The sociometabolic transition of a small Greek island
Assessing stock dynamics, resource flows, and material circularity from 1929 to 2019

Dominik Noll1 | Christian Lauk1 | Willi Haas1 | Simron Jit Singh2 | Panos Petridis1 | Dominik Wiedenhofer1

1 Institute of Social Ecology (SEC), University of Natural Resources and Life Sciences (BOKU), Vienna, Austria
2 School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, Canada

Correspondence
Dominik Noll, Institute of Social Ecology (SEC), University of Natural Resources and Life Sciences (BOKU), Schottenfeldgasse 29, 1070 Vienna, Austria.
Email: dominik.noll@boku.ac.at

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Abstract
Their geomorphological characteristics make island systems special focal points for sustainability challenges. The Circular Economy (CE) Action Plan of the European Union foresees tailored solution sets for Europe’s outermost regions and islands to tackle region-specific sustainability challenges. We address the question of how islands can achieve more sustainable resource use by utilizing the socioeconomic metabolism (SEM) framework to assess and explore CE strategies for the Greek island of Samothraki. For this purpose, we apply material and energy flow analysis on a regional level and derive, as one of the first studies, a complete time series from 1929 to 2019 for socioeconomic biophysical stocks and flows according to mass-balance principles for an island economy. Results show that in the past 90 years Samothraki’s material stocks grew fivefold, domestic material consumption threefold, and solid waste generation fivefold. Samothraki transitioned from an almost entirely circular biophysical economy toward one in which 40% of input materials and 30% of output materials are estimated as non-circular. This transition resulted in an accumulated solid waste stock on the island almost half the size of current material stocks in use. With this study we aim at providing ideas and opportunities for achieving more sustainable and circular material use on small islands. The published SEM database aims at supporting the public and the private sector and the island community at large with information key to establishing more sustainable material and energy use patterns on Samothraki. This article met the requirements for a Gold–Gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS
circular economy, industrial ecology, islands, material flow analysis (MFA), social metabolism, urban metabolism
Their geomorphological characteristics make island systems special cases for sustainability challenges (Deschenes and Chertow, 2004). The transformation of many island economies during global industrialization has led to increasing dependence on imports and, in many cases, excessive depletion of local key resources (e.g., Bahers et al., 2020; Gowdy and McDaniel, 1999; Krausmann et al., 2014). While the inclusion of islands into the global economy has enabled higher standards of living for these communities, it has also resulted in increased ecological burdens on island ecosystems and beyond. Physical barriers of islands constrain flows of imported materials, while waste management options are often limited. This leads to accumulation of waste in the domestic environment and marine pollution (Camilleri-Fenech et al., 2017; Eckelman and Chertow, 2009; Eckelman et al., 2014; Meylan et al., 2018). Small islands with limited and undiversified economies are also vulnerable to shocks, whether socioeconomic or environmentally induced (Bradhaw et al., 2020; Merschroth et al., 2020; Popescu et al., 2020; Symmes et al., 2019). The highly contested question of how islands can be sustainable regarding their bounded and isolated characteristics makes them great focal points for industrial ecology research (Chertow et al., 2013; Singh et al., 2020). Addressing sustainability challenges on small islands require systemic approaches, focusing on multiple aspects of their socioecological systems, to assist local policy makers in developing long-term strategies for sustainable development. Studies systematically investigating the interlinkages between environmental pressures, socioeconomic drivers, and long-term material use patterns of an entire island economy have, according to our knowledge, so far not been developed.

Circular economy (CE) has become more relevant in recent years as a diverse research field and policy agenda that could comprise useful strategies for overcoming sustainability challenges on small islands. CE is supposed to provide an alternative to the largely linear model that currently shapes our global biophysical economy (Schöggel et al., 2020). As a systemic sustainability approach, CE encompasses identifying potentials for slower, narrower, and more circular material use patterns, effectively reducing the scale of resource use, waste, and emissions (Haas et al., 2020; Korhonen et al., 2018; Wiedenhofer et al., 2020). CE is also part of a concerted strategy within the Green Deal of the European Union (EU), which strives for a climate neutral, resource efficient, and competitive economy (European Commission, 2020). The policy framework also acknowledges the significance of cities and regions and promises tailored solution sets for EU’s outermost regions and islands.

Research on CE in the island context has recently gained momentum, for example, by assessing potentials for enhanced secondary resource use (Elgie et al., 2021; Millette et al., 2019; Mohammadi et al., 2021). As inhabited islands increasingly rely on imported goods, exploring economic opportunities for domestic recycling is of high relevance. However, recycling can only be one part of the solution as it does not necessarily reduce virgin material demand and is not applicable to all islands to the same extent. Further, too broad definitions and applications of the CE concept increase the risk of undermining initially good intentions and often fail to establish empirical links between CE and sustainable development (Kirchherr et al., 2017). There is also growing acknowledgement of the lack of systemic assessments of CE, as most studies focus only on specific materials, substances, or products, each with its own relative indicator or rate (Pauliuk, 2018). Only few studies assess CE on a more systemic level (e.g., Haas et al., 2020; Haupt et al., 2017; Mayer et al., 2019; Nuss et al., 2017; Wiedenhofer et al., 2020). We are not aware of any study that systematically analyzes scale and circularity of a complete island economy.

