corresponds to silicon intensity coefficient applied in green energy technologies for country "n" in year "t"; and "N" is the total number of analyzed countries.

The recycling stage, reflects both a well-established EoL PVs collecting system and well-developed silicon recovery technologies. The global stock of available silicon for the recycling stage through secondary production ($R_p(t)$) calculates with Equation (9). $T_p(t)$ corresponds to the collection rate of silicon from used product "p" in the year "t". $Re_p(t)$ is the silicon recycling rate from product "p" in the year "t" which is calculated with Equation (10). θ_p is recycling efficiency of product "p".

$$R_p(t) = \int_{t_0}^{t} \left(T_p(t) - Re_p(t) \right) dt + R_p(t_0) \tag{9}$$

$$Re_p(t) = \theta_p * R_p(t) \tag{10}$$

Accordingly, the stock of recyclable silicon (Sec(t)) is evaluated with Equation (11). $J_p(t)$ shows the amount of recovered silicon used product "p" in the year "t" which is calculated with Equation (12). ρ_p is recovery efficiency of product "p".

$$Sec(t) = \int_{t_0}^{t} \left(Re_p(t) - J_p(t) \right) dt + Sec(t_0) \tag{11}$$

$$J_p(t) = \rho_p * Sec(t) \tag{12}$$

3.2. Energy and water use within silicon processing

Equations for environmental assessment of silicon flows used in green energy technologies are given in an identical form within the dynamic model. In particular, the main processes correspond to i) industrial silicon production, ii) MG-Si production, iii) SoG-polysilicon production, iv) EG-polysilicon production, v) ingot casting of polycrystalline SoG-Si, vi) crystallization and ingot casting for monocrystalline SoG-Si, vii) crystallization and ingot casting for monocrystalline EG-Si, viii) wafer cutting of polycrystalline and/or monocrystalline SoG-Si and EG-Si, ix) recycling EoL PVs, x) using MG-Si and SoG-Si in producing new PVs and xi) using EG-Si in producing LiBs (LMR-NMC-Gr-Si).

First of all, the capacity of global energy sources considered in three main categories i) renewable energy sources including biomass, geothermal, hydro, solar, wind, storage, wave and tidal ii) non-renewable energy sources including coal, gas, nuclear, oil, and pet-coke. iii) other energy sources including cogeneration and waste. The main sources of energy throughout silicon flows includes fossil fuel, natural gas, non-fossil fuel, petroleum, nuclear, renewables, coal and biomass. Generally, the energy flows include those related to exploration, extraction, transport, processing, production, distribution, collection, treatment and recovery. Furthermore, water is also required for all stages in addition to the generation and transmission of the required energy. Energy consumed in silicon mining is mainly associated with the equipment used for the power intensive industrial processes.

Data for silica mining, industrial silicon and MG-Si production can be found in databases like the USGS [68] and Ecoinvent LCA [69]. To meet the required silicon purity levels for green energy technologies, SoG-Si and EG-Si production are more energy-intensive processes cf. MG-Si. Data for LCA of manufacturing processes is available via the GREET approach [70] and other technical reports [71–73]. Accordingly, the "direct" energy (i.e. energy required for processing of one tonne of silicon at each stage of supply chain) and the "indirect" energy (i.e. the upstream energy needed for the fuel and power flows) were considered in the model. Equation (13) calculates total energy consumed in silicon flows. Where, $E_{nq}(t)$ is the total cumulative amount of energy consumption in country "n" through the stage "q" (with q = 1,2, …,8) including mining, MG-Si processing, monocrystalline EG-Si production, monocrystalline SoG-Si production, polycrystalline SoG-Si production, MG-Si recovery, SoG-Si recovery, EG-Si recovery in the year "t". $AE_{nq}(t)$ represents the annual amount of energy consumed in country "n" through the silicon flows in the stage "q" in the year "t" (Equation (14)). Where, $Si_{nq}(t)$ is the amount of silicon mass in country "n" through the stage "q" in the year "t", and ν_{qm} is the energy required per one tonne of silicon flow in stage "q" mainly from eight energy sources (m = 1,2, …,8) including fossil fuel, natural gas, non-fossil fuel, petroleum, nuclear, renewables, coal and biomass.

$$E_{nq}(t) = \int_{t_0}^{t} AE_{nq}(t) dt + E_{nq}(t_0) \tag{13}$$

$$AE_{nq}(t) = Si_{nq}(t) \times \sum_{q=1}^{6} \sum_{m=1}^{8} \nu_{qm} \tag{14}$$

Consumption of water in different processes of silicon supply chain assessed from the perspective of "direct" and "indirect" water use. Direct water use considers the amount of water directly linked to the processing production of each separate silicon grade silicon including MG-Si, SoG-Si and EG-Si or final produced PVs or electric products. Indirect water use corresponds to the "hidden" part of the silicon flows in several processes that are directly linked to the sources of energy used at the processing location. Equation (15) and Equation (16) corresponds to the total cumulative and annual amount of direct and indirect water consumed in global silicon flows for $W_{nq}(t)$ and $AW_{nq}(t)$, respectively. Where, ω_{ql} corresponds to the intensity of water source "l" required per one tonne of silicon flow in stage "q", $l = 1,2, \ldots,4$ includes water cooling, water mining, water process, and water reservoir.

$$W_{nq}(t) = \int_{t_0}^{t} AW_{nq}(t)dt + W_{nq}(t_0) \tag{15}$$

$$AW_{nq}(t) = Si_{nq}(t) \times \sum_{q=1}^{6} \sum_{l=1}^{4} \omega_{ql} \tag{16}$$

3.3. Emissions of the global supply chain of silicon

GHG emissions and other pollution including global particulate organic carbon (POC), black carbon (BC), nitrous oxide (N_2O), methane (CH_4), sulfur oxides (SO_x), particulate matter with <2.5 μm (PM2.5), airborne particulate matter with sizes <10 μm (PM10), nitrogen oxides

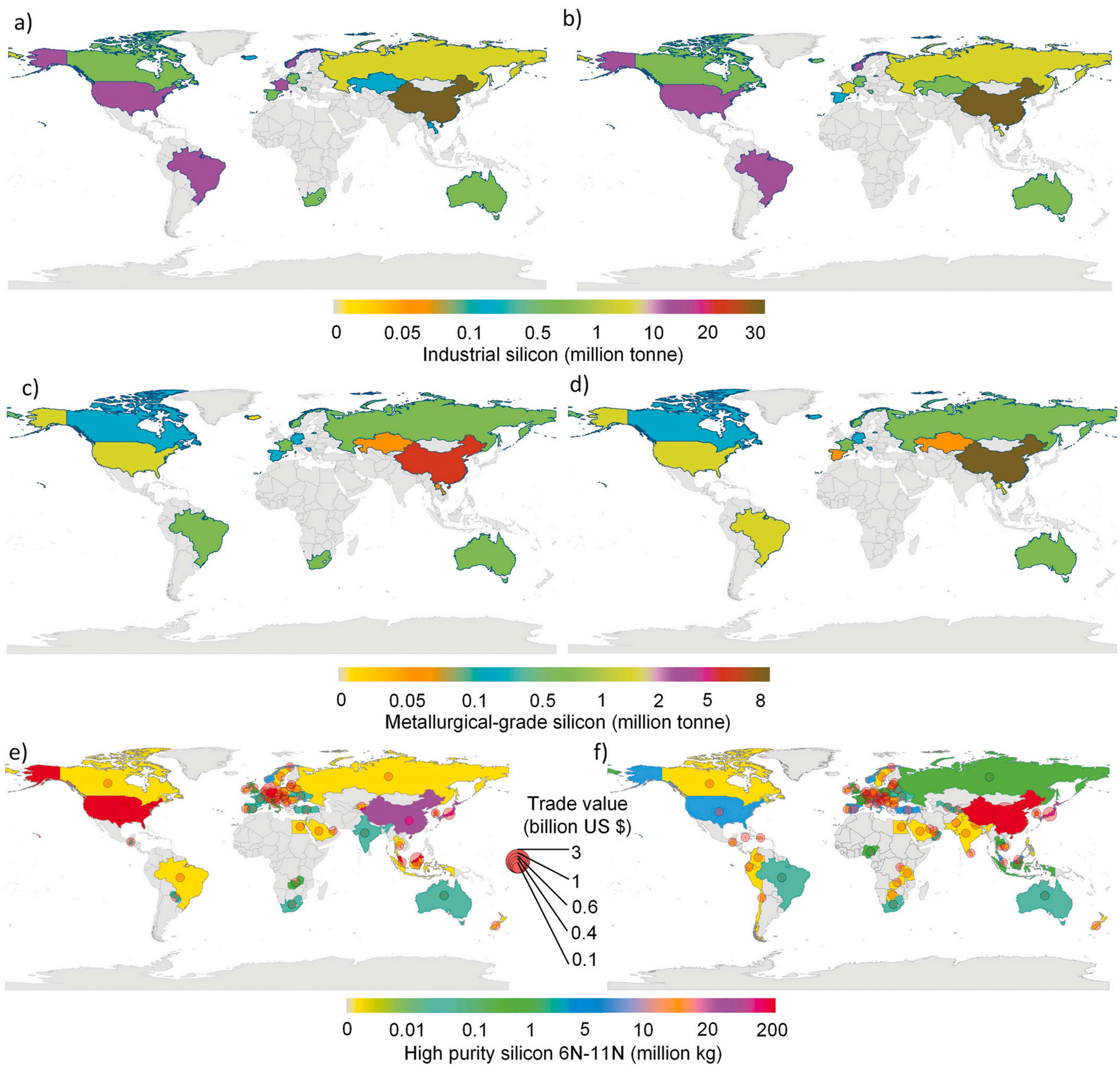

Fig. 2. Global mass flow of silicon (tonne) in 10-year intervals (between 2010 and 2030) and trade of high-purity silicon (6N–11N) (kilogram) in 2021. a, Cumulative industrial silicon in the period 2010–2020. **b**, Cumulative industrial silicon in the period 2020–2030. **c**, Cumulative metallurgical grade silicon in the period 2010–2020. **d**, Cumulative metallurgical grade silicon in the period 2020–2030. **e**, Export of high-purity silicon in 2021. **f**, Import of high-purity silicon in 2021.

