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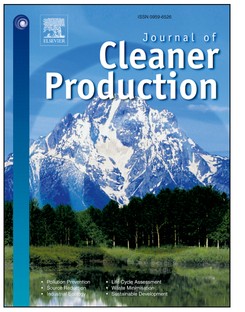

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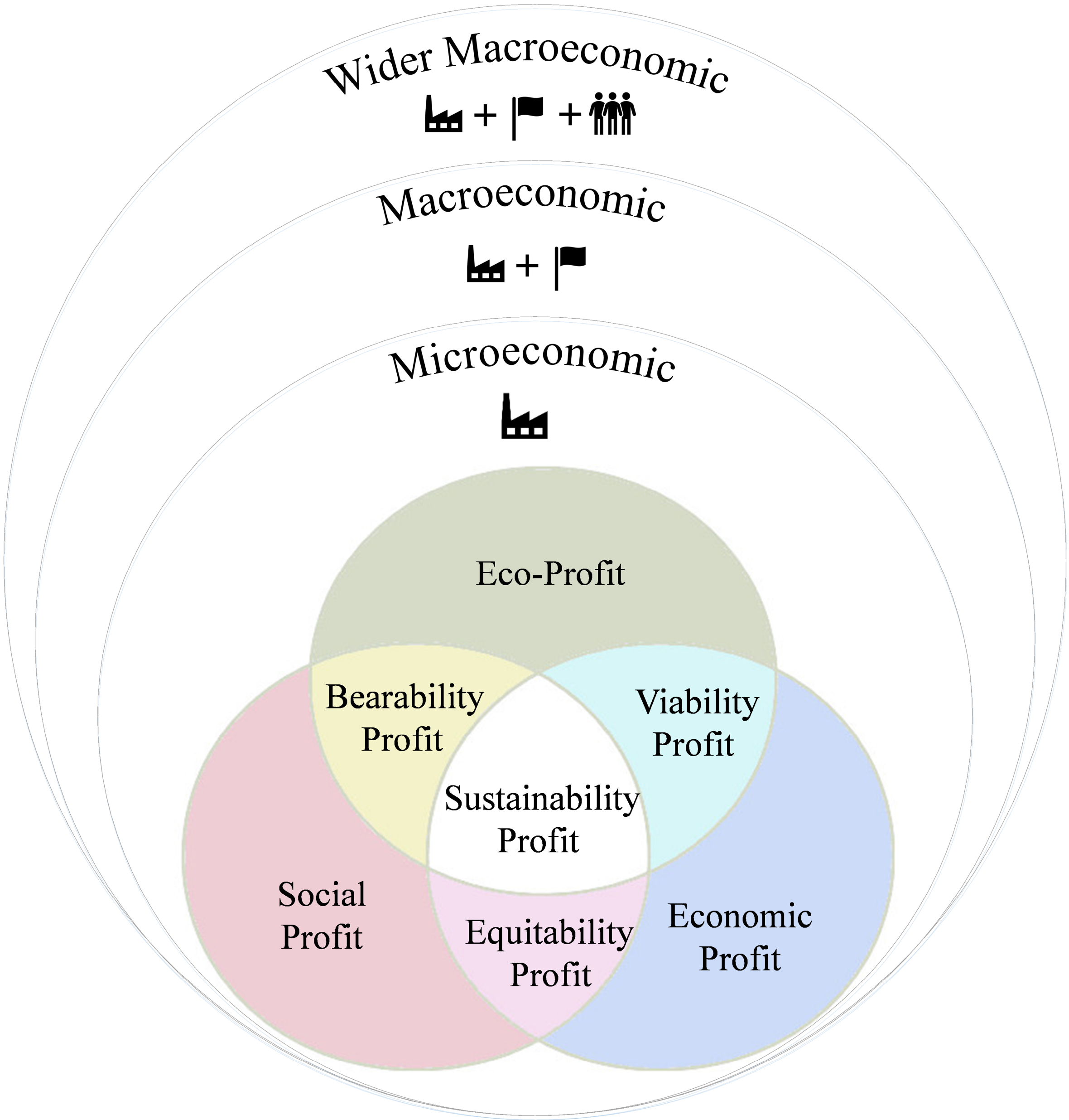

