



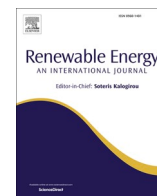
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Assessing material requirements, supply and circularity potentials for photovoltaic systems – the case of Cyprus

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ABSTRACT

Solar photovoltaic (PV) systems play a crucial role in the global green energy transition, but their material requirements present challenges in terms of supply chain resilience. The required materials include concrete, steel, silver, cadmium, tellurium, indium, and selenium, as well as a range of other materials (aluminium, copper, silicon, germanium and gallium) that are considered either critical or strategically important due to their supply risks and economic importance. Although the challenges for PV systems are addressed in the ambitious European Green Deal of the European Union (EU) through circular economy strategies, implementation at the national level faces obstacles. To analyse the material implications of a green energy transition dominated by solar PVs, this paper focuses on Cyprus, an island country with a high solar energy potential and ambitious PV deployment targets. We use Material Flow Analysis to examine the retrospective and prospective material accumulations and trends under three scenarios: Business-As-Usual (BAU) that reflects a continuation of historical trends; With Existing Measures (WEM) which incorporates currently adopted and legislated policies; and Net-Zero Scenario (NZS) that targets full climate neutrality by 2050. The results show a substantial increase in material stocks across all scenarios, with the NZS projecting the most-significant growth, followed by the WEM and BAU. The NZS also demonstrates a more balanced evolution of material demand over time, potentially mitigating supply chain risks. If circular economy practices are effectively implemented, it is possible for aluminium, copper, silicon, and germanium to meet future material needs through recycling of materials recovered from decommissioned PV systems in Cyprus towards year 2050. We emphasize the importance of policy interventions to initiate waste management activities and to promote circularity in the PV industry, potentially through collaborations with recycling initiatives and other EU countries. Our findings highlight the need for strategic planning and a balanced approach to PV deployment, so as to ensure a resilient and sustainable energy transition for Cyprus, while emphasizing the potential of the NZS for achieving these goals.

1. Introduction

Global climate change mitigation necessitates a transition away from the use of fossil fuels to net-zero carbon energy systems over the next decades. This transition will mainly be driven by increased renewable energy technologies and increased electrification of sectors such as transport and industry. Life Cycle Assessment methodologies confirm that these technologies consistently have a lower greenhouse gas footprint than fossil-based alternatives throughout their entire life, even when including the embodied emissions linked to their production [1]. However, along with social and environmental implications, the uses of raw materials that are an indispensable part of the green energy

transition, including the supply risks and geopolitical dynamics, are worthy of consideration [2].

Despite sufficient global reserves [3], studies on the availability of the materials that are essential for the green energy transition suggest classifying some of these materials as *critical* due to global market constraints. The World Bank's 2020 study has identified 17 minerals for which there are concerns regarding potential supply shortages that could hinder the *speed and scale* of the energy transition [4]. Similarly, the European Union (EU) has acknowledged the anticipated heightened resource demands in its pursuit of climate neutrality by year 2050. In its latest assessment, the EU has listed 33 raw materials that are considered to be either critical or strategically important, of which around 11 are

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essential for the production of green energy technologies and 5 are relevant to the PV technology (hereinafter “PV critical materials” – aluminium, copper, silicon, germanium and gallium) [5].

Despite continued expansion of globally installed non-renewable power capacity (close to 22 % added capacity between years 2013 and 2023), renewable energy sources (RES) are increasingly capturing a larger share of new capacity additions, leading to unprecedented levels of demand for materials [6]. Over the last decade, renewable energy capacity has almost tripled [6], and the latest forecasts from the International Energy Agency (IEA) indicate that to reach the net-zero target by year 2050, there will be a six-fold increase in the demand for materials that are essential for building these technologies [7]. Amongst all the technologies, solar photovoltaic (PV) systems will play a key role in this transition, especially in sunny regions, including the Mediterranean countries. Yet, the widespread deployment of PV systems requires significant inflows of materials for manufacturing and installation. Currently, solar photovoltaics is the most widely deployed renewable electricity technology globally, and it shares its dominant role with wind turbines in the EU-27 (Fig. 1) [6].

Solar PVs are the predominant technology for utilizing solar energy (>99 %) in the EU-27, followed by the Concentrating Solar Power (CSP) systems, which make a negligible contribution to the installed solar power capacity. According to the IEA, at the global level solar PV capacity additions will more than double by year 2028, while maintaining a generation growth rate for the net-zero emissions target will require capacity additions close to three-fold higher than those of year 2022 until year 2030 [8]. Therefore, the pivotal role of solar PVs in reaching the net-zero target is not only expected to continue, but will substantially expand in the coming years.

The anticipated increase in PV capacity raises concerns about the ability of material supply chains to meet the increasing demand for raw materials, and the ways in which this could increase the prices of these materials. In year 2021, raw materials constituted 35 %–50 % of solar module costs [9], raising concerns about future price spikes [7]. The potential concerns are not limited to the costs of the materials and their effects on the costs of the final products. International studies, such as those conducted from the World Bank [4] and IRENA [10] warn that the ability of the supply to meet the demand should not be taken for granted, signalling possible supply chain bottlenecks along with geopolitical considerations, such as trade restrictions. In addition, a large share (96 %) of the solar panels imported into the EU are produced in China [11], and this constitutes 80 % of the solar PV demand in Europe [12]. China

controls significant fractions of the global supply of the critical materials included in PV cells, such as silicon, gallium and germanium, accounting for 76 %, 94 % and 83 %, respectively [13]. This dominance is especially evident in the EU where China supplies 71 % and 45 % of the needed gallium and germanium, respectively [13]. Therefore, the supply of raw materials that are important for both the green energy transition and the economy as a whole entails risk that can induce vulnerabilities within the PV supply chain, potentially jeopardizing the progress towards year 2050.

Focusing on the EU, the European Green Deal (EGD) sets ambitious targets for achieving net-zero greenhouse gas emissions and decoupling economic growth from resource use across the EU (The European Green Deal, 2021) [14]. Material efficiency and circularity lie at the core of this strategy. Accordingly, to achieve its sustainability goals, the EU is promoting policies such as recycling, resource substitution, and efficient material use [5]. An important aspect of this strategy is reflected in the EU’s Waste from Electrical and Electronic Equipment (WEEE) Directive, which regulates PV panels and is currently under review with ongoing discussions on creating separate PV category and new waste calculation methods [15]. PV technology not only stands as the most-deployed renewable technology globally (Fig. 1), but it is also a candidate source of materials. Compared to other renewable electricity sources, the modular nature of the PV systems simplifies their end-of-life management and collection processes. This is particularly important for PV critical materials in the EU, e.g., aluminium, copper, silicon, gallium, and germanium. End-of-Life Recycling rates (EoL-RR), which is defined by the EU Raw Materials Information System (RMIS) as the share of secondary materials recovered and functionally recycled at the end-of-life compared to the total waste generated, vary across the materials (see S 3). For instance, copper, which is extensively used in PV systems, has a 53 % EoL-RR, with a 30 % contribution to meeting the new material demand in the EU [13]. While aluminium has a higher EoL-RR (72 %), its input to the new material demand is 18 % [13]. These figures are higher than the EU’s average circular material use rate of approximately 12 % [16] and are promising in terms of closing the loop for these two materials. However, the accelerated pace of the green energy transition and the extensive use of copper and aluminium, not only in PV systems but in whole EU economy, suggest that reliance on primary resources will likely remain substantial in the foreseeable future. The situation is even more concerning for the other PV-critical materials – silicon, gallium and germanium - which currently lack or have very limited established recycling processes [13]. Overall, the

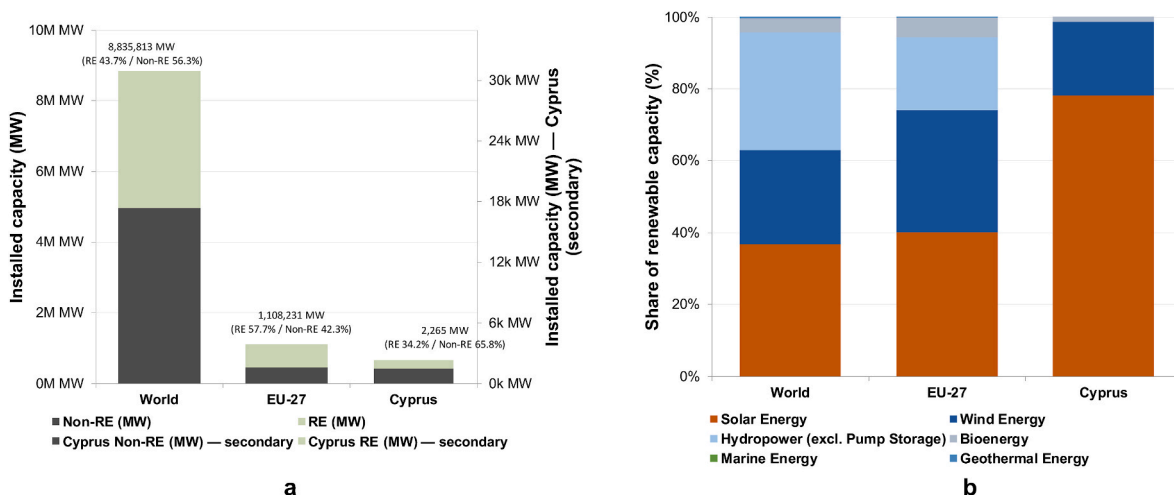


Fig. 1. Installed electricity capacity in the World, EU-27 and Cyprus (a) Total installed capacity split into non-renewables and renewables (MW). World and EU-27 share the primary MW axis; Cyprus is shown on a secondary MW axis for readability. (b) Composition of renewable capacity by technology (100 % stacked; share of renewables). Hydropower excludes pumped storage; storage technologies are not shown; non-renewables include fossil fuels and nuclear. Data source: IRENA Renewable Capacity Statistics 2024 [6].

potential of decommissioned PV systems as a source for the supply of secondary materials, which could play a pivotal role in ensuring a resilient and sustainable energy transition for the EU, currently remains low as most solar PV systems are relatively new and their recycling rates are negligible. However, considering that most PV systems have been installed in recent years and have lifetimes of some 20 years, the expected continuous expansion provides some time to develop efficient PV recycling systems. Data from Eurostat WEEE Statistics [17] indicates that PV panel collection volumes in the EU remain inconsistent in reporting amongst the member state. In 2019–2023, only 15 of the Member States reported data. Among the reporting member states, collected quantities are ranging from tens of tonnes in smaller countries to over 21 kt in Italy. Belgium, Germany, Italy and Spain reported collection volumes that indicate a scaling up trend, however, in some cases, we can observe inconsistencies in reporting such as missing waste generation data. Cyprus, for instance, reported no PV panel collection in this period despite having reported volumes of generated waste (560 tonnes). While mirroring the broader differences among the Member States, these discrepancies in reporting, makes it impossible to calculate a reliable EU collection rate for PV panels at this stage.

In reaching the collective targets set by the EGD, another important aspect is that the challenges facing the expansion of renewable energy differ between EU Member States. Each Member State, with its unique geography and climate, has its own potential for renewable energy. While some Member States are able to harness energy from diverse RES, for some the potential is very limited. As these differences are further amplified by the distinct economic contexts of each Member State, there is a need for country-specific studies that tailor national strategies to support both national and regional circular economy practices. Thus, concentrating on Member States with relatively lower circular material use rates (for instance, Cyprus, Portugal, Ireland and Romania) [16] and low levels of performance in relation to meeting the requirements of the WEEE directive [18] (for instance, Cyprus, Greece and Malta) would provide further grounds for more-tailored policies for overcoming the challenges associated with the supply chain bottlenecks.