(NOx), carbon monoxide (CO), volatile organic compounds (VOC), and carbon dioxide (CO_2), are investigated for all flows within the silicon supply chain. Finally, the environmental impact of silicon recovery is assessed through abiotic depletion, acidification, aquatic eutrophication, freshwater aquatic ecotoxicity, human toxicity potential cancer effects, human toxicity potential non-cancer effects, ionizing radiation ecosystems, marine eutrophication, and ozone layer depletion. Equation (17) and Equation (18) are used throughout the life cycle stages of PVs and LiBs supply chains for the assessment of cumulative and annual related emissions of silicon flows, $CG_{nqh}(t)$ and $AG_{nqh}(t)$, respectively. IPCC AR5 100-year Global Warming Potential values [74] of 1 (CO_2), 36 (CH_4), and 298 (N_2O) is used for GHG intensities calculations. λ_{qh} stands for the annual rate of emission "h" (with h = 1,2, …,12) including GHG, POC, BC, N_2O, CH_4, SO_x, PM2.5, PM10, NOx, CO, VOC, and CO_2 generated in in stage "q".

$$CG_{nqh}(t) = \int_{t_0}^{t} AG_{nqh}(t)dt + CG_{nqh}(t_0) \tag{17}$$

$$AG_{nqh}(t) = Si_{nq}(t) \times \lambda_{qh} \tag{18}$$

In the recycling stage, the global environmental impact of recovering MG-Si and SoG-Si, $EG_{kd}(t)$, is compared by using Equation (19), where δ_{kd} is intensity of environmental impact "d" (with d = 1,2, …,9) including abiotic depletion, acidification, aquatic eutrophication, freshwater aquatic ecotoxicity, human toxicity potential - cancer effects, human toxicity potential - non-cancer effects, ionizing radiation ecosystems, marine eutrophication, and ozone layer depletion for recovered silicon grade "k".

$$EG_{kd}(t) = J_p(t) \times \delta_{kd} \tag{19}$$

4. Results and discussion

4.1. Trends in global silicon production and trade

Fig. 2 outines the geographical distribution for the cumulative production of industrial silicon and MG-Si, as well as the trade flows of high-purity silicon (6N–11 N). High-purity silicon will be used as SoG-Si or EG-Si. The distribution corresponds to two ten-year intervals between 2010 and 2030, which illustrate around 15 % and 28 % growth rates across the two decades (2010–2020 and 2020–2030) for industrial silicon and MG-Si, respectively - reflecting a significant improvement in MG-Si processing technology [75,76]. Additionally, the calculations estimate a 1.4 times increase in silicon primary production between 2010 and 2030. Of the estimated total cumulative industrial silicon production, around 20 Mt occurred in China between 2010 and 2020 and this is expected to reach around 25 Mt over the next decade (2020–2030). Furthermore, around 5 Mt of global MG-Si was produced by China in 2010–2020, with growth anticipated to reach ~7 Mt between 2020 and 2030.

Detailed information on the quantity and value of exports and imports of high purity silicon - based on reports of 51 exporters and 75 importers in the United Nations Commodity Trade Database (UNCOMTRADE) - shows that in 2021, exports and imports of high-purity silicon reached around 200 thousand tonnes (kt) with the value of USD 4.4 billion and 190 kt with the value of $4.2 billion, respectively. Analysis shows that Germany with 66 kt and an approximate value of $1.6 billion as the top exporter, followed by the US (51 kt, $1.2 billion), Malaysia (32 kt, $620 million), Japan (13 kt, $465 million), China (12 kt, $140 million), and Korea (6 kt, $115 million). In contrast, top Importers include China with 116 kt and value of $2.1 billion, followed by Japan (15 kt, $665 million), South Korea (8 kt, $300 million), and Germany (6 kt, $160 million).

4.2. Trends of solar energy and silicon in technologies

Worldwide cumulative installed solar capacity up to 2018 was estimated to be around 463 GW. Top solar energy users in 2018 were China, India, Spain, Mexico, Brazil and Chile, with about 175.1 GW, 27.1 GW, 4.8 GW, 2.5 GW, 2.4 GW and 2.1 GW, respectively. Globally, around 275 GW cumulative PV capacity was to be found in Asia, followed by Europe and North America with 119 GW and 55 GW in the same year, respectively. Statistics show that the global installed PV capacity reached over 848 GW in 2021, Asia still predominates (485 GW), followed by Europe (185 GW), North America (104 GW), Oceania (23 GW), South America (20 GW), Africa (10 GW), Eurasia (10 GW), Middle East (8 GW) and Central America and Carib (3 GW). The share of global energy resources is presented in Fig. 3, according to the latest report of IRENA [3] and other data sources [77,78], whereas the distribution of renewable, non-renewable and other energy sources is shown with their capacity by 2021. A BP Statistical Review of World Energy revealed that more than 1370 TW-hours (TWh) of global electricity was generated by solar energy in 2021 [77]. China is the primary driver of solar capacity growth, accounting for about 36 % of the worldwide increase in 2021. Moreover, acceleration of solar deployment through policy and market support may contribute to the predicted 3000 GW annual global capacity in 2030. In addition to the growth of current PV market leaders, increased deployments in Africa, the Middle East, and other non-OECD regions are expected due to green energy policy improvements that encourages solar, green financing and infrastructures in the energy sector.

Fig. 4 shows the geographical distribution of PVs and silicon reserves in 2021. Results show that total global ferrosilicon and silicon production is estimated to be 7.7 Mt and 2.9 Mt in 2020, respectively, reaching around 8.1 Mt and 3.0 Mt in 2030. The leading silicon producers in 2020 are China (2.2 Mt), Brazil (200 kt), Norway (140 kt), France (87 kt), Russia (57 kt), Australia (43 kt), Iceland (27 kt), Canada and Bosnia (25 kt), Kazakhstan (12 kt), Spain (5 kt) and Laos (890 t).

When the silicon required for PVs production is considered, around 36 % of the global consumption growth rate was observed between 2010 and 2020 (a change from 2.2 Mt in 2010 to 3.1 Mt in 2020). Although several novel technologies are under development intended to reduce the use of silicon in PVs, c-Si panels are predicted to retain market dominance up to 2030 and silicon maintains its essential role in producing electricity from solar energy [79,80]. Also, considering the current amount of c-Si PV technology-related waste and the significant levels expected in the near future, the recycling stage in this study focusses on the first-generation market PVs as a secondary raw material source (40 % monocrystalline, 48 % polycrystalline and 2 % ribbon silicon PVs) [81]. Nonetheless, second-generation thin-film technologies and third-generation modules of dye-sensitized and organic PV cells are considered in the projection demand for 2020–2030.

The annual capacity of installed PVs and global silicon consumption per square meter of a PV module is shown in Fig. 5a. It is assumed the distribution of silicon demand used in PVs technology is linked to gross domestic product (GDP) and population. Therefore, the silicon consumption per GDP and per capita as examples for Schengen countries in the EU for the year 2020 is presented in Fig. 5b - with the trends shown in ascending order of GDP per capita. In 2020, the lowest GDP per capita corresponded to Bulgaria, at 48 % below the EU average GDP per capita (16,500 €) and the highest GDP per capita corresponded to Luxembourg, at 140 % above the EU average (76,600€). The highest cumulated PV capacity in 2020 in the EU region accounted for Germany (54 GW), followed by Italy (22 GW), France (12 GW), the Netherlands (11 GW) and Spain (10 GW). Analysis of silicon consumption for green energy technologies shows that—except for Croatia and Luxemburg—there are no significant differences across Schengen countries, while that silicon consumption per capita continues to behave in parallel with the silicon per unit of GDP.