The present study is guided by the following research questions: (1) What historical developments led to the current SEM of Samothraki? (2) What scale and composition of the domestic SEM would support high well-being of the population and their socioeconomic developments while at the same time make the island resilient and respecting local and global environmental boundaries? (3) What potential does CE hold in helping Samothraki as well as small islands in general to achieve sustainability and resource security?

We approach the question of island sustainability by applying the conceptual framework of sociometabolic research (SMR) to explore circular economy (CE) strategies for the Greek island of Samothraki. We provide estimations of material and energy use, the accumulation of material stocks, and all subsequent outputs of waste and emissions for the island from 1929 to 2019, by following standardized sociometabolic system boundaries. Section 2 introduces the island of Samothraki. Section 3 explains the conceptual background, data sources, and modeling approaches. Section 4 presents the transformation of the domestic biophysical economy by depicting dynamics of biophysical stocks, scale indicators for material and energy use, as well as waste and emissions, and circularity rates. In Section 5 we reflect on limitations and opportunities for more sustainable and circular material use. Conclusions are provided in Section 6.

2 | THE ISLAND OF SAMOTHRAKI AS STUDY SITE

With an area of 178 km² and a population of 2880, Σαμοθράκη is a relatively small island located in the north-eastern Aegean Sea. The island’s outstanding ecological features are shaped by the 1611m mountain range Saos (Supporting Information S1: Fig. 3–4). The high altitude and steep slopes are responsible for a distinct microclimate with lush vegetation on the northern side and rocky plateaus on the southern side. The fertile grounds of the western lower plains enable a rich agricultural diversity (Supporting Information S1: Fig. 5–6). The island has a significant cultural ancient history, reflected in the island’s main archeological site The Sanctuary of the Great Gods (Supporting Information S1: Fig. 7).

Until 1970, the local economy was shaped by livestock herding and some other agricultural production exclusively for the domestic market. During the last four decades moderate tourism development and labor migration generated an alternative source of income for the local population.
Supermarkets and other businesses in the service sector opened, and a regular ferry connection enabled a more frequent exchange with the mainland. Yet, the higher living standards did not come without cost. A gradual shift to an import-based economy, with no possibilities for local waste treatment, significantly increased pressures on local ecosystems. The reduction of the agricultural system to almost exclusively small ruminant production caused substantial degradation of the island’s vegetation, while overfishing through large trawlers left coastal waters empty and small-scale fishermen desperate (Supporting Information S1: Fig. 8-10). Traditional systems of water distribution were abandoned, and some parts now even face water shortages on a water-rich island. Since 2008, socioecological research aims at facilitating a local sustainability transition (Fischer-Kowalski et al., 2020), by sharing insights and expertise with local stakeholders, with the perspective of transforming the island into a UNESCO Biosphere Reserve in the foreseeable future (Petridis et al., 2017). This study marks an important milestone in this project, as it provides a comprehensive empirical basis for the implementation of regional policies and activities or incentives by local stakeholders.

3 FRAMEWORK OF ANALYSIS, MATERIALS, AND METHODS

In this study, we present a novel mass-balanced and consistent time series of socioeconomic materials and primary energy use, the biophysical stocks of buildings, infrastructure and machinery, and all subsequent outputs of wastes and emissions. For this purpose, we apply a material and energy flow analysis (MEFA) on the regional level (Haberl et al. 2019; Wang et al. 2019) and utilize the circular economy (CE) framework introduced by Haas et al. (2015) and Mayer et al. (2019), to derive CE indicators and input and output circularity rates (Figure 1).

We develop a complete time series for socioeconomic biophysical stocks and flows according to mass-balance principles from 1929 to 2019. Through a mixed methods approach (Johnson et al., 2007; Kelle, 2017) we integrate data from official statistics, local surveys, and previously published stock-flow modeling. MEFA data is aggregated into the four main material groups biomass, fossil energy carriers, metal ores, and non-metallic minerals. Indicators are defined in the caption of Figure 1. The spatial scale of the assessment complies with the geographical borders of the island of Samothraki. All materials entering the island are treated as imports and all materials leaving the island are treated as exports. Section 3.1 covers data sources and modeling approaches by providing information about exogenous variables and survey data (Section 3.1.1), and by describing details of utilized modeling approaches for material input and output flows (Section 3.1.2). For detailed descriptions we refer to respective sections in the Supporting Information files (S1 and S2).
### Table 1: Sources of MEFA data on 1-digit level for domestic extraction (DE), imports, exports, and domestic processed output (DPO)