Much research has been conducted on the increasing demands for the materials needed for the green energy transition. However, the studies performed to date have predominantly focused on the global and regional scales. For instance, the Joint Research Centre [19] analysed raw material needs for PV and wind technologies in Europe, while Watari et al. [20] estimated total material requirements for electricity and transport sectors globally. Valero et al. [21] presented global evaluation of material flows across decarbonization pathways. Zhou et al. [22] focused on the dynamic criticality of by-product metals in thin-film PV technologies, and Wellmer et al. [3] provided a broader outlook on the long-term availability of raw materials for future energy supply. A recent review by Liang et al. (2022), confirms this trend and notes the limited attention given to analyses on the national level [23]. This trend also applies to studies carried out by international organizations such as those conducted by the World Bank [4], International Energy Agency [7] and IRENA [10]. To our knowledge, only a few studies have focused on individual EU member states. Viebahn et al. [24] assessed Germany's demand for critical minerals under renewable transition scenarios, Savvidou and Johnsson [25] examined circularity and material intensity for wind energy in Sweden, Van Oorschot et al. [26] modelled national metal flows in the Dutch electricity system and Lallana et al. (2024) [27] assessed metal requirements across energy and digital transition technologies in Spain. These investigations have typically employed a Material Flow Analysis (MFA) to assess the flows and stocks of materials that are essential for the green energy transition. The key differences between these studies relate to scope and interpretation of the results, which are often influenced by the unique circumstances of the countries being analysed. Notably, existing national studies focus primarily on countries that have diverse renewable energy portfolios with relatively higher potentials for RES other than solar PV. The present study fills this gap in the knowledge by examining Cyprus, a country that is well suited

to relying on the PV technology for its energy transition. Cyprus has ambitious PV deployment targets, even though it currently has little PV utilization (i.e., 606 MW out of a total capacity of around 2250 MW, with around 12 % of the electricity generation from renewables) [6]. As the future of solar PV deployment is critical for Cyprus, the country constitutes a suitable case study for analysing the material dynamics for the implementation of this technology. Overall, our paper seeks to increase understanding of the specific material needs of an energy system that currently has very low shares of PV and that is envisioned to transform to having very high shares of PV. We perform a detailed, country-specific analysis and examine the retrospective and prospective material trends of PV systems in Cyprus, with the aim of contributing to the broader body of knowledge in the field, by addressing the following questions:

- I. **Material Accumulation:** How will the accumulation of specific materials within PV systems (i.e., stocks) change over time?
- II. **Material Flows:** How will the material requirements and outflows (i.e., Inflows and Outflows) evolve over time?
- III. **Secondary Material and Circularity Potentials:** What is the potential for decommissioned PV systems to close the material loops?

2. Scenarios for energy transition in Cyprus

We focus on the historical and projected growth of PV capacity in Cyprus to assess the material implications under the following three scenarios: Business-As-Usual (BaU); With Existing Measures (WEM); and Net-Zero Scenario (NZS), with the latter meeting net-zero carbon emissions by year 2050. These scenarios are based on Cyprus' Integrated National Energy and Climate Plan (NECP CY) [28] and additional projections by Zachariadis & Taliotis [29]. Historical data were collected from IRENA [6]. The capacity forecasts used both by the NECP CY and Zachariadis & Taliotis were derived from the Open-Source Energy Modelling System - Cyprus Cost Optimization Model (OSeMOSYS – Cyprus), a model that has also been applied in a recent study by Taliotis et al. [30]. BAU and WEM are the official scenarios of the NECP CY. The NZS was originally proposed by Zachariadis & Taliotis.

Fig. 2 shows the development of the renewable generation mix up to year 2050 for Cyprus in terms of capacities (Fig. 2a) and shares of PV and other renewables (Fig. 2b), for the three scenarios. In line with the structure of the OSeMOSYS-Cyprus model, which considers storage technologies within the broader energy system capacity mix, the projected renewable capacity in Fig. 2 includes lithium-ion batteries. Table 1 provides details of both the assumptions and the evolution of each scenario.

A closer examination of the scenarios reveals that Cyprus has reached a critical juncture in its energy transition. While the country is currently restricted by its isolated (island) grid, the completion of the GSI by year 2029 is expected to increase the potential for renewable electricity shares and reduce the need to curtail electricity generation, particularly from solar PVs. The scenarios suggest that Cyprus will need to accelerate its energy transition efforts post-2029, and increase investments in RES, especially in the decade following the entry into operation of the GSI, in order to remain on course for the emissions target. The effects of the accelerated investment efforts on the material demands within a limited timeframe can be seen from the results in this paper.

Overall, it is important to note the central role that the PV system plays in all three scenarios (Fig. 2). The shares of PVs in all three scenarios indicate the indispensable role of the technology in the island's green energy future. Even in the BAU scenario, which represents the most-conservative approach to the green energy transition, PV systems demonstrate a steady rise in capacity, resulting in a 66 % share of the total electricity capacity at its highest point. The WEM scenario, on the other hand, places greater emphasis on the PV systems, showing a technology contribution to the total electricity capacity of 88 % by year

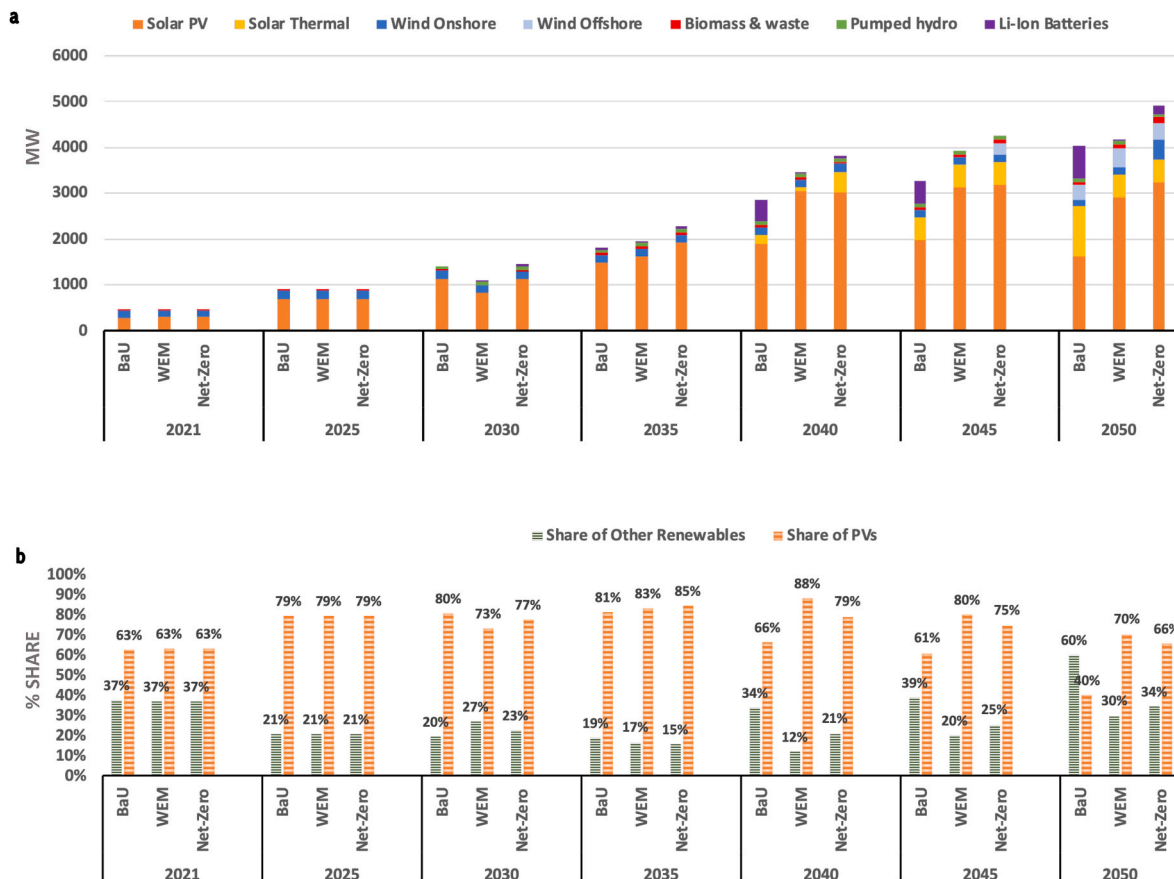


Fig. 2. (a) Renewable capacity mixes and (b) shares of solar PV in the capacity mix in Cyprus in the period of 2021–2050, as obtained from studies that employed OSeMOSYS – Cyprus. Note: Lithium-ion batteries are included in the capacity mix as a supporting storage technology, not as a generation source. They reflect storage technologies which are expected to complement renewable energy deployment.

2040. NZS is the most-ambitious of all the scenarios in terms of the investments proposed for reaching the net-zero target. While the WEM Scenario shows higher PV shares overall, solar PVs also play a central role in the NZS. The absolute installed PV capacity is largest under NZS (327 MW compared to 2911 MW and 1620 MW in WEM and BAU respectively). Even though PVs share of the total electricity capacity peaks at 79 % by year 2040 and declines slightly thereafter, the technology remains a major contributor to the renewable capacity throughout the NZS.

3. Methodology for investigating material requirements

The MFA serves as the primary method to investigate the material dynamics and provides a structured framework to quantify and track material flows and stocks within an energy system [31]. The core principle of MFA is the conservation of the mass balance within the given system boundary, and the MFA's ability to analyse both retrospective and prospective scenarios makes it highly useful for understanding the long-term material implications of the energy transition scenarios presented in the previous section. To enhance the clarity and comparability of the results, we followed the standardized modelling approach offered by the Open Dynamic Material Systems Model (ODYM) [32]. This Python-based software is designed specifically for MFA and offers dynamic modelling capabilities and smooth integration with energy data, making it ideal for our research purposes. Section 2 of the Supplementary material outlines the framework that can be used to analyse the material requirements of the different green energy transition pathways (S Fig. 2).

3.1. The MFA model and definition of system boundaries

Fig. 3 outlines the modelling framework applied for analysing the material requirements of the PV systems (i.e., solar panels and supporting structures) in Cyprus, both for the historical development and for the three scenarios (Table 1) related to the future development. The system definition encompasses PV systems and supporting structures within the energy system and relevant materials, with a geographic boundary that is limited to Cyprus and a temporal boundary that spans the period of 2013–2050. It should be sufficient to extend the boundary back to year 2013, since the expansion of PV systems has occurred only in recent years. Our modelling (Fig. 3) applies a Weibull distribution to model the degradation and decommissioning rates applied to both the retrospective and prospective data for 2013–2050. Employing MFA, our model quantifies and monitors the stocks and flows of materials for the PV technology. By integrating historical data, projections, and dynamic modelling approaches, it provides a detailed understanding of the material needs associated with the PV transition in Cyprus.

The dashed box in Fig. 3 represents the core calculations of the MFA model. The surrounding boxes depict the data inputs and results, as well as their connections to the model itself. Our analysis, which is based on stock-driven and inflow-driven modelling approaches, as discussed in prior work on industrial ecology [33] and dynamic stock modelling methodologies [34] and has four main objectives, as described below.

A. Capacity Inflows (Step 1):

Given the historical and future installed capacity data (stock) and the lifespan distribution, the stock-driven MFA model calculates the newly

Table 1

Key assumptions made for the BAU, WEM and NZS scenarios in Cyprus' Energy Plans.