It is noteworthy that electricity production by solar energy in the EU

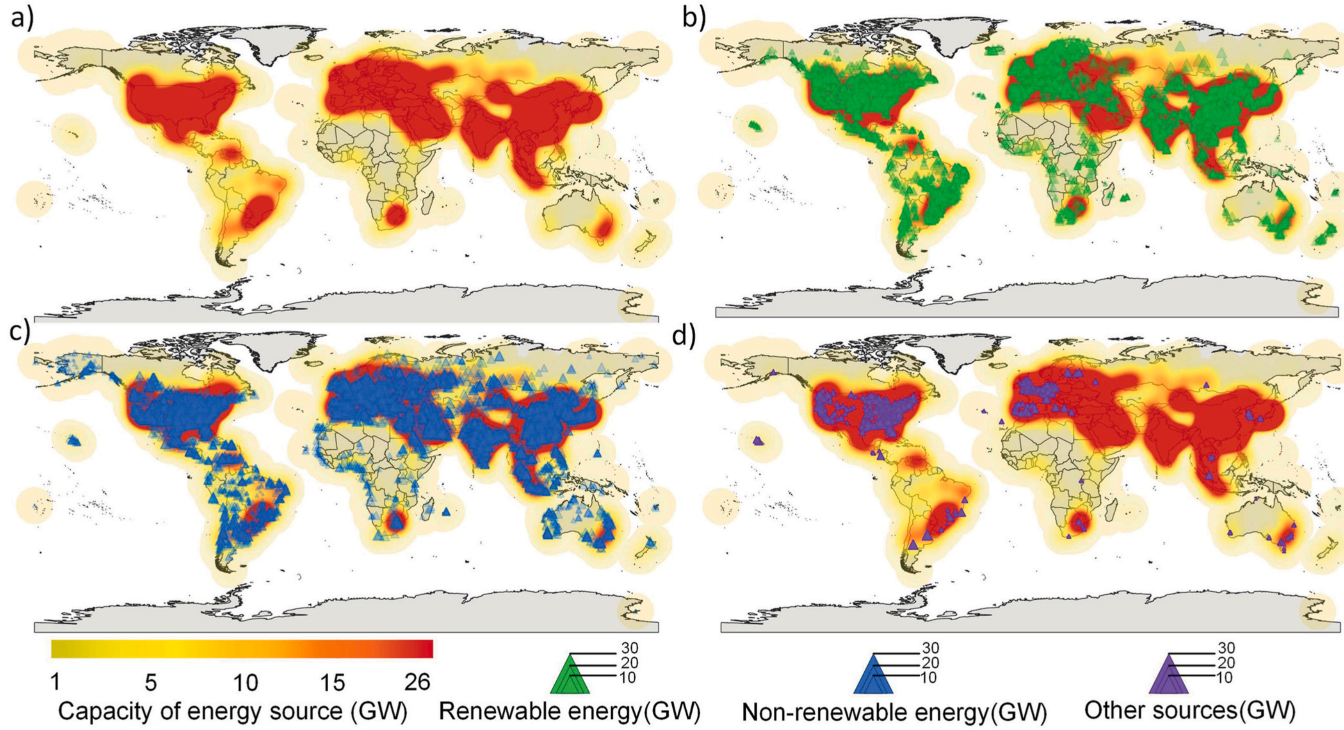

Fig. 3. Distribution of energy sources and their capacity in gigawatts (GW) in 2021. a, Capacity of all energy sources. **b**, Distribution of renewable energy sources including biomass, geothermal, hydro, solar, wind, storage, wave and tidal. **c**, Distribution of non-renewable energy sources including coal, gas, nuclear, oil, and petcoke. **d**, Distribution of other energy sources including cogeneration and waste.

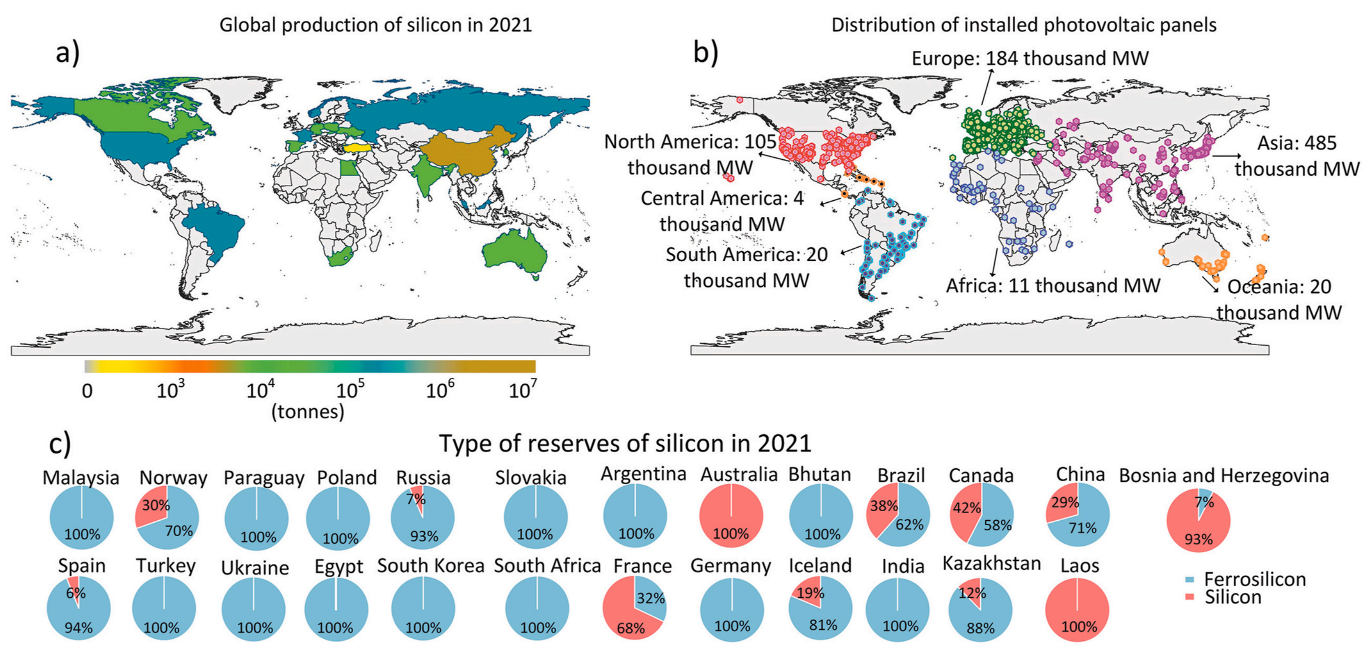

Fig. 4. Global reserves of silicon and distribution of installed PVs in 2021. a) Geographical production of silicon in 2010. b) Distribution of installed PVs and their total capacity by region. c) Type of reserves of silicon by country in 2021.

thrived in 2021 despite the challenges of PVs component supply chains, from disruption of materials to higher module prices in the post-pandemic COVID-19 conditions. The highest PV capacity per capita in 2021 in the EU region was in the Netherlands (815 W/Ca), followed by Germany (706 W/Ca), Belgium (545 W/Ca) and Luxemburg (435 W/Ca). Furthermore, the turmoil in energy markets caused by Russia at the beginning of 2022 intensified the rapid growth in using green energy technologies. Solar energy is one of the main measures of decarbonization in the EU as highlighted by the European Commission report "A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy", which detailed that around 2 % of GDP of the EU is invested in the energy sector [82].

Along with PV technologies, growth in the silicon metal market is expected to continue e.g. in Si-based anode LiBs market demand (e.g.,

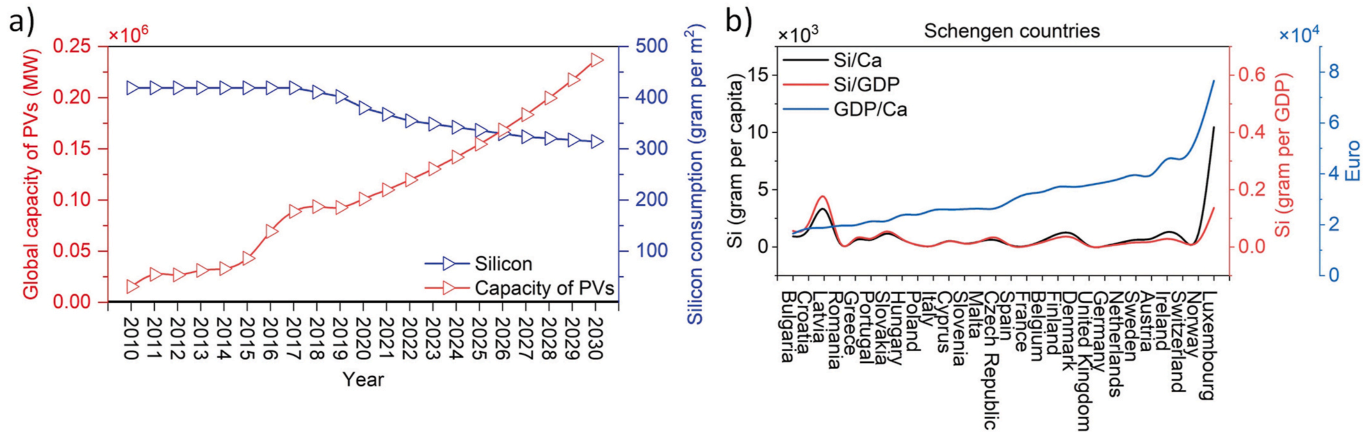

Fig. 5. Trend of silicon consumption applied in green energy technologies. a, Global capacity of installed solar panels and contained silicon. **b**, Behaviour of silicon consumption in 2020 for European countries.