| Indicator                      | 1-digit MFA | 1929–1970 | 1971–1992 | 1993–2019 |
|-------------------------------|-------------|-----------|-----------|-----------|
| **Domestic extraction**       |             |           |           |           |
| Non-metallic minerals         | Stock-driven model for buildings and infrastructure (Noll et al., 2019) | No domestic extraction of non-metallic minerals |
| Metal ores                    | No domestic extraction of metal ores |
| Fossil fuels                  | No domestic extraction of fossil fuels |
| Biomass                       | Small ruminant endosomatic metabolism model (Noll et al., 2020) | Derived from calculations of domestic heating demand of houses (Supporting Information S1: 1.3.4) |
|                              | Statistical area data (ELSTAT) in combination with yield data (FAO) | Statistical production data (ELSTAT) |
| **Imports**                   |             |           |           |           |
| Non-metallic minerals         | Stock-driven model for buildings and infrastructure (Noll et al., 2019) | Derived from domestic processed output—waste (Supporting Information S1: 1.3.1) |
| Metal ores                    | Stock-driven model for buildings and infrastructure (Noll et al., 2019) | Derived from domestic processed output—waste (Supporting Information S1: 1.3.1) |
| Fossil fuels                  | No imports of fossil fuels | Stock-driven model for buildings and infrastructure (Noll et al., 2019) | Derived from waste flows and from per capita trend of national demand of energy carriers (Supporting Information S1: 1.3.1; 1.3.4) |
| Biomass                       | No imports of biomass | Stock-driven model for buildings and infrastructure (Noll et al., 2019) | Small ruminant endosomatic metabolism model (Noll et al., 2020) |
|                              | Derived from waste flows and from per capita trend of national demand of energy carriers (Supporting Information S1: 1.3.1; 1.3.4) | Endosomatic metabolism model for food/feed demand of humans and livestock (Supporting Information S1: 1.3.3; 1.4) | |
|                              | Statistical area data (ELSTAT) in combination with yield data (FAO) | Statistical production data (ELSTAT) |
| **Exports**                   |             |           |           |           |
| Non-metallic minerals         | No exports of non-metallic minerals | Statistical data on waste exports (2013–2019) |
| Metal ores                    | No exports of metal ores | Statistical data on waste exports (2013–2019) |
| Fossil fuels                  | No exports of fossil fuels | Derived from usage of lubricants for engines (Supporting Information S1: 1.3.4) |
|                              | No exports of municipal solid waste | Statistical data on waste exports (2013–2019) |
| Biomass                       | No exports of biomass | Extrapolation of statistical export factors in relation to production | Statistical data on exports of agricultural products (ELSTAT) |
| **Domestic processed output** | Emissions to air | Tier 1 IPCC emission factors for fossil fuel and biomass combustion (Supporting Information S1: 1.4) | |
| Waste disposal                | Extrapolation of per capita waste generation data in combination with waste composition data for years 1929–2012 and statistical data of waste exports for years 2013–2019 (Supporting Information S1: 1.3.1) | |
| Dissipative use of products   | Endosomatic metabolism model for food/feed demand of humans and livestock (Supporting Information S1: 1.3.3; 1.4) | Calculation of composting process for biomass waste |
| Dissipative losses            | Calculation of biomass combustion residues |
|                              | No usage of lubricants | Derived from usage of lubricants for engines (Supporting Information S1: 1.3.4) |

Periods 1929–1970, 1971–1992, and 1993–2019 were chosen according to different data sources and calculation/extrapolation methods. Further details of calculation/extrapolation methods are described in Section 3.1.2.

### 3.1 Primary data and modeling of stocks and flows utilized

Data was collected from a variety of sources and estimation procedures. Table 1 provides information on the sources of MEFA data in the four material categories on digit 1 level for imports, domestic extraction (DE), exports, and domestic processed output (DPO). Mass balancing was achieved by calculating input and output balancing items (Supporting Information S1: section 2). We build on two previously published studies applying a
dynamic stock-driven "bottom-up" MEFA approach to derive information on non-metallic minerals and biomass stocks and flows. In the first study we assessed buildings and infrastructure dynamics, associated material demands, as well as construction and demolition waste (CDW) generation from 1971 to 2016 (Noll et al., 2019). In the second we focused on biomass flows associated with the small ruminant population on the island for the years 1971 to 2016 (Noll et al., 2020). Both previous modelings were updated to cover the entire period of 1929–2019. For reconstructing material stocks, livestock, and the human population we used official statistical census data (for details see Supporting Information S1: Table 1). To estimate remaining material input and output data we applied various data estimation and extrapolation approaches.

3.1.1 Qualitative expert interviews and other survey data

To evaluate the feasibility of proposed measures and enable a more accurate evaluation of local conditions, we took direct measurements and used data from 14 semi-structured expert interviews. We used direct measurements on the island for the estimation of waste composition, material intensities for buildings and infrastructure, and heating demand for local households (for more information on these methods see Fischer-Kowalski & Petridis, 2019; Petridis & Fischer-Kowalski, 2020). We refer frequently to expert interviews conducted on various occasions between 2013 and 2018, including two tavern owners (Experts 1 and 3), the owner of the local dairy (Expert 2), the owner of a trading business (Expert 4), a local agricultural consultant (Expert 5), the president of an olive oil association (Expert 6), an employee of the technical department of the municipality (Expert 7), two owners of construction businesses (Expert 8 and 10), a local carpenter (Expert 9), the owner of two fish trawlers (Expert 11), a local electrical engineer (Expert 12), the owner of the sole gas station (Expert 13), and a member of the association Sustainable Samothraki (Expert 14).