	BAU	WEM	NZS
Scenario Description	Reflects continuation of current trends without implementation of additional energy/climate policies, where limited enforcement of existing measures and low decarbonization ambition is assumed as outlined in the Cyprus NECP.	Includes all currently adopted and legislated policies and measures including officially planned emission reductions up to 2030 as outlined in the Cyprus NECP.	A more ambitious scenario developed by Zachariadis & Taliotis, aiming for net-zero emissions by 2050, with high investment in RES.
Fossil Fuel Use ^a	Heavy reliance on oil until year 2024; thereafter, integration of natural gas	Reduction of oil use, strong shift towards usage of natural gas and RES	High penetration of RES, and some use of natural gas with CCS in power generation
GHG Emissions in ETS Sectors	High levels of GHG emissions without significant reductions	Greater reductions in GHG levels due to energy efficiency measures and a shift to cleaner sources	Net-zero emissions by year 2050
Techno-Economic Data	Based on Cyprus Hydrocarbons Company forecasts for oil and natural gas prices, Ministry of Finance for GDP	Based on Cyprus Hydrocarbons Company forecasts for oil and natural gas prices, Ministry of Finance for GDP	Based on Cyprus Hydrocarbons Company forecasts for oil and natural gas prices, Ministry of Finance for GDP
Electricity Demand	Steady growth, highest at all times until year 2050 compared with the other two scenarios	Steady growth, energy lowest at all times until year 2050 compared with the other two scenarios.	Steady growth, lower than BAU
Electricity Interconnection ^b	Great Sea Interconnector (GSI) operational by year 2029.	GSI operational by year 2029.	GSI operational by year 2029.
Investment Assumption	Minimal investment compared with the other two scenarios	Emphasis on cost-effective renewable solutions	Substantial investment for complete transition, i.e., 80 billion €, close to 1 % of GDP annually
Total non-renewable capacity in 2050	1095 MW	774 MW	870 MW ^c
Total renewable capacity in 2050	4037 MW	4138 MW	4923 MW
PV capacity in 2050	1620 MW	2911 MW	3227 MW
RES share in years 2025, 2030, 2040, and 2050	31 %, 45 %, 70 %, and 79 %, respectively	34 %, 42 %, 83 %, and 84 %, respectively	34 %, 49 %, 81 %, and 85 %, respectively
PV Share of Total RES in years 2025, 2030, 2040, and 2050	79 %, 80 %, 66 %, and 60 %, respectively	79 %, 73 %, 88 %, and 70 %, respectively	79 %, 77 %, 79 %, and 66 %, respectively

^a All of the scenarios initially projected natural gas availability for electricity generation by mid-2024, representing a shift from the late-2021 target in the previous NECP.

^b Until year 2029, Cyprus will operate as an isolated grid, independent of neighbouring countries. This isolation is expected to end due to the ongoing construction of the Great Sea Interconnector (GSI). This crucial infrastructure project is expected to enable the integration of additional renewable energy sources (RES) and reduce the need to curtail solar and wind power production.

^c A significant development across all scenarios will be the inclusion of Combined Cycle Gas Turbines with Carbon Capture and Storage (CCGS with CCS) in the energy mix by year 2030. NZS includes a higher share of CCGT with CCS, as a low-carbon balancing option to ensure grid stability under very high shares of renewable and CCGT with CCS is counted here as non-renewable. Although this increases non-renewable capacity relative to WEM, emissions are lower due to CCS deployment.

installed capacities needed per year (inflows). The capacity inflows are calculated as in Equation (1):

$$CI_{PV}(t) = CS_{PV}(t) - \sum_{\tau=t_0}^{t-1} CI_{PV}(\tau) \propto (t - \tau) \quad (1)$$

The capacity inflow (CI_{PV}) of the PV system for each year (t) in each scenario is calculated as the difference between the capacity stock (CS_{PV}) in that year and the sum of the remaining shares of the past inflows of the PV systems (Equation (1)). As illustrated in Fig. 3, we use a Weibull distribution for the lifespan of 22 years and a standard deviation of 5 years, based on predictions of the lifespans of PVs systems from the literature (see Section 3.5).

B. From Capacity Inflows to Material Flows and Stocks (Step 2):

The model calculates the material inflows (entering the system), stocks, and outflows (leaving the system) associated with PV system deployment and decommissioning.

To quantify the inflows of materials into the system ($I_{mat}(t)$), we multiply the new capacity inflow (CI_{PV}) by the numbers for the Annual Market Shares ($MS_{subtech}(t)$) and Material Intensities ($MI_{mat}(t)$) of each sub-technology, as in Equation (2):

$$I_{mat}(t) = CI_{PV} * MI_{mat}(t) * MS_{subtech}(t) \quad (2)$$

Given the material inflows from Step 2 and the lifespan distribution, the inflow-driven MFA model calculates the material stocks according to Equation (3):

$$S_{mat}(t) = \sum_{\tau=t_0}^t I_{mat}(\tau) \propto (t - \tau) \quad (3)$$

Material outflows ($O_{mat}(t)$) are calculated based on the principle of mass balance. Therefore, the outflow in period t is the difference between the inflow and the addition to the stock in the same period ($\Delta S_{mat}(t)$), as expressed in Equation (4):

$$O_{mat}(t) = I_{mat}(t) - \Delta S_{mat}(t) \quad (4)$$

All of the above processes facilitate the calculations of the values for the annual and cumulative stocks, inflows and outflows of materials relevant to the PV systems and are within the scope of this study.

C. Material Demand for Replacement & Expansion (Step 3)

Based on the preceding analysis, we can interpret the inflows of materials in terms of the demands for expansion and replacement for each material in year (t). The demand for expansion, $Expansion_{mat}$, in period (t) appears only if the capacity flows in the same period are greater than those in the previous period. In this case, the incremental increase in capacity inflows (ΔCI_{PV}) can be translated as the material demand for expansion, whereas the remainder of the material inflow can be attributed to the material demand for replacement [35]. This is expressed in Equations (5) and (6) as follows:

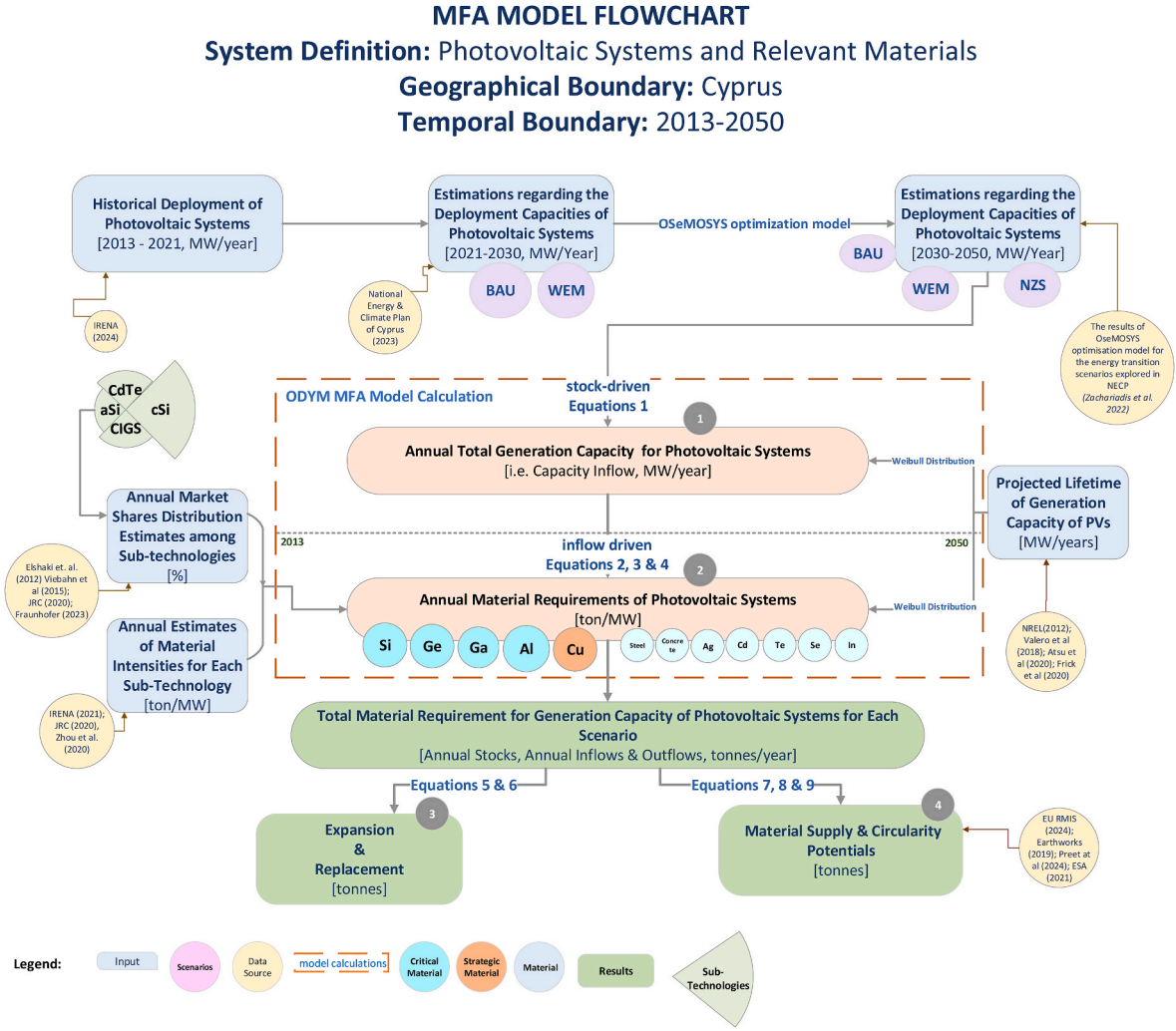


Fig. 3. Flowchart for the MFA model applied in this work.

$$\text{Expansion}_{\text{mat}}(t) = \begin{cases} \Delta CI_{PV}(t) * MI_{\text{mat}}(t) * MS_{\text{subtech}}(t), & \Delta CS_{PV}(t) > 0 \\ 0, & \Delta CS_{PV}(t) \leq 0 \end{cases} \quad (5)$$

$$\text{Replacement}_{\text{mat}}(t) = \begin{cases} I_{\text{mat}}(t) - \text{Expansion}_{\text{mat}}(t), & \Delta CS_{PV}(t) > 0 \\ I_{\text{mat}}(t), & \Delta CS_{PV}(t) \leq 0 \end{cases} \quad (6)$$

D. Material Supply Potentials and Circularity Potentials (Step 4):

To determine the Material Supply Potential (MSP) from decommissioned PV technologies, we use the outputs from the MFA model for the NZS. Thus, the MSP of the system can be considered in two ways: 1) the MSP realized within the temporal scope (2013–2050); and 2) the MSP after year 2050.

The MSP within the temporal scope (T_s) is calculated as the sum of the outflows of a material ($\sum O_{\text{mat}}$) that is expected to become available for recycling from the decommissioned PV systems within the temporal scope (T_s), as shown in Equation (7):

$$MSP_{\text{mat}}(T_s) = \sum MO_{\text{mat}}(T_s) \quad (7)$$

The MSP that is created but still maintained within the system (i.e., stocks) during the period of 2013–2050 ($MSP_{\text{mat}}(t>2050)$), will become available (as outflows) for recycling after year 2050. This is calculated as the difference between the total inflow ($\sum I_{\text{mat}}$) and the total outflow ($\sum O_{\text{mat}}$) of a material that occurs during the temporal scope (T_s), as

shown in Equation (8). It is important to note that this calculation does not account for additional potential investments in PV systems beyond year 2050.

$$MSP_{\text{mat}}(t>2050) = \sum I_{\text{mat}}(T_s) - \sum O_{\text{mat}}(T_s) \quad (8)$$

For the purpose of this study, the circularity potential of the decommissioned PV systems within the temporal boundaries is defined as the tonnes of materials needed for new installations (inflows) that could be reduced by the circular activities using the MSP of the decommissioned systems. This potential can help us to understand how many of the PV material loops that Cyprus can close, assuming that circularity strategies for PV Systems are implemented in the country.

For these calculations, we took the current EoL-RR in the EU and the potential EoL-RRs for years 2024 and 2050, respectively (see Section 4.6). Then, we used linear interpolation to model the potential for increasing circular economy efforts over time. Our focus is on the MSP within the temporal boundary for PV critical materials under the NZS.

$$\text{Circularity Potential}_{\text{mat}}(t) = \frac{MSP_{\text{mat}}(t) \times RR_{\text{EoL,mat}}(t)}{I_{\text{mat}}(t)} \times 100 \quad (9)$$

Accordingly, Equation (9) calculates the percentage of the material demand that can be met through recycling at a given time (t). We determine the circularity potential by multiplying the Material Supply Potential ($MSP_{\text{mat}}(t)$) by the EoL-RR, and then dividing by the material inflow ($I_{\text{mat}}(t)$) and converting the result into a percentage.