LMR-NMC) for automotive applications in the future [83]. It is estimated that there will be around 500 million EVs globally in 2030 [84] and the related development of technologies to increase battery capacity is rapidly growing [85]. Statistics show that the Asia-Pacific region accounted for around $621 million of the global market for anode materials in 2018, followed by North America about $378 million and Europe $128 million. Several detailed studies have demonstrated the advantages of partially replacing the graphite by Si in LiBs anodes [86–88] and the associated technological trends of silicon anodes from the 1970s to 2020 is comprehensively outlined by Cui [89]. Considering the large-scale implementation of Si anodes for high energy density and low-cost LiBs in the next generation of electric vehicles, this study considers previously introduced technologies [57,61,90,91] for the recovery of Si from PV waste to process into nano-silicon for use in LiBs. This strategy used as a basis to investigate the contribution of the recycled silicon into its supply chain [92] more specifically as secondary raw material for LIBs.

Fig. 6 represents the impact of the silicon circularity from EoL monocrystalline, polycrystalline, ribbon silicon PVs and electrical products on its primary production between 2010 and 2030. Results indicate that the available amount of primary silicon for the global production of monocrystalline, polycrystalline, ribbon silicon PVs and electric products was about 20 kt, 240 kt, 10 kt, and 125 kt in 2020, respectively. This estimation highlights that the silicon demand for the global production of all products will total around 480 kt, in 2030 cf. 395 kt (2020). Assessment of functional recycling of different grades of silicon demonstrates that there is a significant possibility to supply around 15 % of global industrial silicon through secondary production by 2030, assuming a recovery efficiency of 90–95 %. This highlights the potential of silicon circularity not only for PVs, but also to other green energy technologies. Nevertheless, recycling alone cannot bridge the gap in the silica required annually for the development and production rate growth of the investigated technologies [93,94]. Therefore, mining remains necessary to meet the minerals demand needed for key decarbonization technologies.

Detailed analysis shows that cumulatively around 53 % of metallurgical grade silicon required for PVs industry and around 99 % of solar-grade silicon could be supplied from EoL PVs by direct MG-Si and SoG-Si recovery as of 2030. In addition, it is estimated that around 8 % of electric-grade silicon can also be supplied by direct EG-Si recovery in the same year. This result underlines the need to boost circularity activities while recycling will be carried on when EoL volumes become sufficient to ensure a profitable business by considering current stock and the expected future changes. It is worth noting that there are several technological challenges in recycling silicon from PVs waste to satisfy a high and consistent quality [95]. Most current recovery methods only produce metallurgical grade and require further purification for use in SoG-Si or EG-Si [96,97]. The variety in types of silicon modules on the market and lack of impurity control intensify the recycling stage's technological challenges stage [92,98]. Therefore, there is still an urgent

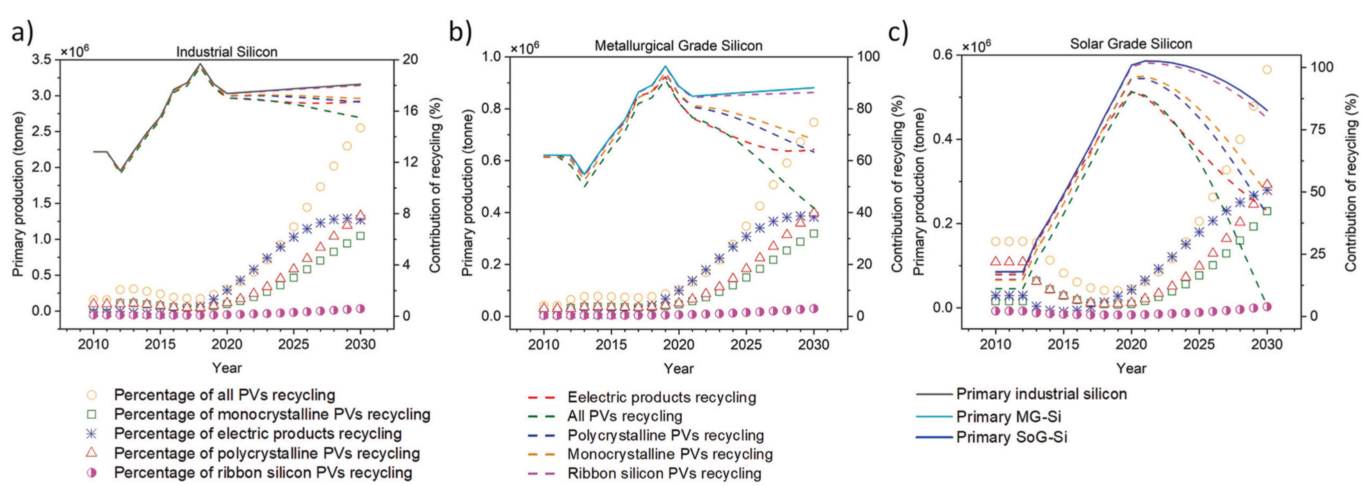

Fig. 6. The impact of circularity of silicon on its primary production between 2010 and 2030. a, Annual global industrial silicon production. **b**, Annual global metallurgical grade silicon production. **c**, Annual global solar grade silicon production.

need for technological improvement to boost low recovery rates. Development of maintenance, refurbishment, and repurposing strategies aim to significantly extend the lifecycle of green energy technologies, e.g. ensuring PVs optimal operation and after their useful life repurposing for other applications. This approach reduces waste, conserves resources, and contributes to overall green energy technologies sustainability.

The findings show that the estimated total amount of secondary silicon can be used to produce around 116 million PVs in 2030. Hence, there is the potential to generate on average about 40 GW of electricity by PVs from secondary silicon by 2030. Furthermore, the growth of material production – either from primary or secondary resources – involves an associated increase in energy and water consumption and related emissions through the industrial processes, which will cause climate impacts with substantial economic consequences. Therefore, in the next step, the environmental performance of the silicon supply chain stages required for the green energy transition are assessed.

4.3. Trends in environmental impacts of silicon mining and processing

Silicon global flows and their environmental impacts are assessed by using the proposed dynamic model. The total annual energy and water consumption related to the silicon global primary production by country in 2010–2030 are displayed in Fig. 7. A 42 % increase in global energy and water consumption for the primary production of silicon, including mining and processing, is observed within 20 years. Results show that energy consumption in silicon mining and processing stages increased from 4.5 billion GJ in 2010 to 6.1 billion GJ in 2020 and is expected to reach 6.4 billion GJ by 2030. An identical trend is shown for the use of water (from 3.1 million cubic meters (m^3) in 2010, which increased to 4.1 million m^3 in 2020 and is further estimated to reach 4.4 million m^3 in 2030).

Fig. 7 shows that in 2010 the highest consumer of global energy and water for producing primary silicon were: China (61 %), the US (9 %), Norway (8 %), Brazil (6 %), South Africa (3 %), Russia (3 %), Australia (1 %), Canada (1 %), Spain (1 %), Germany (1 %) and Bosnia, Laos and Kazakhstan (<1 %) in 2010. Considering the diversification of supply needed to meet the actual demand for primary silicon, in 2020, a significant increase was observed by China (72 %), however, many other countries remained at the approximately the same level: US (6 %), Norway (5 %), Brazil (6 %), Russia (2 %), Australia (1 %), Canada, Spain, Germany, Bosnia, Laos and Kazakhstan (<1 %).

The annual GHG emission trends between 2010 and 2030 and other related pollution (POC, BC, N_2O, CH_4, SO_x, PM2.5, PM10, NO_x, CO, VOC and CO_2) in the year 2020 generated through mining and processing of primary silicon are given in Fig. 8. It is estimated that GHG emissions from primary silicon production will grow in China by 70 %, from 57.7 Mt CO_2 eq in 2010 to 98.2 Mt CO_2 eq in 2030.

Detailed calculations show China as country with the highest environmental impact among all silicon mining countries in 2020, releases 1.6 kt of POC, 536.8 t of BC, 2.4 kt of N_2O, 211.8 kt of CH_4, 76.5 kt of SO_x, 5.9 kt of PM2.5, 9.5 kt of PM10, 85.6 kt of NO_x, 46.9 kt of CO, 12.1 kt of VOC and 87.1 Mt of CO_2. Also, China in the processing silicon in 2020 emitted 7.1 t of POC, 32.1 t of BC, 196.7 t of N_2O, 9.5 kt of CH_4, 1.2 kt of SO_x, 482.6 t of PM2.5, 883.7 t of PM10, 6.8 kt of NO_x, 2.4 kt of CO, 577.6 t of VOC and 5.3 Mt of CO_2. This shows the need to design and act on various measures intended to increase silicon circularity.

4.4. Comparison of environmental performances of silicon supply chain stages

The global environmental impacts of several stages of silicon flow utilized in green energy technologies are evaluated over the period 2010–2030. Annual energy and water used, as well as GHG emissions generated during the value chain, are presented in Fig. 9, along with an assessment of other pollution in 2020. Outcomes indicate that silicon mining accounts for about 51 % of global energy consumption for the entire supply chain, followed by production of electrical products (30 %), monocrystalline PV (8 %), polycrystalline PV (7 %), processing silicon (3 %) and recovering MG-Si, SoG-Si and Si grade used in LiBs (LiBs-Si) (<1 %). For the water assessment, mining of silicon consumed about 69 % of the total required amount of water followed by production of electrical products (16 %), monocrystalline PV (5 %), polycrystalline PV (9 %), and processing silicon as well as recovering MG-Si, SoG-Si and LiBs-Si (<1 %). Furthermore, it is estimated that energy and water consumption for the mining stage will reach 6.1 billion GJ and 4.3 million m^3, respectively.