3.1.2 Details of data estimation and extrapolation methods

In this section we provide further explanations for the data sources shown in Table 1, including details about estimation and extrapolation methods that were utilized to compile the sociometabolic long-term database for the island. We describe in this section methodological specifications for the estimation of agricultural production, material use, energy use, trade, and DPO waste and emissions. We provide further methodological details in the respective sections of the supporting information, to which we refer at the end of each paragraph.

Agricultural primary and livestock production was covered by official statistical data for the years 1993–2016. For the reconstruction of primary agricultural production for the years 1929–1992 and 2017–2019, we used official data for cultivated area, applied average crop yields for Greece and calculated crop residues, based on standard harvest indices (IPCC, 2019). Samothraki-specific data for fisheries in the years 1964–1992 and 2014–2019 were derived from region-specific fisheries data and human endosomatic energy requirements (Supporting Information S1: section 1.3.2; Supporting Information S2: Table 2).

Material use (mUse) was derived from gross addition to stocks (GAS) and use of packaging materials. Estimates for GAS are based on the extended model described in Noll et al. (2019), except for agricultural machinery, household appliances, and durables. Material use for purchase of agricultural machinery is based on statistical data and respective material intensities. Material use for the consumption of household appliances and durables was estimated based on municipal waste generation data. Expert interviews helped to assess origins of resources (Expert Interview 5; 7–10; 13). Household consumption of packaging materials was reconstructed based on municipal waste generation data (Supporting Information S1: sections 1.2 and 1.3.1).

Energy use (eUse) was derived through the application of an endosomatic metabolism model for livestock and humans and several calculation and extrapolation methods for technical energy consumption. Feed and food consumption are based on the endosomatic requirements for humans and livestock. Data on daily food intake and origin of consumed food was derived from Petridis and Huber (2017). Diets prior to 1971 are based on the typical traditional Mediterranean diet described in Nestle (1995). Diets between 1929 and 1970 were adjusted in regard to the availability of local food resources, while the overproduction was used as input data for bacterial metabolism in composting. Livestock feed demand is based on the extended model described by Noll et al. (2020) and feed intake values from Krausmann and colleagues (2018). Feed rations for all livestock species are based on FAO data (FAO, 2018) and adapted to the local availability of animal feed, while the rest of the demand from ruminants is covered by grazing (grazing gap) (Supporting Information S1: section 1.3.3; Supporting Information S2: Table 5). Technical energy consumption on Samothraki is based on biomass and oil for domestic heating and fossil fuels for electricity production from 1971 to 2000, marine and terrestrial transport and domestic cooking from 1971 to 2019. For the annual consumption of fossil fuels, we used survey data for the years 1990, 1995, 2005, and 2015 (Expert Interview 13). Numbers before 1990 and after 2015 were reconstructed by applying per capita fossil fuel consumption trends for Greece based on official statistical data. Calculations for diesel consumption for local electricity production are based on technical data for the used diesel generators and the electricity consumption of the island. Cooking gas consumption is based on per capita values for Greek households from 1994 to 2019 (Supporting Information S1: section 1.3.4; Supporting Information S2: Table 6).

Trade reportedly has commenced in the beginning of the 1970s, therefore we set most starting points for imports and exports to 1971 (Expert Interview 5). Export data was available for 1993–2013 for animal products. The average export rate relative to meat production for the years 1993
to 2013 was applied to meat production for the years 1971 to 1992. Export factors for all other agricultural products and fish are based on survey data (Expert Interview 2; 4; 5; 6; 11). For details refer to Supporting Information S1: section 1.4.

DPO of waste and emissions are based on the extended bottom-up model described in Noll et al. (2019), extrapolation of official municipal solid waste (MSW) data, an accounting model for the endosomatic metabolism of livestock and humans, and the assessment of composting and combustion processes on the island. For the estimation of MSW generation, we used official waste export data for the years 2013–2019 in combination with waste composition data from surveys. Missing years were reconstructed using official Greek household data and waste composition data. For the complete timeline and before waste exports commenced in 2013, we assumed that 75% of burnable MSW was burned openly while the rest ended up in the local environment. Excrements/manure and emissions from livestock was calculated based on inputs, digestibility and composition of feed, output of livestock products, and basic metabolic principles, using a model describing the endosomatic metabolism of livestock and humans (Krausmann et al., 2018, Gingrich et al., 2021) (Supporting Information S1: section 1.4).