4. Definitions of the system and data

4.1. Photovoltaic systems

The modules in PV systems exhibit a diverse array of material compositions due to differences in their types. Therefore, we studied different PV sub-technologies and detected variations in the dynamic material intensities and market shares. Wafer-based crystalline silicon (c-Si) is currently the predominant technology, followed by alternative thin-film options [36]. The wafer-based c-Si category is divided into two modules: mono-crystalline silicon and multi-crystalline silicon. The thin-film alternatives consist of amorphous silicon (a-Si), copper-indium-gallium-selenide (CIGS) and cadmium-telluride (CdTe) modules. We focus on these four distinct sub-technologies. The c-Si modules currently dominate the PV market and account for the majority of PV installations worldwide due to their established technology [36], relatively high efficiency, and widespread use in residential, commercial, and utility-scale applications. For details of each sub-technology and their current market dynamics, see Supplementary Material Section 2b, Table 1.

4.2. Historical & future capacity data

Historical deployment data were gathered from the International Renewable Energy Agency (IRENA) [6] for the period of 2013–2021 and correlated with the NECP CY Data for 2023–2030 [28]. For the prospective analysis from 2030 to 2050, we leveraged capacity forecasts from OSeMOSYS [30] – Cyprus, while introducing the NZS aligned with official NECP goals [29]. It is important to note that as real-time deployment data align with the NECP CY capacity data, our retrospective analysis covers the period of 2013–2024. Accordingly, the prospective analysis focuses on the period of 2025–2050.

All the modeling results are compared to the period of 2021–2025 as the baseline.

4.3. PV technology market shares

Dynamic market share data are fed into the model calculations, considering the historical, current, and projected trends. Focusing on the EU, we have collected market share data from the literature (see Fig. 3) and utilized linear interpolation techniques to estimate the values for the intervening years. The historical data show that c-Si dominated the market with a share of >96 % in year 2013 [37], thereafter slightly declining to approximately 95 % by year 2021 [36]. According to the EU's Clean Technology Observatory the market share held by c-Si is projected to decrease further to 90 % by year 2050 [38]. Thin-film technologies, such as CdTe and CIGS, have had smaller but growing market shares, with CdTe increasing from 1.4 % in year 2013 [22] to a peak of 1.75 % in year 2021, although it is expected to drop to 0.45 % by year 2050. CIGS is projected to grow from 1 % in year 2013 to 4.5 % by year 2050 [19]. The a-Si technology, while holding a minimal market share, is expected to maintain a steady presence [22]. Current market shares have been synthesized from Fraunhofer institute [36]. Supplementary material, Table 2 provides more information on the market share assumptions that were synthesized from the literature and used in this paper.

4.4. Material intensity reduction potential of PV technologies

We calculated the material intensity reduction potentials (MIRPs) for the four PV sub-technologies. With regards to the critical materials, aluminium and copper are the predominant materials used in frames, converters, wiring, cabling, and inverters. Both materials show a slight decreasing trend in material intensity over the years (S 2d), suggesting improvements in the efficiency of the materials used in production, based on reports from the EU Joint Research Center [19] and IRENA [9,

Table 2

Summary of the key assumptions and input parameters used in the dynamic MFA model and analysis for PV systems in Cyprus.

Parameter	Value/Range/ years	Source(s)	Notes
Geographical Boundary	Country, Cyprus	M 3.1	This study focuses exclusively on domestic stocks and flows
Modelling Period	Years covered between 2013–2050	M 3 and S 4; see link provided for Excel Workbook under S 4	Retrospective (2013–2024) and prospective (2025–2050)
Historical and Future Capacity Data	Unit: <i>Megawatt</i> MW Capacity between 2013 and 2050	Cyprus NECP, 2023; IRENA, 2023; Zachariadis & Taliotis, 2023; see link provided for Excel Workbook under S 4	Used to calculate capacity inflows based on BAU, WEM and NZS.
PV Technology Market Shares (2013 & 2050)	Unit: % c-Si: 97 % → 90 % CdTe: 1 % → 4.5 % a-Si: <1 % → 1 % CIGS: 1 % → 2 %	S Table 2; Elshaki et al., 2013; Viebahn et al., 2015; Fraunhofer ISE, 2023; EC JRC, 2020	Historical and future market share data were collected for all available years between 2013 and 2050. Multiple linear interpolations were applied only between known values to model continuous evaluation over time
Material Intensity Reduction Potentials (2013 & 2050)	Unit: <i>Tonnes per Megawatt</i> Concrete: 53.8 → 50.8 t/MW Steel: 91.95 → 58.55 t/MW Al: 13.25 → 12.9 t/MW Cu: 5.8 → 5.6 t/MW Si (c-Si): 4 → 2 t/MW Si (a-Si): 0.15 → 0.07 t/MW Ag: 0.02 → 0.002 t/MW Cd: 0.06 → 0.01 t/MW Te: 0.04 → 0.02 t/MW Ge: 0.04 → 0.02 t/MW In: 0.02 → 0.007 t/MW Ga: 0.005 → 0.002 t/MW Se: 0.045 → 0.014 t/MW	S Fig. 3, Zhou et al., 2020; EC JRC, 2020, IRENA, 2024; see supplementary information Excel Workbook	MIRP values were gathered for all available data years. Multiple linear interpolations were applied only between known values to model continuous evaluation over time
PV Life-Time	Mean 22 years; Standard Deviation 5 years	M 4.5; Frick et al. (2020), Atsu et al. (2020)	Weibull distribution is used to model the stock and outflows
Potential End-of-Life Recycling	Unit: % Al: 72 % → 81 %	EU Raw Material Information System,	Linear interpolation

(continued on next page)

Table 2 (continued)

Parameter	Value/Range/ years	Source(s)	Notes
Rate of PV Critical Materials (2024–2050)	Cu: 53 % → 81 % Si: 0 % → 81 % Ge: 12 % → 80 % Ga: 0 % → 81 % (Collection Rate 85 %)	2024; Earthworks, 2019; Preet et al., 2024; ESA, 2021; See S2e	applied to model the gradual increase in EoL- RR.

Al – Aluminium; Cu – Copper; Si – Silicon; Ge – Germanium; Ga – Gallium; Ag – Silver; Cd – Cadmium; Te – Tellurium; In – Indium; Se – Selenium.
M – Main Manuscript; S – Supplementary Information.

10]. Silicon, which is an essential component of c-Si and a-Si panels, is also projected to undergo improvements in material efficiency towards year 2050, as reported by the Fraunhofer Institute [36] and JRC Study [19]. In addition, a study conducted by Zhou et al. (2020) has provided data for the germanium and gallium contents of the a-Si and CIGS technologies, respectively, which allow us to derive the MIRPs of these two technologies towards year 2050 [22].

4.5. PV lifespan and degradation considerations

Solar panels gradually lose efficiency over time, in a process known as *degradation*. This decline in performance is typically measured as a percentage of the annual power output [39]. Depending on climatic conditions, commercial solar panels typically last 25–30 years, although they can generate electricity beyond their warranty periods with annual degradation rates of between 0.5 % and 3.5 % [39]. Cyprus' Mediterranean climate, characterized by high temperatures, dust storms, and intense sunlight may accelerate the degradation rates for PV systems, potentially reducing their lifespans [40]. Due to the lack of real-time, end-of-life data for PV systems in Cyprus and accounting for the accelerated degradation rates observed in similar climates, our study adopts a reference lifespan of 22 years with a standard deviation of 5 years.

4.6. End-of-Life Recycling rates

We collected data from different sources for the current and potential EoL-RRs. We focused on the critical and strategically important materials in PV systems. Data for the current EoL-RRs were obtained from EU RMIS [13]. For aluminium, copper and gallium, potential PV-specific recycling rates were taken from the report “Responsible Mineral Sourcing for Renewable Energy” (published in collaboration with Earthworks), which assumes 85 % collection efficiency and up-to 95 % material specific recovery efficiencies [41]. For silicon, we combined the Earthworks methodology with data from Preet et al. [42]. For germanium, we relied on the European Space Agency [43] which projects ~100 % theoretical recovery efficiency and again applied the 85 % collection rate to remain consistent with Earthworks methodology. Our aim is to show the circularity potential (Section 3.1D). Considering the accelerated efforts of the EU towards PV recycling, we assumed a steady increase in EoL-RR between the years 2024–2050 (S 2e).

4.7. Summary of key assumption

A summary of the key assumptions and parameters used in the MFA model and analysis is presented in Table 2. Full datasets, year-by-year input values, results and ODYM-python model structure are provided in Supplementary Information along with excel files and code repository.

5. Results

5.1. Material accumulation in the PV stock

Fig. 4 shows the results from the MFA analysis, comparing the projected changes in material stocks for solar PVs between the baseline period (2021–2025) and the period of 2046–2050 for the BAU, WEM, and NZS scenarios. The BAU scenario requires a 3.4-fold increase in material stocks in PVs by 2046–2050 compared to the baseline period, even without additional policy interventions and aligning with the capacity forecasts presented earlier. More significantly, the WEM scenario requires a 5.8-fold increase by 2046–2050 compared to the baseline period. The NZS projects a 6.2-fold increase in material stocks.

Fig. 5a shows the accumulations of all the materials relevant to PV systems over the period of 2013–2050 for each scenario, as obtained from the MFA analysis [Equation (3)]. Although a comparatively lower capacity for PVs is projected under the BAU scenario, the results show that there is still a substantial accumulation of materials, with a peak total accumulation by year 2045 (approximately 266,000 tonnes of materials), and the stock levels drop to around 206,000 by year 2050. The rapid increase in PV deployment under the WEM scenario increases the material stocks to 418,000 tonnes by year 2045, and this gradually drops to around 386,000 tonnes by year 2050. Finally, the NZS anticipates a gradual but ultimately more-substantial material accumulation, representing the highest material stock of approximately 428,000 tonnes by year 2050.

Panels 5b, 5c and 5d in Fig. 5 show the average stock levels within specific 5-year intervals, allowing us to compare the differences in accumulation patterns between all the materials and the critical and strategically important materials in the short, medium and long terms, as compared to the baseline (2021–2025). We opted to illustrate the two critical materials, namely germanium and gallium, in a separate graph (Fig. 5d), as the relatively low stocks of these materials do not allow visualization of their accumulation patterns when plotted together with the other materials.

There is a clear increase in the average material stocks from the baseline period in all the scenarios, even in the short term (Fig. 5a). Although having lower average stocks, the PV critical materials (Fig. 5c) show similar trends. The rapid growth in material stocks after 2029 under the WEM, is driven by the accelerated deployment of PV capacity to meet renewable targets upon the completion of the Great Sea Interconnector (GSI) that will allow greater system flexibility and higher RES penetration (see section 2). Under WEM, major capacity additions take place decade following 2029, and then slowdown in the later decades. Accordingly, inflows decrease and outflows from decommissioned system rise, while the overall energy system reaches to a maturity. Consequently, this dynamic first caused a peak in in-use stocks and later a gradual decline especially after 2045 as the installed PV systems complete their useful life. The NZS maintains the highest accumulation levels throughout the medium (2041–2045) and long (2046–2050) terms. Steel, concrete, aluminium and copper are the materials with the highest accumulation patterns in terms of average stocks, followed by silicon, silver, cadmium, tellurium, germanium, indium, selenium and gallium with respect to their average numbers of tonnes in the short, medium and long terms, as compared to the baseline. Germanium and gallium (Fig. 5d) show significant increases in all the scenarios in the medium term. However, despite the increased market shares of the sub-technologies utilizing these two materials, the average stocks in all of the scenarios show a decrease in the long-term. This aligns with the increased MIRP assumptions made for these two materials (S 2d), and indicates that although they enjoy greater market shares (S T4), the new PV sub-technology installations for CIGS and a-Si contain lower levels of these two materials compared to those decommissioned before year 2045.