This finding emphasises the necessity of technological improvement in the silicon mining stage. Estimates for 2030 show secondary production of silicon will require about 43.1 million GJ of energy and 0.02 m^3 of water. About 88 % of total energy and 61 % of the total water used for secondary production corresponds to silicon production for LiBs. A comparison of results shows that salvaging MG-Si consumes 10 % more energy than SoG-Si, while water used for SoG-Si recovery is 5 % higher. Moreover, silicon mining generates about 46 % of global GHG emitted for the total supply chain followed by production of electrical products (34 %), monocrystalline PV (9 %), polycrystalline PV (7 %), processing silicon (3 %) and recovering MG-Si, SoG-Si and LiBs-Si (<1 %). These findings indicate the positive contribution of secondary silicon production cf. primary production in saving energy and water consumption and mitigating GHG emissions. The results also show manufacturing monocrystalline silicon PV emits the highest amount of black carbon (around 15 t) among other stages in 2020. Nonetheless, mining produces the highest level of other pollutants, including POC (0.23 t), N_2O (0.34 t), CH_4 (29.2 t), SO_x (10.5 t), PM2.5 (0.8 t), PM10 (1.3 t), NO_x (11.8 t), CO (6.5 t), and VOC (1.7 t). The minimum pollution levels for 2020 were observed for LiBs-Si production (BC (0.73 kg), CO (53.1 kg), N_2O (2.2 kg), NO_x (70.1 kg), PM2.5 (1.7 kg), SO_x (14.4 kg) and VOC (28.9 kg)) and also for the production of electric products (CH_4 (26.5 kg) and PM10 (54.3 kg)) compared to other stages.

Detailed analysis shows that global circularity of silicon aims 54 % saving of energy consumption (3.5 billion GJ) and 69 % of water use (3.1 million m^3) by 2030. Moreover, secondary production of silicon mitigates around 45 % of total GHG emissions, ~65.3 Mt CO_2 eq in the same year.

Fig. 10 represents the annual trend of contaminations through the silicon supply chain between 2010 and 2030 with the amount of contamination generated by each stage discernible from the outcomes. It can be seen from Fig. 10 that the CO_2 emissions (in Mt) associated with mining (87.8–125.1), processing (5.3–7.5), production of monocrystalline PVs (7.5–23.6), polycrystalline PVs (3.9–18.3), electrical products (7.9–92.5) and LiBs (0.09–1.2) all increase between 2010 and 2030. Moreover, the rapid increase in silicon use for green energy technologies over the given period (2010–2030) causes an exponential growth of pollution through different stages of the supply chain, e.g., 2.2 times in monocrystalline PVs production, 3.6 times in polycrystalline PVs production, 10.7 times in electric product production and 12.6 times in LiBs production. Additionally, there is an estimated 42 % increase in pollution due to mining and processing stages over the same time period.

Comparison of the environmental impact due to the recovery of metallurgical and silicon solar grades by 2030 is illustrated in Fig. 11. As can be seen, there is a clear ecological tradeoff between different silicon grade recoveries. Predictions show that around 89 % of acidification, 77 % of aquatic eutrophication, 61 % of freshwater aquatic ecotoxicity and 99 % marine eutrophication result from the MG-Si recovery as part of silicon circularity. In contrast, around 99 % of abiotic depletion, human toxicity potential cancer and non-cancer effects, ionizing radiation ecosystems and 76 % of ozone layer depletion result from reclamation as SoG-Si.

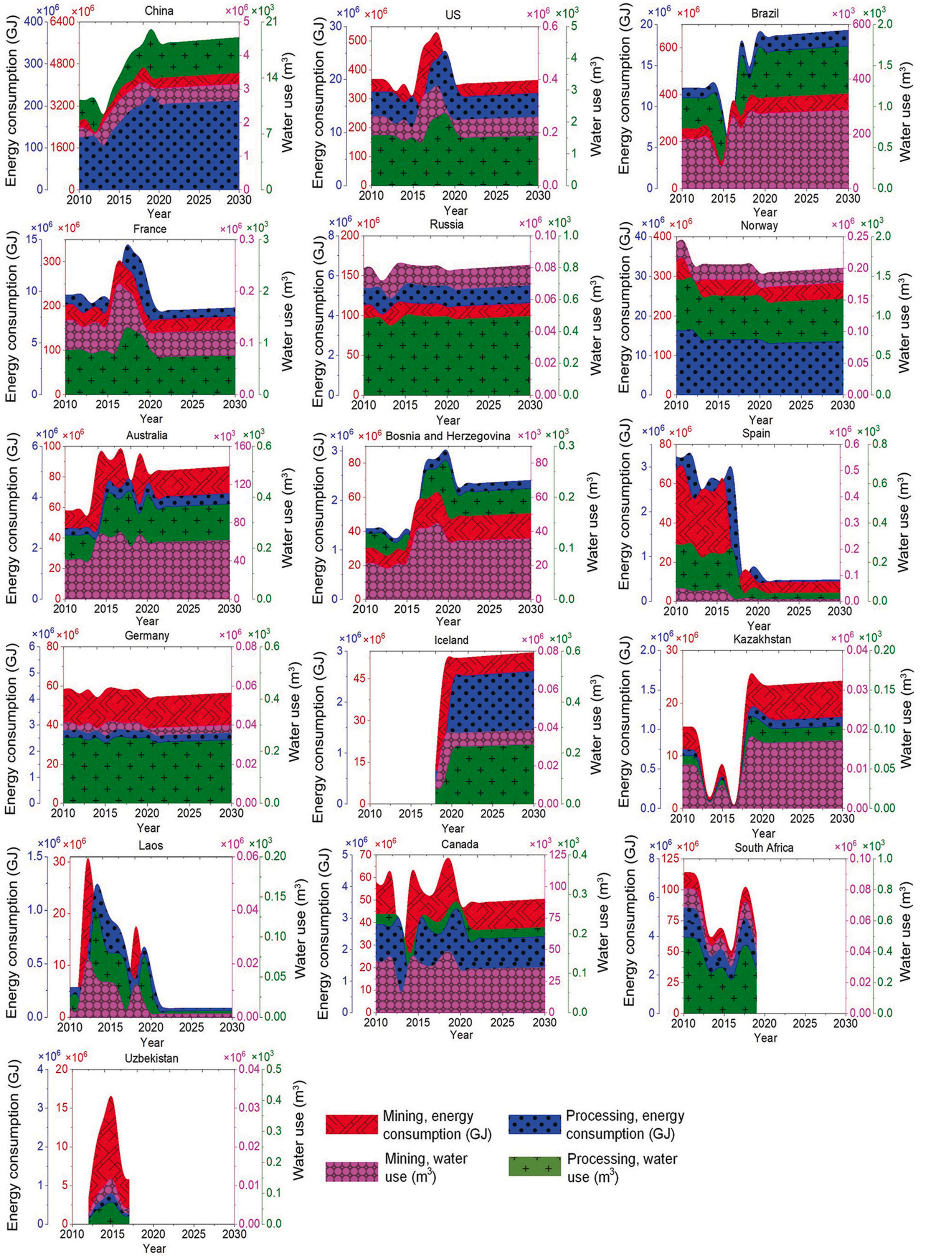

Fig. 7. Global energy consumption, in gigajoules (GJ) and water use, in cubic meters (m^3) for primary production of silicon in the mining and processing stage by country between 2010 and 2030.