3.2 | Uncertainty and data constraints

Uncertainty of utilized sociometabolic models was assessed in the two precursory studies through sensitivity analyses for stocks and flows associated to infrastructure and buildings and the small ruminant system for the years 1971 to 2016 (for details refer to Noll et al., 2019, 2020). Low data availability, especially for historical accounts, increase potential uncertainty levels of the present study, why we extended the uncertainty evaluation by applying confidence ratings similar to the ones described by Laner et al. (2014) in reference to Graedel et al. (2004). Details of the uncertainty evaluation and other data constraints are provided in Supporting Information S1: section 3.

4 | RESULTS

The present study provides long-term estimates for the dynamics of biophysical stocks (Section 4.1), resource use (Section 4.2), and material output in terms of waste and emissions (Section 4.3) for the island of Samothraki, Greece, from 1929 to 2019. Section 4.4 depicts the whole island economy for the years 1929, 1955, 1975, 1992, 2004, and 2019. Circularity rate indicators are shown in Section 4.5. For complete data sets see the respective figures in Supporting Information S2: Fig. 2–6.

4.1 | Dynamics of material stocks, livestock, and the human population

Material stocks (MS) diversified and increased from 186 kt—consisting almost exclusively of traditional stone buildings—in 1929 to 992 kt of stone and brick/concrete buildings, sewage systems in two settlements, some agricultural machinery, a paved road network, and two ports in 2019 (Figure 2a). MS per capita rates increased from 48 t/cap in 1929 to 351 t/cap in 2004, declining again to 327 in 2019 (Figure 2b).

Livestock units (LSU) increased from 2204 LSU in 1929, consisting of large grazing animals, and a small number of pigs, poultry, sheep, and goats, to 7854 LSU in 2002 (Figure 2c). Rates stabilized since 2008 at levels around 5100 LSU. The human population increased from 3190 people in 1929 to 4258 in 1951. After a period, in which numbers declined to 2593 in 1981, mainly due to labor migration, population numbers stabilized and since then fluctuate between 3100 and 2700. As the latest census was in 2011, we do not know the exact population as for today. Tourism commenced in the early 1970s, as did the construction of secondary homes. If total number of annual visitor days and people who leave the island for the winter are considered, Samothraki currently has an average population of about 3500 people.

4.2 | Material and energy use

Domestic material consumption (DMC) increased threefold from 17.5 kt/yr in 1929 to 49.2 kt/yr in 2019 (Figure 3a). The outliers of a DMC of 118 kt/yr in 1970 and 223 kt/yr in 1990 are caused by the construction and extension of port structures. Road constructions also required large amounts of non-metallic minerals in 1964, 1966, 1983, 1984, and 1996. DMC per capita values increased from 4.5 t/cap/yr in 1929 to 23.4 t/cap/yr in 2004, declining to 16.5 t/cap/yr today (Figure 3b). Port construction and extension events led to 38.3 t/cap/yr in 1970 and 76.8 t/cap/yr in 1990. For better comprehensibility of data, we removed these outliers in Figure 3b.

Domestic energy consumption (DEC) is the sum of materials used locally for energy provision (eUse) and electricity imports through a deepsea cable from the mainland since 2001. The energy mix of Greece for the respective years was used to estimate shares of fossil fuels, renewables, and waste incineration. DEC increased from 240 TJ/yr in 1929 to 997 TJ/yr in 2003 and then declined to 730 TJ/yr in 2019 (Figure 3c). In 1929, human food (dark green) represented 7%, livestock feed (light green) 49%, and biomass combustion (green) 44% of total DEC. In
(a) Types of material stocks in use; (b) Material stocks per residential capita; (c) Development of livestock units (LSU) according to species; (d) Human population only residential (black) and including seasonal fluctuations due to visitors and seasonal workers. Data underlying this figure are available in Supporting Information S2.

2019 human food represents 3%, livestock feed 56%, biomass combustion for domestic heating 22%, fossil fuels (orange) 18%, and renewables and waste incineration (blue and purple) 1% of total DEC. DEC per capita increased from 62.1 GJ/cap/yr in 1929 to 188.2 GJ/cap/yr in 2019 (Figure 3d).

4.3 Domestic processed output of waste and emissions

Domestic processed output (DPO) was calculated according to Eurostat categories and is divided into DPO waste and DPO emissions. Figure 4a depicts total DPO waste generation according to the categories (construction and demolition waste (CDW), municipal solid waste (MSW), dissipative use of products (manure, sewage sludge, dead bodies from humans and animals), and dissipative losses (lubricants dissolving into the environment and ashes from combustion processes). DPO waste increased from 4.0 kt/yr in 1929 to 25.8 kt/yr in 2003, declining to 20.1 kt/yr in 2019. The high fluctuations in CDW stem from road construction events that allowed to reuse large fractions of output materials, thus lowering total DPO in respective years. Since 2013, about 1.2 kt/yr of MSW are exported to landfills and recycling facilities on the mainland. Before waste exports we assumed that 75% of burnable materials were combusted, translating into DPO emissions, while 25% ended up in the domestic environment as DPO waste. For more detailed data regarding DPO waste generation of specific categories refer to Supporting Information S2: Table 3.