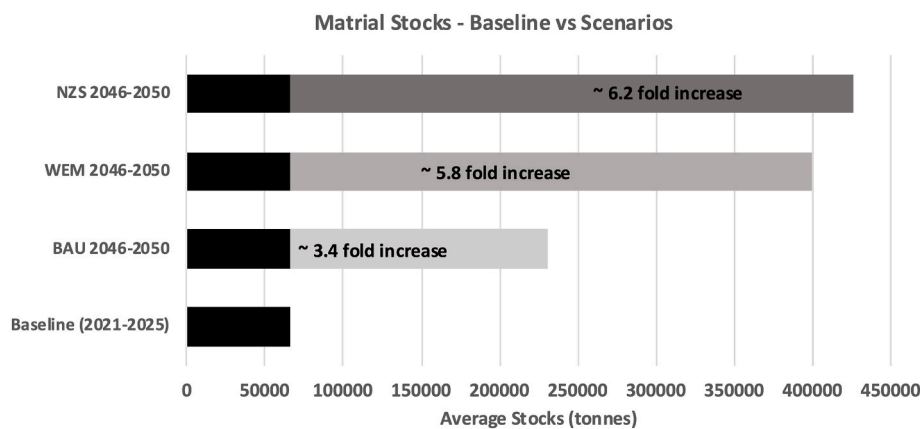


Fig. 4. The material stocks in PVs comparing the baseline scenario and the three scenarios, as obtained from the MFA analysis in this work.

5.2. Material flows

5.2.1. Inflows and outflows

Fig. 6 accounts for all materials relevant to the PV technology and illustrates the differences between the three scenarios in terms of material inflows and outflows for the PV stock in Cyprus. Each of the scenarios experience peak inflows, albeit with the peaks occurring at different times and volumes. The WEM scenario, however, exhibits the highest peak in terms of inflows around the period of 2036–2040, accumulating 211,000 tonnes of materials.

The BAU scenario peaks in terms of inflows between 2036 and 2040, and experiences a sharp decline towards year 2050. These results align with the investment assumption made for this scenario (Table 1), as after the substantial investment in PVs, the technology is losing capacity to other energy sources, such as Solar Thermal and Combined Cycle Gas Turbine with Carbon Capture and Storage (Supplementary, Fig. 1).

The surge in inflows, however, is followed by a gradual decrease, whereas the outflows are increasing. The highest overall inflows are expected under the NZS with nearly 600,000 tonnes of materials. However, the surge in inflows under the NZS (Fig. 6c) is lower than that under the WEM scenario. The sharp drop in inflows under WEM around 2026–2030 period reflects the scenario-specific assumption of slower PV investments. Thus, despite having the highest overall inflows, NZS adopts a more-balanced approach, as the results show that this scenario adopts a more-distributed demand for materials over the years, as compared with the WEM scenario. This is in agreement with the scenario assumptions presented earlier and reflects a more-distributed investment plan for PV systems over time in the NZS compared with the WEM scenario, i.e., providing greater flexibility to mitigate possible supply chain risks. Notably, while the BAU and WEM scenarios both show decreases in inflows towards year 2050, the NZS is the only scenario in which PV deployment continues to increase all the way up to year 2050, and possibly beyond.

Outflows, on the other hand, show relatively similar trends for all the scenarios. This is due to several reasons. First, all the scenarios share the same historical deployment data, whereas they differ in terms of their capacity inflows only after year 2025. Second, the long lifespan of the PV technology, together with the time boundaries of this analysis, do not allow us to see the potential divergences among the different scenario outflows, given that many of the PVs deployed between year 2025 and year 2050 will be decommissioned after year 2050. Nevertheless, the difference between the outflows from the NZS and the other two scenarios is still observable for the 2045–2050 period, reflecting slightly greater outflows resulting from the inflows linked to the gradual and continuous PV growth trajectory (i.e., installed capacity) of the NZS (see Fig. 2), especially between 2025 and 2040.

Fig. 7 presents the flow trends of each material under the NZS, i.e., showing the early signs of the potential of each material outflow to meet

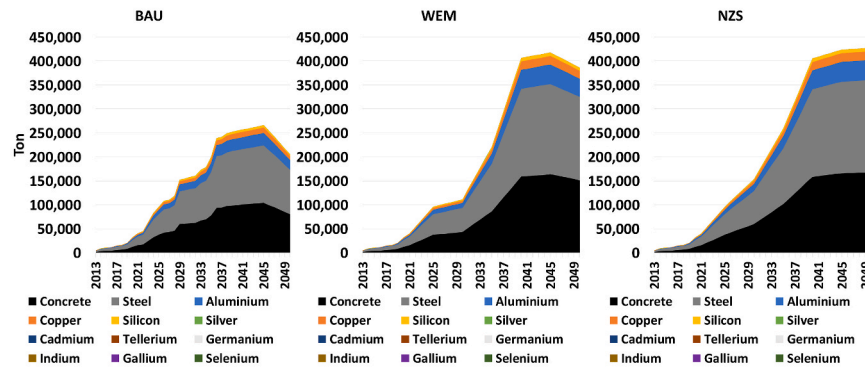
the new requirement under the NZS. Accordingly, three of the twelve materials that are analysed in this study – namely, silicon, germanium and silver, show signs of potentials to satisfy the future requirements, as their outflows from the decommissioned PV systems surplus the inflows required for expansion and/or replacement needs. Two of these materials (silicon and germanium) are classified among the EU's critical raw materials, while the third (silver), although not considered critical by the EU, is nevertheless highly demanded in PV manufacturing. The outflows for these materials begin to match their inflows as early as year 2041, and increasingly exceed their inflows towards year 2050. The outflows of concrete, steel, aluminium, copper and cadmium, on the other hand, closely match their inflows. While tellurium, indium, gallium and selenium show increasing outflows, their outflows remain below their corresponding inflows. Overall, aluminium and copper show a very close match in terms of inflows and outflows in the last ten years before year 2050, while the outflows of silicon and germanium actually exceed their inflows within the same time frame. Thus, four out of the five PV critical materials are already demonstrating potential for self-sufficiency.

5.2.2. Demands for expansion and replacement

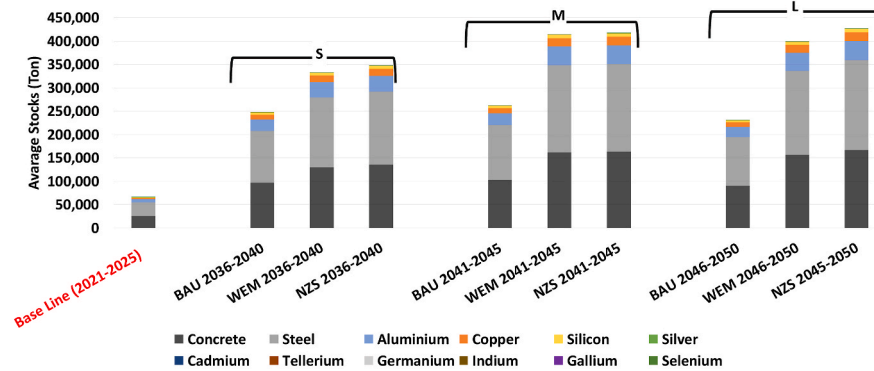
The material flows for expansion and replacement in each scenario are shown in Fig. 8. The red line in the graphs represents the outflows. The total demand for expansion during the period of study is almost 266,000 tonnes of materials (with around 33,000 tonnes being critical materials), while 146,000 tonnes of inflows (with 24,000 tonnes being critical materials) are demanded for the replacement of the decommissioned PV systems. Our results correlate with the scenario capacity inflows for the PV systems. Accordingly, the highest peaks for expansion in the BAU scenario occur in the 2021–2030 period, aligning with the initial capacity investments in PV systems during those years. In the WEM scenario, the material demand to meet the expansion needs to peak between year 2030 and year 2040, reflecting the high PV capacity forecasted for the period under this scenario. In the NZS, the demand for expansion to deploy new PV systems (required to meet the energy demand, as well as the net-zero target) is spread across different periods; it still peaks between year 2030 and year 2040, while the increase is less steep than in the WEM scenario.

In all the scenarios, the material flow related to the replacement of the decommissioned PV systems to maintain the capacity needed for the energy needs of the island, begins to require inflows already in the 2030s. Unlike the various trends observed for expansion in the different scenarios, the material flows are similar in all the scenarios, except for the last 5 years because the BAU and WEM scenarios do not assume capacity improvements (i.e., additional investments) during the 2046–2050 period. Similar trends for replacement in all the scenarios correlate with our historical capacity data (2013–2025). With the assumption of a PV lifespan of 22 years, the PV systems need to be

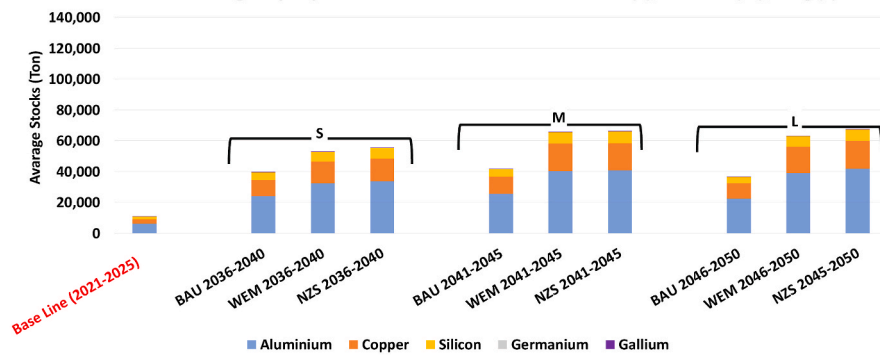
a. Stocks - All materials from 2013 - 2050



b. Stocks - all materials - Base Line vs. Short (S), Medium (M), Long (L) Terms



c. Stocks - Critical and strategically important materials - Base Line vs. Short (S), Medium (M), Long (L) Terms



d. Stocks - Germanium and Gallium - Base Line vs. Short (S), Medium (M), Long (L) Terms

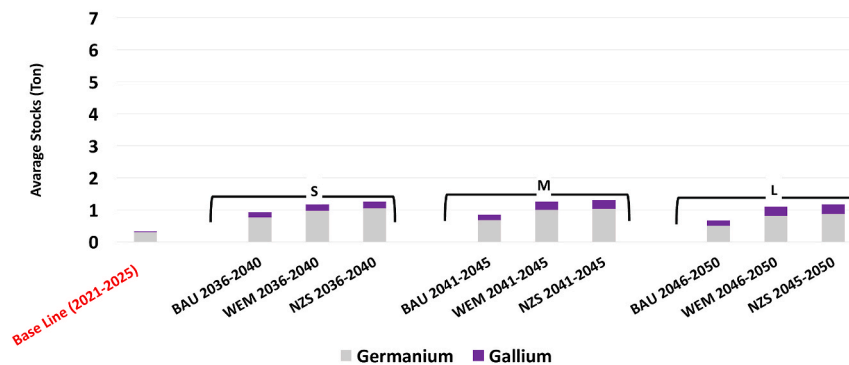


Fig. 5. PV System Material Stocks: Stocks over time in the BAU, WEM, and NZS scenarios for: a) All materials for the period of 2013–2050; b) All materials: Baseline vs. short (S), medium (M), and long (L) terms; c) PV Critical Materials: Baseline vs. for S, M, and L terms; d) germanium and gallium: Baseline vs. S, M, and L terms. Note: All data from the MFA.

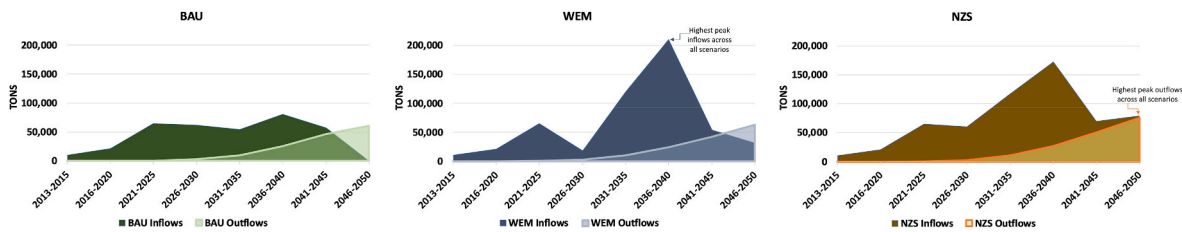


Fig. 6. Total Inflows and Outflows of all materials for the PV systems in the three scenarios for the period of 2013–2050, as obtained from the MFA analysis in this work. The peak inflows (WEM) and peak outflows (NZS) are highlighted.

replaced post-2030 in all the scenarios. The red lines in Fig. 8 indicate the increasing levels of total outflows. Without examining the contribution of each individual material to the total outflow, we can observe that in all the scenarios the total outflows almost match the inflows required for expansion and replacement.