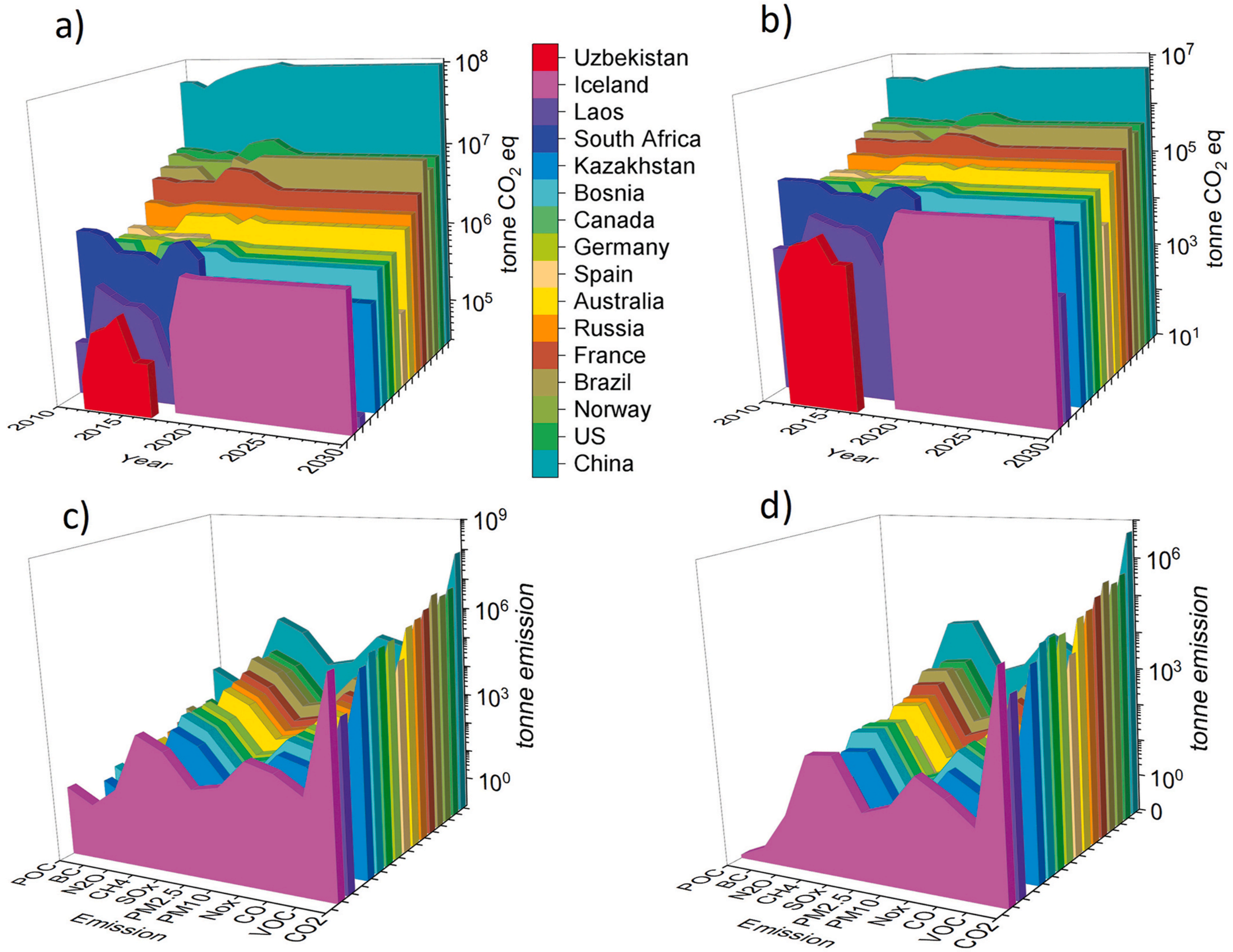

Fig. 8. Environmental performance of primary production of silicon in the mining and processing stage between 2010 and 2030. a, Annual global greenhouse gas (GHG) emissions for mining stage by country, in tonnes CO_2 eq. **b**, Annual global GHG emissions for processing stage by country, in tonnes CO_2 eq. **c**, Global pollution through silicon mining by country in 2020, in tonnes. **d**, Global pollution through silicon processing by country in 2020, in tonnes. Pollution includes Particulate organic carbon (POC), black carbon (BC), nitrous oxide (N_2O), methane (CH_4), sulfur oxides (SO_x), particulate matter with sizes smaller than 2.5 μm (PM2.5), airborne particulate matter with sizes smaller than 10 μm (PM10), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and carbon dioxide (CO_2) emissions.

4.5. *Synergy of green energy technologies by circularity of silicon*

The methods to mitigate the degradation issues associated with silicon, such as the expansion and contraction of the material during charge-discharge cycles are under investigation. By optimizing the recycling process, it may be possible to recover silicon in a form that exhibits improved stability and cycling performance, thereby enhancing the overall silicon-based LiBs efficiencies. Silicon recovery from solar PVs waste and its reuse in LiBs aligns with circular economy principles by conserving resources, reducing waste, improving energy efficiency, minimizing environmental impact, and creating economic opportunities. By embracing these principles, there is a possibility to achieve sustainable resource management and move towards a more sustainable and circular future. Fig. 12 represents the environmental performance of silicon circularity through several scenarios from 0 to 100 % of recovery for MG-Si, SoG-Si and EG-Si between 2020 and 2030.

Scenario analysis shows that the median energy consumption occurs at around 50 % recovery of MG-Si and 25 % recovery of each SOG-Si and EG-Si. In comparison, the median of water consumption is evident after approximately 50 % recovery of SoG-Si and 25 % for MG-Si and EG-Si, respectively. Regarding GHG emissions, the median amount would be either by recovery of 50 % EG-Si and 25 % of each MG-Si and SoG-Si or 50 % SoG-Si and 25 % of each MG-Si and EG-Si.

Interestingly, the results show that if all recovery flows in 2030 were dedicated for EG-Si used in LiBs industry, maximum energy (about 38 M GJ) and water (about 0.014 million m^3) consumption would be expected, whereas GHG emissions (about 1 Mt CO_2 eq) is at the minimum level. In contrast, energy consumption can be minimised (at about 5000 GJ) by focusing on 100 % recovery of SoG-Si for application in the PVs industry. Alternatively, the minimum water use level could be enabled by 100 % recovery of MG-Si PVs applications. Consequently, the tradeoff between recovering silicon in the form of MG-Si, SoG-Si and EG-Si is estimated at a maximum of around 38 M GJ, 0.011 million m^3 and 4 Mt CO_2 eq, respectively. Furthermore, these calculations clearly demonstrate the necessity for new EG-Si recovery technologies to save energy and water consumption and for MG-Si recovery to mitigate associated GHG emissions. A bi-directional positive reinforcing causal relationship is demonstrated between the mass of silicon and the generation of GHG emissions. An exponential growth of GHG emissions in five-year intervals shows the urgent requirement for improved methodologies to

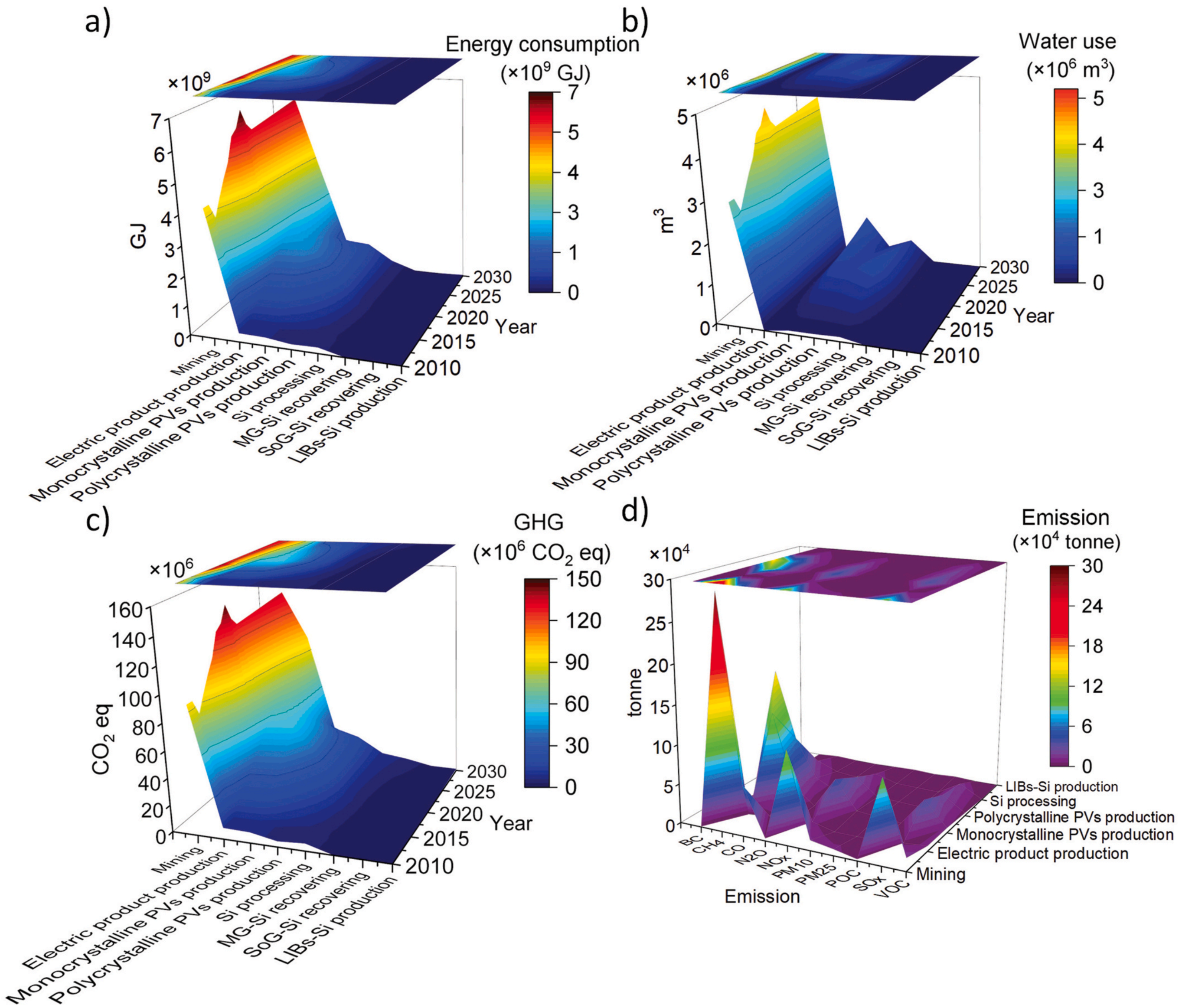

Fig. 9. Environmental impact of all stages of silicon supply chain between 2010 and 2030. a, Global energy consumption, in gigajoules (GJ). **b**, Global water consumption, in cubic meters (m^3). **c**, Annual global greenhouse gas (GHG) emissions in tonnes CO_2 eq. **d**, Global particulate organic carbon (POC), black carbon (BC), nitrous oxide (N_2O), methane (CH_4), sulfur oxides (SO_x), particulate matter with sizes smaller than 2.5 μm (PM2.5), airborne particulate matter with sizes smaller than 10 μm (PM10), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOC) emissions through stages of silicon supply chain in 2020, in tonnes.

enable silicon recycling in large volumes with less air pollution generation. Notably, an identical trend in energy and water consumption growth rate through all scenarios over five-year intervals until 2030 means no environmentally technical progress based on the current use of resources can be observed. Furthermore, it is visible from the results that there is an almost linear trend over the given period related to energy and water consumption and the mass of silicon flows.