DPO emissions (Figure 4b) increased from 4.5 kt/yr in 1929 to a maximum of 23.8 kt/yr in 2003, declining to 14.2 kt/yr until 2019. Domestic open combustion of MSW resulted in average emissions of 0.7 kt/yr between 2010 and 2013. Today, technical biomass combustion for heating is responsible for 41%, fossil fuel combustion for 10%, livestock and human respiration and composting for 49% of total emissions.

4.4 The long-term transformation of the biophysical island economy at a glance

The local biophysical economy of Samothraki changed significantly in multiple respects over the past 90 years (Figure 5). Between 1929 and 2019 material stocks (MS) grew fivefold, domestic material input (DMI) threefold, domestic extraction (DE) twofold, and DPO waste fivefold. Imports
increased threefold and exports fivefold between 1975 and 2019. All scale indicators peak between 2000 and 2008, which is mostly caused by the peak of livestock numbers in 2002, the shutdown of the diesel generators in 2000, and the onset of the global financial crisis in 2008. The non-biomass fraction of DPO waste that has always been (mostly illegally) disposed in the domestic environment, increased by 400 kt between 1929 and 2019, indicated by the accumulated solid waste stock on the right bottom side of the Sankey diagrams. Socioeconomic cycling could only be ascertained for road construction activities in which some shares of the output materials are being reused for new roads or
Figure 5 The transformation of the biophysical economy of Samothraki from 1929 to 2019. Selected years are shown in Figure 2 and represent different consumption patterns. Units for all flow data is in kt/yr for material stocks and kt for solid waste stock. Data underlying this figure are available in Supporting Information S2.

Maintenance works. The share of biomass within DE declined from 88% in 1929 to 69% in 1955 before it increased to 100% during the 1990s. The decline of non-metallic minerals in DE in the 1990s is related to an extraction ban that was implemented in 1991. In 1929 imports represented only 1% of DMI, increasing to 35% in 2004 and 27% in 2019.

4.5 How circular is Samothraki’s economy?

Samothraki transitioned from a largely circular biophysical economy, toward one in which circularity rates were reduced to 61% of input materials and 71% of output materials (Figure 6). Current input circularity rates are 77% for biomass, 0% for metals, and 22% for non-metallic minerals. Current output circularity rates are 82% for biomass, 0% for metals, and 33% for non-metallic minerals. Fossil fuels are in general non-circular.

The underlying assumption for non-circular use of biomass is built on the univocal assessment of several studies that livestock grazing currently overuses the vegetation by 50% (Fetzel et al., 2018; Fischer-Kowalski et al., 2020; Noll et al., 2020; Panagopoulos et al., 2019). Further, since the onset of the economic crisis, households increasingly substitute heating oil with (often illegally) extracted wood, which poses another hazard to the
recovery of domestic forests (Figure 3c; Expert Interview 7). Every household is officially allowed to collect 6 tons of firewood per year from private or public forests (Brody et al., 2019). Thus, Samothraki’s 1167 households (census 2011) can legally extract 7 kt/yr of fuel wood, representing 80% of current estimates. Pruning of Samothraki’s olive trees (900 ha) potentially yields 2.5 kt/yr of wood fuel (Spinelli and Picchi, 2010), while 4.5 kt/yr are extracted from other forests. We thus defined 20% of fuel wood extraction as non-circular. Wood ashes are usually discarded in gardens or other natural environment and assumed here as circular. We also assume that fieldstones, used for stone buildings, are circular as they are locally extracted and often used for other purposes after houses disintegrate (not accounted for as socioeconomic cycling in Figure 5). Equations for calculating circularity rates are provided in Supporting Information S1: section 6.

5 DISCUSSION

5.1 Limitations and opportunities for a more sustainable and circular material use

Our data shows that Samothraki experienced a sociometabolic built-up phase starting in the 1950s with two acceleration phases. One after the construction of the main port in 1971 and another one after accession to the EU in 1981. Stock expansion and material consumption levels peaked between 2002 and 2008, before the onset of the Greek debt crisis. Since then, stock expansion came to a halt and material in- and outflows declined and seem to have stabilized at relatively high levels. Maintenance requirements of the increased material stock, feed requirements of the large livestock population but also consumption patterns of the residential and visitor population keep the socioeconomic metabolism (SEM) and therefore environmental pressures at high levels. In the following sections we explore Samothraki’s potentials to increase its circularity rates and reduce its overall sociometabolic scale. We do so by separately assessing limitations and opportunities for biological (Section 5.1.1) and socioeconomic (Section 5.1.2) cycles and by exploring possibilities to reduce the island’s dependence on fossil fuels for primary energy provision (Section 5.1.3).

5.1.1 Biological cycles: Toward more sustainable and circular use of biomass

Biological cycles are distinguished from socioeconomic cycles as they consist mainly of flows of renewable biotic resources, which decompose and re-enter the biosphere after their consumption (Navare et al., 2021). The distinction between circular and non-circular use of biomass is not straightforward. Haas et al. (2020) described the use of biomass as the “blind spot of circular economy” and distinguished between circular and non-circular use of biomass. At the global level, net-zero emissions from land use were discussed as a minimum requirement for a sustainable scale of biomass production. This approach requires an assessment of all carbon emissions from biomass consumption and land use (changes), for which there is not sufficient data for the island of Samothraki. In our case we can refer to the locally assessed overuse to establish a proxy for unsustainable use (Section 4.5).