5.3. Material supply potential

Focusing on the potential supply of materials from decommissioned PV systems under NZS, Fig. 9 shows the outflows of PV materials within the system's temporal boundary (2013–2050) and after year 2050. As the NZS has the most-ambitious targets regarding PV deployment, we choose to focus on this scenario to examine the upper limits of the circularity potential. To assess the MSP of PV deployments in the period of 2013–2050, Fig. 9 considers exclusively PV systems installed within this timeframe, excluding any further investments made beyond year 2050. The values at the left-hand side of the figure indicate the outflows within the system boundary. In other words, the amount of each material that will be ready to be recycled from the decommissioned PV systems before year 2050. The values on the right-hand side of the figure show the amount of each material that will be ready for recycling after year 2050.

Up to year 2050, approximately 600,000 tonnes of materials (93,000 tonnes being PV critical materials) are entering the system (i.e., inflows). The MSP is very limited within the temporal scope, as in total around 168,000 tonnes of material are leaving the system before year 2050. However, after year 2050, the data show that the potential for supplying materials is almost doubled. As mentioned previously, most of the PV systems will not reach their end-of-life within the defined temporal boundary. In essence, this signifies that the PVs that remain in use within the system are projected to have an MSP after year 2050. Table 3 shows the shares of the MSP for each material during and beyond the temporal scope.

The MSP up to year 2050 is limited to an average of 31 % of the materials entering the system up to year 2050. The remaining 69 % of the inflows are estimated to become available for secondary use beyond year 2050. Reflecting their extensive uses in PV system infrastructures, concrete exhibits the largest outflow, followed by steel, aluminium, and copper (see Fig. 9). Silicon, although used extensively in PV system infrastructure, exhibits relatively lower outflows due to the increasing MIRPs assumed for the cSi and aSi technologies. This also explains the slightly larger share of silicon (35 %) that becomes available within the temporal scope, as compared with the shares of concrete, steel, aluminium and copper. This is because technologies with lower MIRPs that have been deployed historically (2013–2025) are more likely to be decommissioned within the period studied, while those with higher MIRPs are estimated to be decommissioned beyond year 2050. Similarly, as we assumed a 90 % increase (comparison of MIRPs in years 2013 and 2050) in the MIRP for silver used in the c-Si technology, more than half of the material becomes available during the period up to year 2050. Other materials, such as cadmium, tellurium, germanium, indium, gallium, and selenium, display smaller outflows in tonnes, indicating their specialized roles in PV systems. However, germanium, which is one of the key minerals used in the a-Si technology, exhibits high shares (44

%) of the total inflows that become available up to year 2050. This is due to several reasons. First, in similarity to silver, we assume an increasing MIRP for germanium, while those PV systems with lower MIRPs (and therefore, higher material content) are likely to be decommissioned in the period up to year 2050. Although the market share for the a-Si technology is increasing over time, results for MSP until 2050, only accounts the fraction of this increase due to the long lifespans of the PV systems and this explains the moderately lower potential compared to silver.

5.4. Circularity potential

Table 4 shows the percentage requirement for PV critical materials that could be met through the MSP from the decommissioned PV systems within the temporal boundary.

We see a positive trajectory for the circularity potentials of all PV critical materials. This is in line with the self-sufficiency indicated by the results (comparison of the inflows and outflows of each material) shown in Fig. 7. The increase in circularity potentials over the years is due to the increasing volumes of outflows as well as increasing EoL-RR assumed for this paper over the years. The MFA analysis shows that germanium reaches full circularity potential during the last 10 years of the modelled period (from year 2040 and onwards). This is followed by silicon, which reach full circularity potential during in year 2045. The circularity potentials for aluminium and copper reach almost 80 % by year 2050. The circularity potential for gallium, which is used in the CIGS technology, remains low relative to those of the other four materials (Table 3). Despite the increasing MIRP (60 % increase 2013 and 2050), the increase in the market share of the CIGS technology (from 1 % in year 2013 to 5 % in year 2050), and the resulting rise in requirement for gallium to fulfil the new capacity expansion and/or replacement prevents the material from reaching full circularity potential. However, the circularity potential of gallium, still indicates that the material loop could be potentially half closed by year 2050.

5.5. Sensitivity analysis

5.5.1. Sensitivity to PV lifetime assumption

We assume a 22-year PV lifetime as our base case to reflect a realistic performance expectation for systems deployed in Cyprus (see Section 4.6). To test the sensitivity of the results to this assumption, we also examined two alternative PV lifetime assumptions - 15-year and 30-year cases. The 15-year case (± 5 years) reflects field evidence from harsher climates in the Eastern Mediterranean and Middle East Region, where PVs showed up to 75 % degradation after 13 years [44]. The 30-year case (± 5 years) corresponds to typical assumptions in LCA and MFA literature and represents a well-maintained upper bound. Fig. 10 shows the impact of PV system lifetime assumptions on annual inflows and outflows. Our results confirm that both the magnitude and trajectory of material flows over time are sensitive to lifetime assumptions. Shorter lifetimes lead to earlier and more frequent peaks in both inflows and outflows, while longer lifetimes shift and smooth these trends over time.

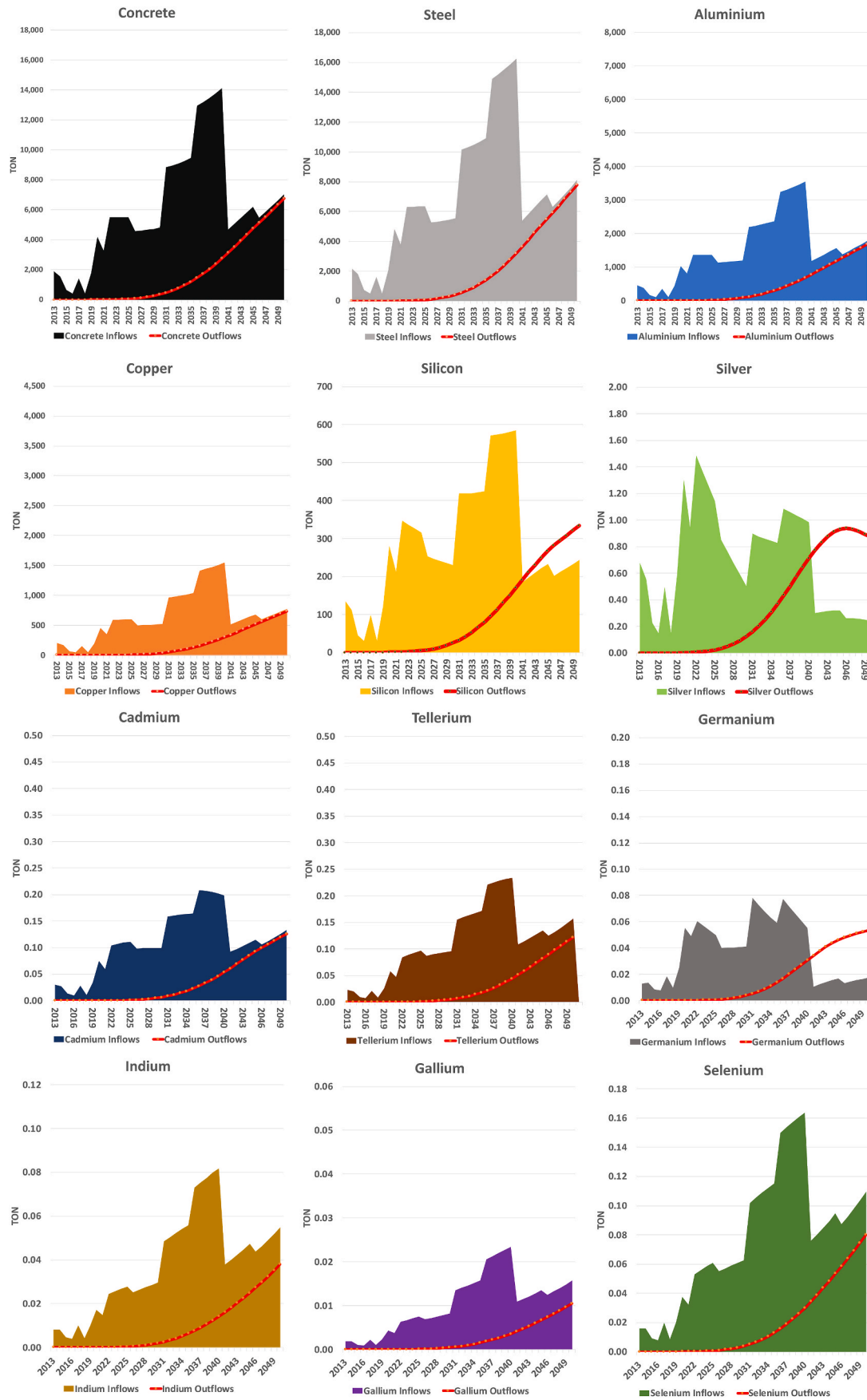


Fig. 7. Inflows and outflows of each material considered essential for PV systems in the period of 2013–2050 under the NZS, as obtained from the MFA analysis.

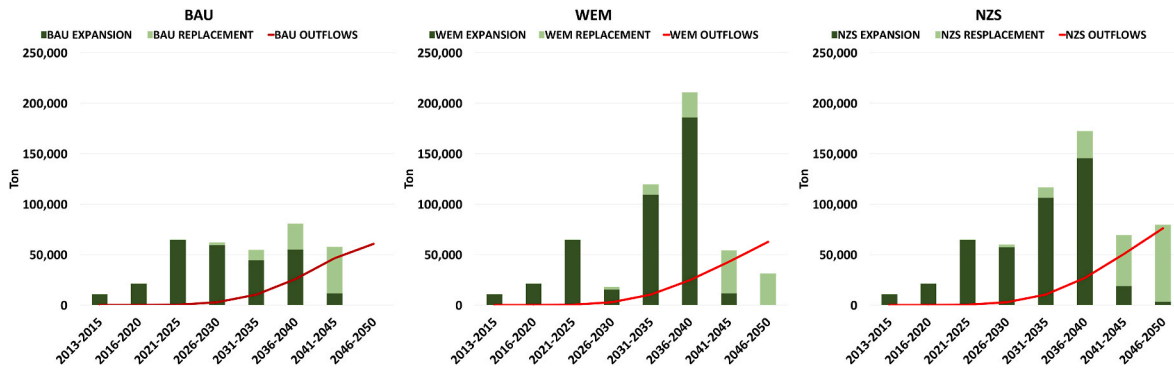


Fig. 8. Periodic flows for expansion and replacement in the period of 2013–2050 for the three scenarios, as obtained from the MFA analysis.