Increased silicon recycling is crucial to achieve environmental objectives that align with sustainable development goals (SDGs). As silicon is a vital element in the development and implementation of green energy technologies, ensuring a sustainable and affordable supply through recycling activities can have a positive impact on SDG 7 (Access to affordable, reliable, sustainable, and modern energy for all). Additionally, primary silicon production results in higher levels of waste generation. By promoting secondary silicon production through recycling, we can directly contribute to the attainment of SDG 12, which seeks to establish sustainable consumption and production patterns. Furthermore, recycling silicon can also contribute to SDG 13, which focuses on climate change mitigation. By reducing the need for primary silicon production, which often involves energy-intensive processes, we can help reduce GHG emissions and mitigate climate change impacts.

In addition, the economic viability of silicon recovery and its use in advanced LiBs is a crucial factor. The cost of implementing the recycling process, including collection, sorting, processing and refining, needs to be economically feasible. Also, the transportation of silicon wastes modules should be carefully evaluated to minimize its environmental impact and ensure that the overall environmental benefits outweigh the associated emissions and energy consumption. Therefore, more comprehensive macro-level research is needed, to help boost policy-maker awareness of the environmental issues related to critical materials' supply chains [99,100]. These policies align with the efficient use of resources and mitigation of emissions by integration of open- and closed-loop supply chains as shown in this study for the cases of solar PVs and advanced LiBs. It should be considered that stakeholders

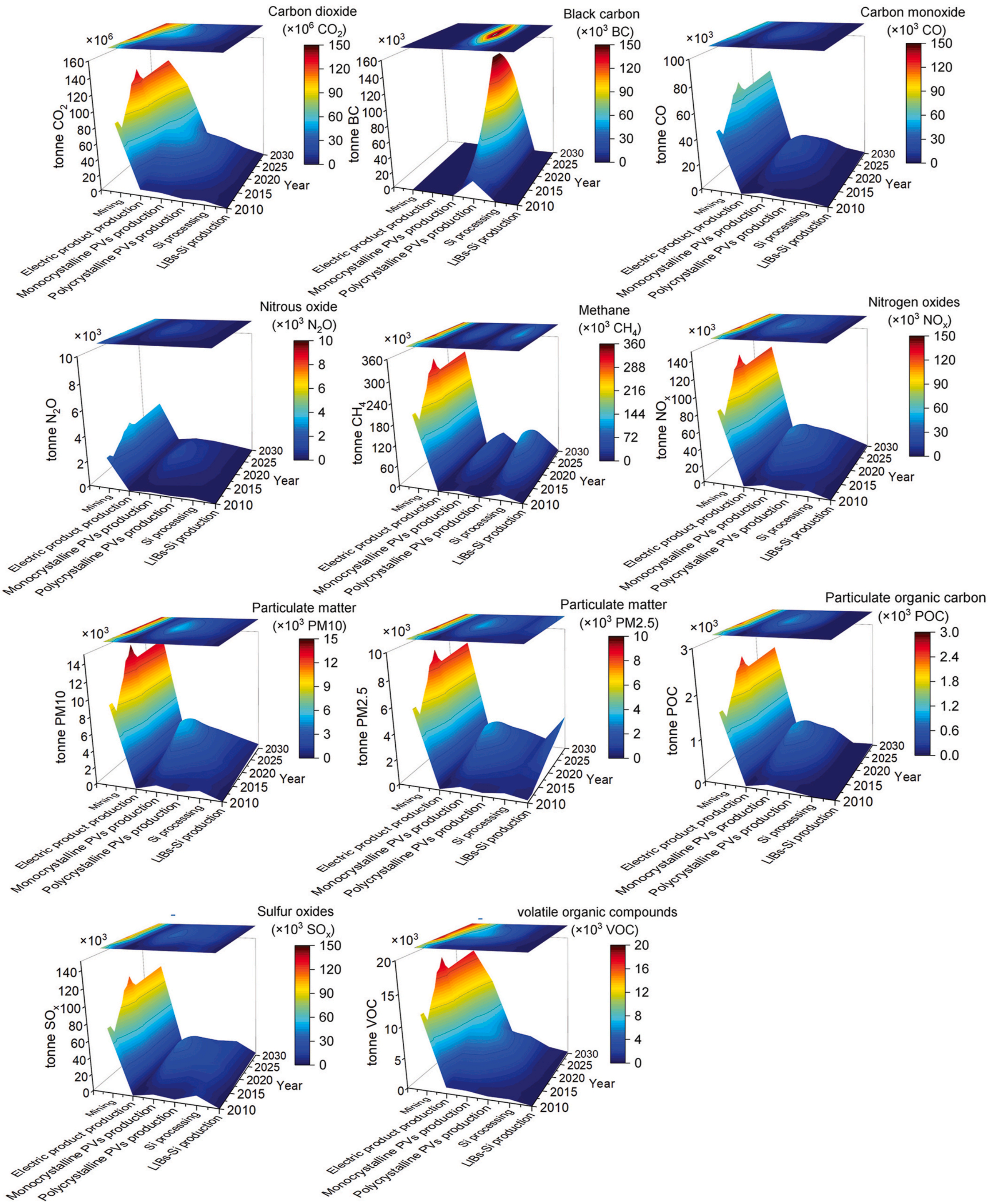

Fig. 10. Trends of global emissions generated by stages of silicon supply chain between 2010 and 2030.

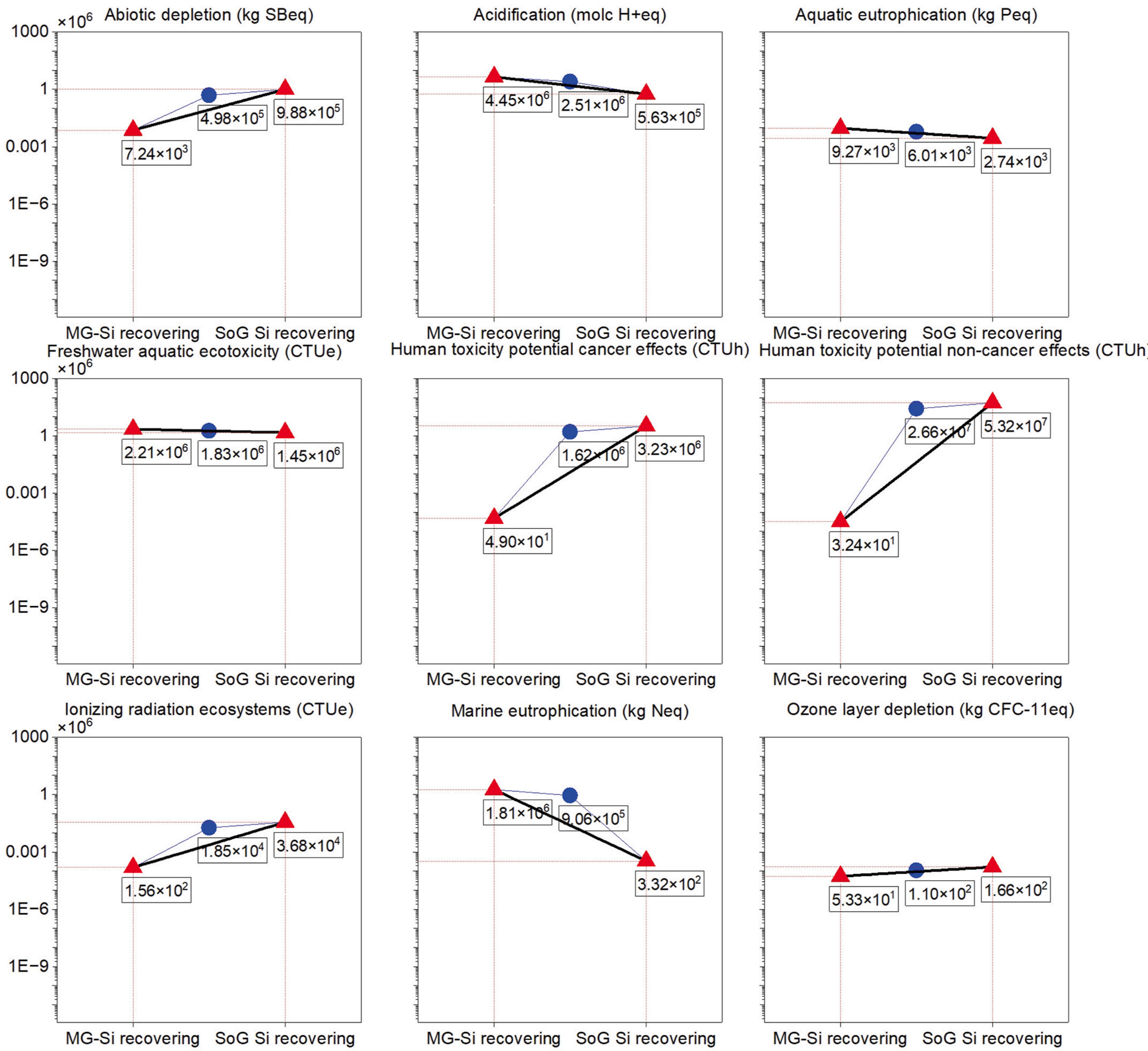

Fig. 11. Environmental effects of the recovering metallurgical and solar grades of silicon by 2030. The blue circle represents the centroid point.

including manufacturers, recyclers, and policymakers have a significant role in implementing integrated material flows of silicon within energy technology sectors. For example, a manufacturer can propose a circular design of solar PVs, ensuring that the silicon used in PVs can be efficiently recovered and reused. Upgrading the solar energy systems by new module designs tailored to promote circularity could improve the future lifecycle resource efficiency of PVs. Moreover, recyclers should collaborate with manufacturers to establish collection and recycling programs, to ensure that EoL PVs and batteries are properly managed and recycled.