A more sustainable use of biomass does not only imply a reduction of material input levels but holds numerous potentials, if focusing on synergistic effects between the island’s economic sectors. If wood combustion for domestic heating would be reduced by 20% it still produces 1.2 kt/yr of wood ash which could be used to replace cement, fertilizers, or could be used in road construction (Gaudreault et al., 2020; Oburger et al., 2016). Even if reduced by 50%, Samothraki’s sheep would still produce 75 tons of wool annually, a valuable resource with a broad spectrum of applications, currently not utilized (e.g., as fertilizer pellets in horticulture or as isolation material). If animal numbers are reduced, some share of Samothraki’s 5

![FIGURE 6](image-url) (a) Input cycling and non-circular rates; (b) Output cycling and non-circular rates. Data underlying this figure are available in Supporting Information S2
kt/yr of crop residues fed to livestock could be used for other purposes. Straw- and wood-based building techniques could be a sustainable alternative, even if their implementation would require overcoming initial skepticism of homeowners and the construction industry (Göswein et al., 2020). Currently it does not seem possible to further exploit Samothraki’s forests for construction wood. This would require the establishment of a sustainably managed forest that would probably only enable a moderate income in many decades from now. It could be set up as a long-term project supported through carbon sequestration funds, tree adoption, or crowdfunding and could help to restore Samothraki’s highly eroded areas (Expert Interview 14). Taking all these options into account and assuming a replacement of 1.2 kt of imported non-circular materials such as cement, sand, and isolation materials with domestic renewable resources would reduce non-circular biomass use to 0%, would increase input/output cycling rates, and significantly reduce scale indicators. This could be a starting point to discuss options for improving Samothraki’s socioeconomic cycling rates.

### 5.2 Socioeconomic cycles: Toward more sustainable and circular use of non-metallic minerals, metals, and plastics

Samothraki’s options to further increase its socioeconomic cycling rates locally are limited. Many materials are not available on the island, domestic recycling is often not feasible due to mostly economic reasons and exports of recyclable waste is costly. Since 2013 the municipality tries to establish a waste management system in which recyclable waste is separately collected from mixed waste and both are exported to landfills or recycling facilities on the mainland at high cost (Expert Interview 7). This is an improvement to former practices such as illegal dumping grounds for household appliances and open combustion of municipal solid waste (MSW). However, MSW only represents 12% of total domestic processed output (DPO) non-organic waste and currently there is no management concept for dealing with the rest. Samothraki’s accumulating solid waste stock grew by an estimated 400 kt since 1929 and will, if current practices continue, outweigh domestic material stocks in service between 2070 and 2080 (Figure 5; Supporting Information S1: Fig. 11–14).

Main challenges for the local treatment of construction and demolition waste (CDW) are discussed in Noll et al. (2019). The authors conclude that in order for Samothraki to reach EU recycling targets, local authorities must implement strategies to avoid imports of environmentally problematic materials, impede further expansion of material stocks, increase their service lifetimes, and raise awareness among stakeholders of construction projects for the correct handling of CDW. Use of organic materials in the construction sector as outlined in Section 5.1.1 entails enormous potentials for CDW reduction and climate change mitigation, and their feasibility should be further explored (Churkina et al., 2020; Pittau et al., 2019). Reuse potentials of fieldstones were not explored in the present study but could also provide a domestically abundant renewable resource for construction purposes. Also, the use of plastics for household appliances and as packaging materials is problematic. Samothraki being an island, this is a problem affecting the terrestrial and the marine environment and can locally only be tackled by reducing imports of plastics through substitutions where possible and improving the domestic collection of recyclable waste (Williams and Rangel-Buitrago, 2019).

### 5.3 Dependence on fossil fuels: Toward a more sustainable and circular energy system

Domestic fossil fuel use on Samothraki is in decline since it peaked in 1996 and is currently at levels of 2.2 kt/yr. Looking at the island’s SEM, its dependence on fossil fuels is comparatively low. Still, it poses challenges that need to be overcome to lead the island toward a more sustainable SEM. Ground and marine transport and domestic heating are key challenges for further reducing the island’s dependence on fossil fuels.