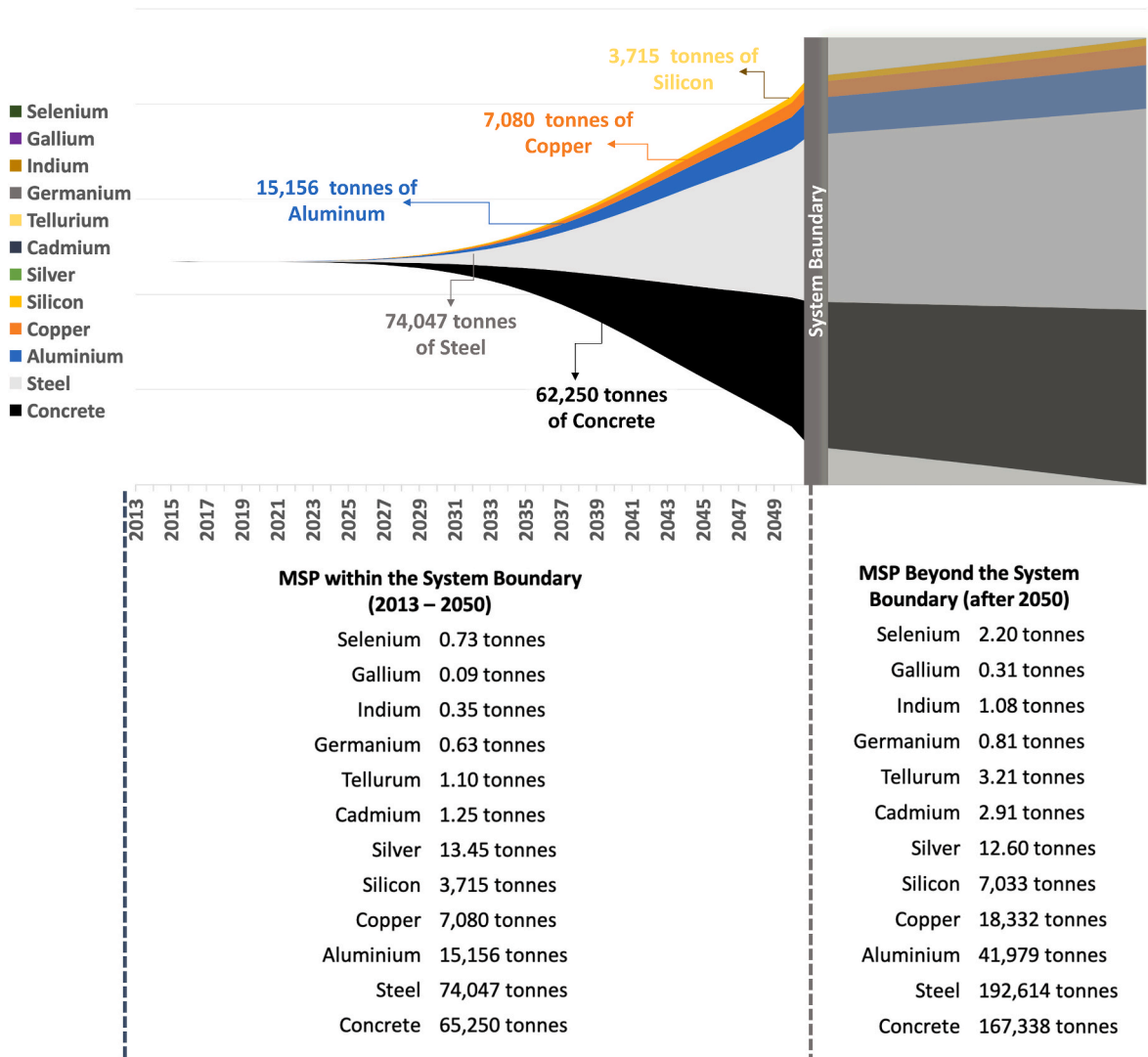


Fig. 9. Material Supply Potential (MSP) for the period of 2013–2050 with an illustrative continuation beyond the system boundary under NZS scenario. MSP beyond 2050 lies outside the defined system boundary and is not included in the model. It is shown solely for visualization purposes to highlight the potential scale of future secondary material availability that is, indeed, beyond the scope of this paper. Results are obtained from the MFA analysis.

5.5.2. Sensitivity to material intensity assumptions

In the main analysis, we employed dynamic material intensities to account for projected reductions in material use driven by technological advancements. Here we test the sensitivity of our results to this assumption and include a fixed material intensity case using constant values over the entire period. This not only reflects the earlier-stage

scenario models such as those of the World Bank (2020) [4] but also allows us to assess how strongly material demand outcomes are influenced by the inclusion or absence of technological improvements on material intensity reduction. We narrowed the focus to the five PV critical materials identified earlier in the study: aluminium, copper, silicon, germanium and gallium. The results of this sensitivity test are

Table 3

Temporal distribution of the MSP from decommissioned PV systems under the NZS.

	% Share of the MSP until year 2050	% Share of the MSP after year 2050
Concrete	28 %	72 %
Steel	28 %	72 %
Aluminium	28 %	72 %
Copper	28 %	72 %
Silicon	35 %	65 %
Silver	52 %	48 %
Cadmium	30 %	70 %
Tellurium	26 %	74 %
Germanium	44 %	56 %
Indium	24 %	76 %
Gallium	23 %	77 %
Selenium	25 %	75 %

shown in Fig. 11.

Reflecting the underlying assumptions, the total material inflows are higher under the fixed intensity assumption, with the magnitude of difference depending on the material. As expected, two base materials - aluminium and copper, show minimal change (1.5 % and 1.7 %). This reflects the relatively small material intensity reductions assumed in the main case (around 3 % for aluminium and 4 % for copper between the years 2013 and 2050). However, the remaining critical materials which were assumed to have higher material intensity reduction potential, namely; gallium (60 %), silicon (50 % for cSi; 53 % for aSi) and germanium (50 %) show substantial increases in inflows under the fixed material intensity case.

Table 4

Circularity potentials of critical and/or strategically important materials under the NZS, as obtained from the MFA analysis (shares of potentially recycled outflows to inflows for years 2025, 2030, 2035, 2040, 2045, and 2050, as well as the period of 2024–2050).

Material	2025	2030	2035	2040	2045	2050	2025–2050
Aluminium	1 %	6 %	10 %	15 %	62 %	77 %	26 %
Copper	1 %	4 %	8 %	14 %	54 %	77 %	22 %
Silicon	1 %	7 %	14 %	22 %	89 %	111 %	31 %
Germanium	0 %	3 %	10 %	32 %	179 %	242 %	33 %
Gallium	0 %	1 %	3 %	8 %	32 %	54 %	16 %

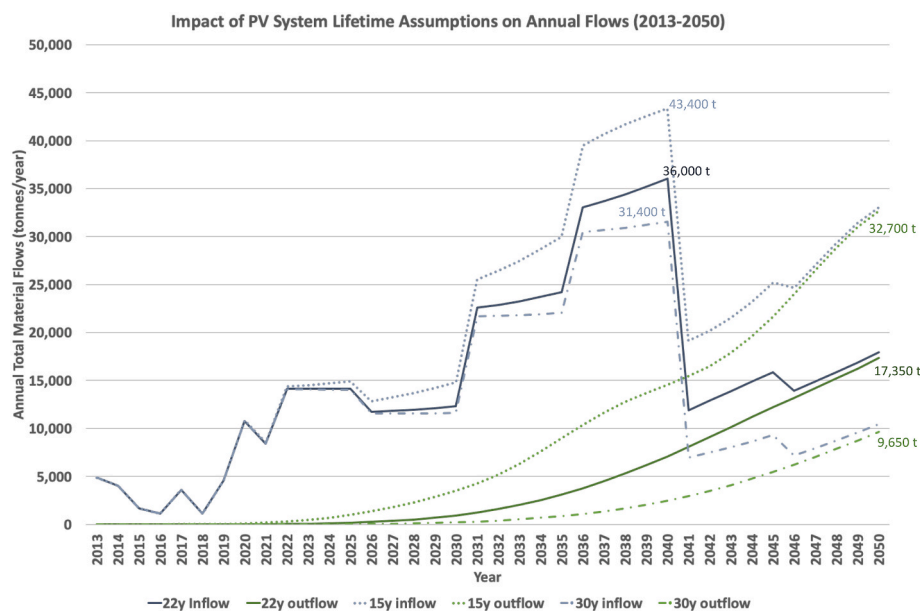


Fig. 10. Total annual inflows and outflows of PV system materials under different PV lifetime assumptions between 2013 and 2050: 22 years lifetime (solid lines), 15 years lifetime (dotted lines) and 30 years lifetime (dash-dotted lines). Values represent combined material flows across all sub-technologies.

5.5.3. Sensitivity to market share assumptions

Each sub-technology analysed in our study relies on different materials and this affects the projected material demand directly. In our main case, historical market shares are based on Elshaki et al. (2013) [37] and Viebahn et al. (2015) [24], for the current trends Fraunhofer Ise (2024) [36] and for the future trends EU Joint Research Center (2020) [19]. However, to test how a shift in technology preferences could change material flows, we developed a sensitivity case with higher uptake of thin-film technologies. We echoed the spirit of Dong et al. (2025) [45], who showed how market share changes can have a significant influence on material flows. We kept the historical and current trends as in the base case, and adjusted the 2050 market shares to assign thin-films a 40 % share (15 % for CdTe, 10 % for a-Si and 15 % for CIGS). All other parameters - including, life time, total installed capacity and material intensities, were kept constant. Sensitivity of our model is tested for the EU listed critical materials. As shown in Table 5, the market share adjustments lead to notable differences in silicon, germanium and gallium. While the inflows of widely used structural materials (i.e. aluminium and copper) remain unchanged, materials specific to thin-film technologies show significant variations. For instance, the inflow of silicon which is predominantly used in cSi and to a lesser extent in aSi technologies declines by approximately one quarter due to reduced cSi uptake. Conversely, gallium inflows more than double and germanium inflows rise more than six-fold given the increased uptake of aSi and CIGS technologies respectively.

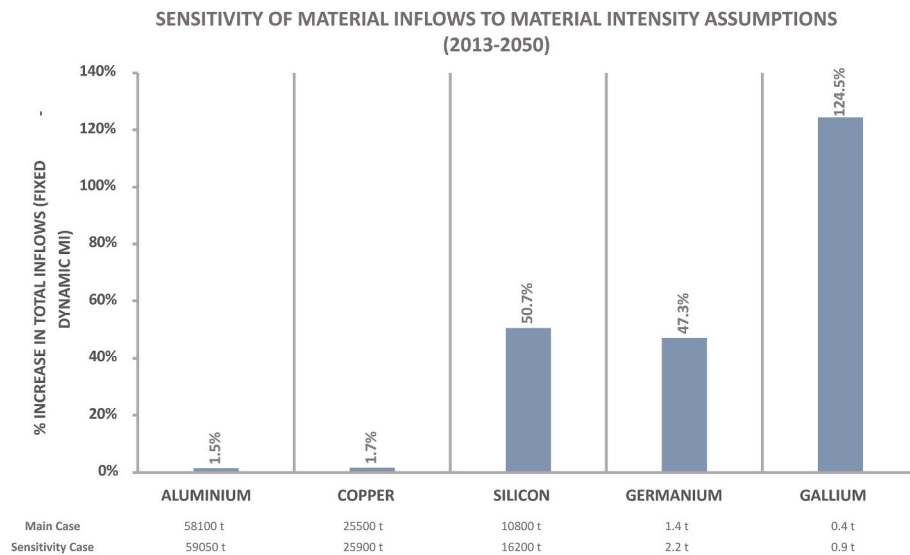


Fig. 11. Percentage increase in cumulative inflows for PV- Critical Materials under fixed versus dynamic material intensity assumptions. The fixed case assumes no reduction in intensity over time, while the dynamic case incorporates material intensity reduction potentials.

Table 5

Sensitivity of material inflows to alternative market share assumptions for PV sub-technologies. The table compares cumulative inflows (2013–2050) and sub-technology contributions for PV-critical materials under the base case and a sensitivity case with increased thin-film uptake.