It should be noted that policymakers can provide incentives and support for research and development in recycling technologies, develop and enforce regulations that promote silicon reuse from waste solar PVs, and encourage synergizing of energy technologies. International collaboration and agreements are essential for promoting the global sustainability of silicon recycling. Through such collaboration, countries can accelerate technological advancements, establish common standards, align policies, develop markets, and collectively address the environmental challenges associated with silicon recycling.

5. Conclusions

Production of green energy technologies requires a larger amount and more diverse range of minerals than their fossil fuel-based counterparts. Consequently, with the increased need for such technologies to mitigate climate change, the related growth of unsustainable materials production leads to increased energy and water use as well as generated associated emissions, which will cause climate impacts with substantial economic consequences. To overcome this obstacle, the indirect link between the proliferation of technologies and damage to the environment has been quantified by focusing on flows of silicon used for green energy technologies. Subsequently, the contribution from the sustainable management of material circularity has been assessed - based on the recovery of different grades of silicon by synergizing the flows of photovoltaic panel and battery technologies. The study shows that increasing silicon recycling impacts on multiple SDGs, including SDGs 7,

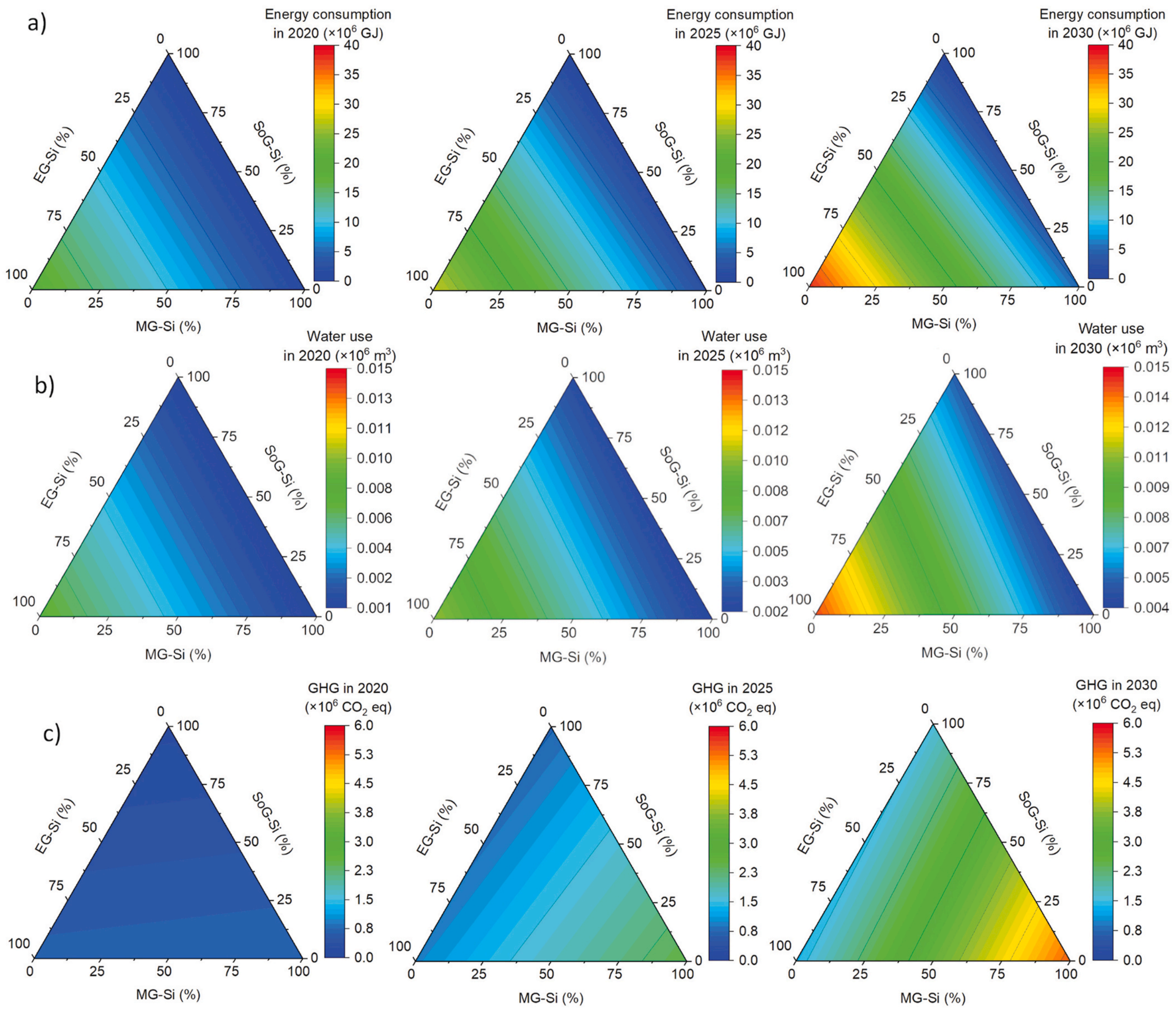

Fig. 12. Environmental impact of silicon recovery by integrating its circularity flows between 2020 and 2030 (Scenarios: 0–100 %). a, Energy consumption, in gigajoules (GJ). **b**, Water use, in cubic meters. **c**, GHG emissions, in tonnes CO_2 eq.

12, and 13, which can play a significant role in achieving environmental sustainability and promotion of a more circular economy.

As demonstrated in this study, the energy and water consumption and emissions generated in primary silicon production remain substantial. Results show that an effective global circularity of silicon (use in PVs and LiBs production) would contribute to a 54 % reduction in energy consumption i.e., about 3.5 billion GJ and 69 % of water use equivalent to about 3.1 million m^3 by 2030. Moreover, secondary production of silicon mitigates around 45 % of total GHG emissions, (~65 Mt CO_2 eq). Furthermore, possible synergizes between the flows from the recycling of EoL PVs and production of new LiBs technologies using an optimum scenario (50 % of MG-Si, 25 % of SoG-Si and 25 % of EG-Si) for the recovered volumes different silicon grades could potentially save around 38 M GJ of energy, over 0.01 million m^3 of water and mitigate 4 Mt CO_2 eq of GHG emissions by 2030 that results from green technologies waste management.

The findings of this study indicate how the circularity of critical materials like silica can be managed to minimize their environmental impacts through the propagation of green technologies. In particular, the data obtained address the feasibility and environmental sustainability challenges of PVs recycling and related processing of silicon as a key material for future battery and energy storage technologies. These results aim to improve technology designs for energy systems and formalize theoretical frameworks for material use and recycling. These benefits contribute to more effective utilization of materials and technologies. Also, the environmental assessment results contribute to improving policy development and identifying risks and opportunities to balance the primary and secondary sources of silicon based on available resources with minimum negative environmental impact. The results highlight the significant role that a systematic sustainable management approach to the waste resulting from green energy technologies, can play when carried out in conjunction with current decarbonization activities. Furthermore, policy support to enable technology synergies and scale-up of critical materials recycling will reduce the total amounts of primary raw materials required and alleviate the environmental burdens associated with their production.

The proposed model can be used as a reference for policymakers to understand the role of silicon in green energy technologies and the possible development in circularity of other critical materials by integration of primary and secondary sectors. This approach is applicable for a comprehensive analysis of technology innovation trends in a dynamic competitive energy market and assessing the effectiveness of development policies. These findings prove that it is possible to expand circular economy actions by integrating sectors from a material perspective and offers a first step towards global assessment of synergizing critical material flows in secondary production by combination of open- and closed-loop supply chain dynamics.

Overall, this study can be used to identify areas for further research and sustainable development related to circular economy principles in the field of green energy technologies from a material perspective. Stakeholders can gain a better understanding of the benefits and costs associated with reusing silicon in solar PVs and LiBs by comparing different recovery strategies. The environmental impact and technological feasibility discussed here can guide decision-making related to economic feasibility. Furthermore, it is suggested the social cost of silicon flows aligned with environmental justice and equity for using green energy technologies be investigated holistically.

CRediT authorship contribution statement

Saeed Rahimpour Golroudbary: Conceptualization, Data curation, Methodology, Verification and, Validation, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Mari Lundström:** Conceptualization, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing, Supervision. **Benjamin P. Wilson:** Conceptualization, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Saeed Rahimpour Golroudbary reports financial support was provided by Aalto University.

Data availability

The authors declare that the data supporting the findings of this study are available within the article and its Supplementary Information files available at https://doi.org/10.5281/zenodo.10024343.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.114180.

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