Given the substantial investments required to accomplish a carbon neutral local transport system, it is difficult to think of solutions solely on a local level. Currently the island consumes 830 t/yr of diesel and petrol for ground and 660 t/yr of diesel for marine transport. This does not include fuel for the ferry that connects Samothraki with the mainland. A starting point could be the substitution of conventional scooters for tourists with electric ones, in combination with the establishment of some solar powered loading stations, in collaboration with local businesses. Samothraki’s heating oil demand declined substantially since the 1990s. Due to the high cost of oil, systems are increasingly being changed to wood fuel or electric ones, in combination with the establishment of some solar powered loading stations, in collaboration with local businesses. Samothraki’s heating oil demand declined substantially since the 1990s. Due to the high cost of oil, systems are increasingly being changed to wood fuel or electricity. This is a trend visible in most Greek regions, where oil heating systems have been increasingly replaced with cheaper combination of gas and electricity heating systems (Papadopoulos et al., 2008). Changing to gas is not a feasible option for Samothraki and electricity costs are high and due to the high share of lignite in Greek’s energy mix currently also environmentally not beneficial. These circumstances require a domestic strategy for electricity production and for reducing demand through more efficient services, buildings, and mobility.

Samothraki’s population consumes currently 6500 MWh electricity per year (Supporting Information S2: Table 6). Thirty-eight solar panel fields installed on private land that farmers lease to electricity providers and feed into the mainland grid are currently the only renewable energy production on the island (Expert Interview 12). Current plans to build an industrial wind park with 40 large turbines in the most remote natural conservation area of the island for the export of electricity cannot be considered as part of the island’s sustainability strategy and are met with fierce criticism locally (Vlami et al., 2020). Similarly, opportunities for district heating, composting, or biogas production from organic waste are so far neglected. Instead, Samothraki annually exports 500–700 tons of organic waste, as part of mixed waste exports, to landfills on the mainland. The
implementation of a carbon-free transport and domestic heating system based on electricity and district heating thus requires an integrated energy strategy for the whole island, considering supply and demand-side solutions.

6 | CONCLUSIONS: A CIRCULAR ECONOMY STRATEGY FOR (SMALL) ISLANDS AND RESEARCH OUTLOOK

Our study provides the first long-term assessment of the complete socioeconomic metabolism (SEM) of an island economy. Our findings clearly support the conclusions that achieving a more sustainable material use is not only an issue of increasing circularity rates, but first and foremost about lowering the scale of a biophysical economy (Haas et al., 2020; Korhonen et al., 2018). When bringing together the above discussed potentials into a simplified static assessment, we find that the island’s domestic material consumption (DMC) could be reduced by 13.1 kt/yr and domestic processed output (DPO) by 10.9 kt/yr. At the same time input circularity rates could be increased from 61% to 71%, while output circularity would increase from 71% to 77% (Figure 7; Supporting Information S1: Section 7).

For a further reduction of resource demand, more attention must be paid to the material input side of island socioeconomic systems, by lowering overall consumption levels, focusing on replacement of problematic imported materials and potential synergies between local economic sectors. To reach these goals, the public and private stakeholders on Samothraki should explore circular economy (CE) strategies such as refuse when materials are not necessarily required, repair or reuse of materials to keep them in use as long as possible, and rethink to overcome certain practices and investments that impede more sustainable material use (Potting et al., 2017).

The CE Action Plan of the European Union (EU), which foresees tailored solution sets for EU’s outermost regions and islands, should therefore distinguish between the spatial scales at which circularity measures are developed. First, reducing the biophysical scale on the island level requires that the regional governments can and do implement programs that prevent certain materials from ending up in local ecosystems. This includes refusing environmentally problematic materials and supporting small-scale businesses to replace certain imported products with products manufactured from locally available renewable resources. Second, CE strategies need to be implemented on the level of national economies, the European level, or even globally. For these strategies to support island sustainability, it is necessary for them to address all material products still entering an
island and assisting island communities in the organization and financing of a collection and transportation network that enables affordable exports of non-biodegradable materials to facilities on the mainland. Similarly, (inter)national policy directives, standards, and subsidies shape the islands economy and need to be critically scrutinized and adapted.

Future research efforts should address the economic, social, and environmental aspects regarding the feasibility of proposed options, possibly in a transdisciplinary manner involving local representatives and residents to develop strategies and visions for a sustainable island future. A holistic approach must also focus on consumers and business strategies in order to fully evaluate potentials of locally available primary and secondary resources (Schöggel et al., 2020). Currently 40% of all processed materials go into the construction, maintenance, and operation of domestic material stocks. Their role in providing functions and services and the potential for improving demand-side efficiency should be further explored (Haberl et al., 2017; Wiedenhofer et al., 2019). Because islands will face increasing sociometabolic risks in the near future through sea level rise and increased frequency of extreme weather events, infrastructure resilience will increasingly become a crucial topic (Bradshaw et al., 2020; Merschroth et al., 2020; Popescu et al., 2020; Symmes et al., 2019). These risks must be considered as part of local sustainability strategies and their long-term implications on an island’s SEM should be evaluated.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

ORCID
Dominik Noll https://orcid.org/0000-0001-5118-8005
Christian Lauk https://orcid.org/0000-0002-4173-1753
Willi Haas https://orcid.org/0000-0001-5599-9227
Simron Jit Singh https://orcid.org/0000-0001-7012-893X
Panos Petrídís https://orcid.org/0000-0002-9701-0955
Dominik Wiedenhofer https://orcid.org/0000-0001-7418-3477

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