Material	Case	Total Inflows (tonnes)	cSi Share (%)	CdTe Share (%)	aSi Share (%)	CIGS Share (%)
Aluminium	Base Case	58100	91	4	1	4
	Sensitivity Case	58100	64	14	9	14
Copper	Base Case	25500	91	4	1	4
	Sensitivity Case	25500	64	14	9	43
Silicon	Base Case	10800	99.95	0	0.05	0
	Sensitivity Case	8200	99.54	0	0.46	0
Gallium	Base Case	0.4	0	0	0	100
	Sensitivity Case	1.3	0	0	0	100
Germanium	Base Case	1.5	0	0	100	0
	Sensitivity Case	9.2	0	0	100	0

6. Discussion

6.1. The scale and urgency of Cyprus' PV-dominated transition

Cyprus has to accelerate its green energy transition, like all EU Member States and other countries around the world that are aiming to reach net-zero emissions by year 2050. However, it is currently the only EU Member State without an electricity connection to other nations. This means that until the Great Sea Interconnector (GSI) is operational in year 2029, the existing infrastructure's ability to facilitate the uptake of increased use of renewables, and thus, the ability to accelerate the energy transition is currently limited. Accordingly, energy transition scenarios in Cyprus suggest a significant increase in the deployment of RES, particularly solar PV systems that dominate the energy mix especially after the implementation of the GIS. This increase must occur at an unprecedented pace of implementation, independent of the scenario, and this is directly reflected in the results. While this is an expected outcome (as it corresponds to the scenario-specific PV capacity expansion), it provides a quantitative picture of the scale and timing of material requirements associated with each scenario. Our MFA results

confirms that material stocks in PV systems are projected to increase by more than six-fold between the baseline (2021–2025) and 2050 under the NZS (Fig. 5). This study provides clear outlook of the timing for material inflow, stocks and outflows. Results can guide both national planning an EU-level coordination.

6.2. Supply chain vulnerabilities and critical material risks

The Cypriot energy system is relatively smaller than those of the other EU countries. Unlike other EU countries that have greater flexibility in their electricity systems, Cyprus, with a strong motivation to achieve the emissions targets set by the European Green Deal, is substantially increasing its uptake of RES (particularly PV), which explains the need for materials (as shown in Fig. 6), all within a limited time-frame (decade following the completion of the GSI). Solar energy is a dominant RES in EU, making up 37 % of the installed renewable capacity, nevertheless, Cyprus' current reliance on this RES is exemplified by PV comprising 78 % of the currently installed renewable capacity (Fig. 1). In all scenarios, but particularly under NZS, PVs continues to dominate the renewable mix by reaching shares between 66 % and 85 % of the renewable capacity by 2050. (Fig. 2). Dependence on a single technology at such levels makes Cyprus particularly vulnerable to global PV supply chain risks. Given the limited options available to Cyprus, these risks cannot easily be mitigated by switching to other RES.

Therefore, "fair share" or resource-based criticality assessments applied in other studies are considered of limited relevance in the Cypriot case [24]. Materials that are essential for PV technologies, such as aluminium, copper, silicon, germanium and gallium, are already categorized as critical materials at the EU level, despite the lower share of solar technology deployment of the region compared to Cyprus. Hence, it is important for the country to acknowledge the potential supply risks and develop strategies to minimize the vulnerabilities associated with its energy transition's heavy reliance on this technology.

6.3. Waste management and circularity potential in Cyprus

Compliance with the WEEE directive should be a top priority for Cyprus. Initial analysis of the WEEE statistics on waste management operations across the EU show that there are significant differences in waste management systems and reporting practices across the Member States. According to the Eurostat WEEE Statistics, the EU already hosts significant numbers of decommissioned PV systems with limited

recycling [18]. Moreover, some Member States have reported either insufficient or no waste data at all (e.g., Cyprus) across different categories [18].

In the last decade of NZS, the material outflows of the decommissioned PV systems either closely match or exceed the material inflows needed to meet the demand for expansion, replacement or both (Fig. 8). Thus, in theory, the existing PV stocks bear an important potential to support a circular material cycle within the EU. When circularity potential is calculated with dynamic EoL-RR (current EoL-RR linearly interpolated to potential EoL-RR) and fix collection rate (85 %), we see a positive trajectory across all critical materials. Germanium reaches full circularity potential 2040 onwards, followed by silicon by 2045. Aluminium and copper approach 80 % by 2050 while gallium, despite rising demand from assumed expansion of CIGS technology, still demonstrates that secondary materials from the decommissioned systems can meet half of the required inflows (Circularity Potential; Table 3).

However, this potential can only be realized if effective collection, recovery and recycling systems are in place. Still, it is important to note that not all outflows will be recoverable. Losses occur throughout the waste management chains (from collection and dismantling to material separation and remanufacturing). Hence, the availability of secondary materials will depend on the effectiveness of these practices adopted within these chains that often requires investment in technology and innovation. Accordingly, cost competitiveness of secondary materials compared to the primary ones may influence their uptake. While the full quantification of these factors falls outside of the scope of this paper, the results, nonetheless, show a promising opportunity. A previous regional-level study focusing on the EU has indicated that in more than the half of the Member States, including Cyprus, individual recycling plants up to year 2050 will not be economically viable [46]. At the moment, Cyprus does not have a dedicated end-of-life treatment facility for PV systems. Decommissioned modules are typically handled under broader WEEE categories as, there are no active PV-specific recycling operations in the island. Cyprus still lacks a clear national roadmap or any investment plans to build dedicated recycling infrastructure. However, regardless of whether Cyprus can achieve sufficient economies of scale for the recycling of PV systems-related materials at the national level, effective policy interventions are needed to initiate waste management activities. This could include cooperation with PV recycling initiatives and/or PV manufacturers across and outside the EU, to ensure the availability of materials from the decommissioned PV systems, such that materials with potential for secondary use are brought back with added value into the circular economy within the EU.

6.4. Broader circularity considerations beyond PV

Indeed, the true circularity potential of an electricity system is not limited to decommissioned PV systems. A recent study has shown the increasing amounts of metals used in different technologies, as well as in transmission and distribution grids [26]. Although the scope of our paper is limited to PV systems, it is important to acknowledge that a comprehensive assessment would provide a more holistic understanding of the circularity potential of the island's electricity system. Energy transition scenarios for Cyprus forecast the shares of other renewables (onshore and offshore wind, Li-ion batteries, concentrated solar power, pump hydro etc.) as being in the range of 20 %–30 % towards year 2050 (Fig. 2). Some of these technologies (Wind, CSP and Battery Storage) share key materials with PV systems such as aluminium and copper and these interactions may influence overall material availability. Moreover, technologies such as battery storage and wind turbines introduce additional demand for entirely different critical materials – such as lithium, cobalt and nickel for batteries, and rare earth elements like neodymium, dysprosium and praseodymium used in permanent magnets for wind turbine generators. In addition, non-renewable power plants also contain considerable amounts of materials (steel, copper, and

aluminium), which, once demolished, could enter to circular use for PV systems. Accordingly, further investigations into this matter could include other renewable technologies, electrical vehicles, secondary material supply potential of decommissioned non-renewable technologies, as well as the material requirements of the transmission and distribution grids of the island (particularly for materials like copper, aluminium and steel), in order to investigate the true circularity potential in a holistic manner.

6.5. Cyprus between EU and EMME contexts

When contextualising our findings within a broader framework, Cyprus is positioned at the intersection of two distinct yet related dynamics. On one hand, as an EU Member State, the island is subject to ambitious targets and regulatory obligations that shapes the policy landscape both for green energy transition and circular economy implementation. On the other hand, though, Cyprus shares key structural and climatic characteristics with countries in the Eastern Mediterranean and Middle East (EMME) region. A recent scenario-based assessment for the EMME region conducted by Taliotis et al. (2023) [30] reflects these similarities that include high solar potential and growing PV deployment. Moreover, recent regional analysis shows that most EMME countries remain at early stages of end-of-life PV management. Recent assessments confirm that, apart from Greece where a licenced PV recycling scheme became operational in 2025, no other EMME country currently operates a dedicated PV module recycling line and existing facilities (e.g. United Arab Emirates, Jordan, Egypt) are limited to general e-waste management [47]. Additionally, it seems that no country in the region (except Cyprus and Greece as they are EU member states) has introduced a dedicated regulatory framework comparable to the EU's WEEE Directive. Yet, many of the countries in the region are currently investing in domestic PV manufacturing. This dual positioning of the country offers both challenges at the EU-level and opportunities at the regional level (EMME). Cyprus must align with EU-level circularity obligations at the national level while also recognizing its potential role in utilizing regional cooperation and contributing to secondary material supply chains across the EMME region. However, such regional cooperation may be constrained by the EU's evolving Circular Economy Action Plan (CEAP) [48], as well as the revised Waste Shipment Regulation [49] as the current push from the EU is to retain secondary raw materials within the Union. Hence, assessing the feasibility of intra-EU PV waste treatment routes versus regional cooperation outside the EU necessitates further study.

6.6. Uncertainties and limitations

Overall, our findings suggest that material stocks for Cyprus increase substantially in all scenarios as a result of the unprecedented scale of future PV deployments. Differences in the accumulation patterns as well as in the material flow trends in each scenario indicate that the results capture the impacts of different policy choices and investment strategies. Moreover, the results show sensitivity not only to lifespan assumptions (Section 5.5.1), but also to the assumptions related to the dynamic inputs, such as the market shares and material intensity reduction potentials (Sections 5.5.2 and 5.5.3). However, it is important to acknowledge certain methodological limitations, as well as some broader uncertainties. Key assumptions related to PV lifespan, material intensities and market shares may differ from the real world, especially as regards their evolution in the longer term. Moreover, the financial investments required for the transitions envisioned by the scenarios are susceptible to challenges from competing priorities and budgetary constraints. Finally, the EoL-RR used to calculate the circularity potential may change over time and in some cases recovery rates are likely to be lower than the technical potentials assumed.

7. Conclusions

We conducted a dynamic, retrospective and prospective MFA of PV systems to quantify the material implications of three distinct energy transition scenarios for the island of Cyprus. The focus is on the materials that are essential for PV systems (concrete, steel, silver, cadmium, tellurium, indium, selenium, aluminium, copper, silicon, gallium, and germanium), with particular emphasis placed on PV critical materials (aluminium, copper, silicon, gallium, and germanium).

Our analysis provides estimates of the quantities of materials for stocks, inflows (demand for capacity expansion and replacement), and outflows (Material Supply Potential), as well as the circularity potential of the PV systems. The results show that Cyprus will have a greater reliance on solar PV energy by year 2050, entailing substantial increases in the demands for materials required for the penetration of this technology.

The findings highlight the period of 2030–2040, in which all three scenarios show a strong increase in PV deployment. Accordingly, the MFA results indicate high material demands for the same period with increased capacity inflows – which raises concerns in relation to potential vulnerabilities in the PV supply chain. However, the NZS stands out by having a relatively more spread-out and balanced approach to PV system investment, and thereby, a greater ability to tackle the demands for raw materials and mitigate the supply risks. Our findings also suggest that under the NZS, silicon and germanium are showing full circularity potential. Moreover, four out of five PV critical materials (silicon, germanium, aluminium, and copper) show signs of self-sufficiency, especially during the 2045–2050 period, assuming that circular practices are in place. Yet, the calculated Material Supply Potentials until year 2050 only accounts for an average of 31 % of the total potential created but not realized due to the long lifespans of the PV systems.

Cyprus will need to move beyond general policy commitments in order to address the circular economy challenges associated with its PV-dominant energy transition. Specific actions, in line with the recommendations from the European Commission's Joint Research Centre [50], could be the integration of PV-specific obligations within its WEEE legislation such as establishing a dedicated PV category for collection and reporting and mandating PV producers (importer or distributor in the case of Cyprus) with clear responsibilities in financing the take-back schemes through extended producer responsibility. Additionally, given Cyprus' limited market size and lack of domestic PV recycling facilities, a short to medium term strategy for partial dismantling and safe pre-treatment on the island could be a viable option before shipment to specialized facilities for advanced recycling (either EU-based or within the Eastern Mediterranean and Middle East region).

Our results provide clear outlook of the timing for material outflows. Recognizing this in advance gives Cyprus an opportunity to develop targeted collection and recovery systems before volumes peak. As a result, the country can position itself as a strong example of circular readiness in small-scale and solar driven energy transition.

CRediT authorship contribution statement

Ulku Tasseven: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Theodoros Zachariadis:** Writing – review & editing, Validation, Supervision. **Filip Johnsson:** Writing – review & editing, Validation, Supervision. **Georgia Savvidou:** Writing – review & editing, Methodology. **Qiyu Liu:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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