Synthesis of Sustainable Production Systems Using an Upgraded Concept of Sustainability Profit and Circularity

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Abstract

This paper describes an upgraded concept of the sustainability metric named Sustainability Profit (SP) from various micro- and macroeconomic perspectives and how it can be used for the synthesis of production systems in order to increase their circularity. An upgraded concept of SP is presented from three different perspectives: a microeconomic one, representing the company level, a macroeconomic perspective, combining the company and country (government) levels, and a wider macroeconomic one, with the addition of individuals (employees). Basic indicators of circularity, which measure the share of materials and energy reuse, are incorporated in order to synthesize more sustainable systems involving reuse of materials and energy. The concept is demonstrated on two case studies of supply network synthesis. The first case study is a supply network of fossil and renewable electricity production from various energy sources with fixed electricity demand, and the second case study is a larger-scale, renewable-based supply network for producing food, biofuels and electricity, and is applied to Central Europe. The results indicate that, by maximizing SP using the upgraded concept, overall circularity is favoured, and trade-offs between different sustainability pillars are obtained. The study could further be extended to account for uncertainty and more detailed Eco- and Social profit analysis and circularity measures as a good decision support tool in evaluating sustainable production systems.

Keywords: Sustainability profit; Macroeconomic perspectives, Renewable energy supply network; Synthesis of production systems; Circularity; Circularity indicators

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1. Introduction

Nowadays there are numerous environmental, societal and economic challenges, which include climate change, human population and consumption growth, poverty, resource use and scarcity and environmental degradation. The global patterns of production, consumption and trade are not sustainable (Preston, 2012). Sustainable development consisting of three pillars, economic, environmental and social, is thus gaining increasing research and political interest (Waldron, 2014). Almost 40,000 scientific papers exist in Science Direct with "sustainable development" in the title (retrieved in April 2018), and sustainable development is also listed among the goals of many countries, e.g. those in the EU (European Union, 2018). However, many sustainable development goals and targets exist (United Nations, 2015), together with more than 300 indicators (Hák et al., 2016) and more than 500 efforts to develop quantitative indicators (Parris and Kates, 2003). Several of the indicators and goals are only qualitative, especially for measuring social sustainability. Social sustainability is also the least understood sustainability pillar, thus gaining the designation, the "missing pillar" (Boström, 2012). No indicators are universally applicable (Lehtonen et al., 2016), only a few consider all three sustainability aspects (Singh et al., 2012), and there exists no single robust method for managing sustainability (Nawaz and Koç, 2018).

Different indicators typically serve different communities and have distinct purposes (Parris and Kates, 2003). There are indicators designed for specific local community, city, organisation or country and indicators which enable comparisons across local communities, cities, organisations or countries (Lehtonen et al., 2016). Moreover, there are varied views on sustainable development and on each separate pillar, on account of differences in values, interests or contexts (Mascarenhas et al., 2014) and in many cases also geographical diversity. The methods thus differ for different levels, from the micro level (individuals, specific groups, companies and products), up to the macro level (wider level; entire economies). Composite measures of sustainability at the macro level (e.g. the national scale) are not well applicable at the micro level (e.g. the local scale) (Mitchell, 1996), but it is desirable that measures be such as to enable linkages in data and flows (Jeswani et al., 2010). It should also be noted that various views at specific levels are possible. One such example can be pointed out by the following question, which could be asked at any micro or macro level: Is the more sustainable system the one that has the best overall sustainability performance, even though it has, e.g., negative economic performance? Or, is the most sustainable system the one that does not exhibit the best overall sustainability performance but does have a positive performance in all of the specific sustainability pillars?

Indicators of sustainable development can be divided into an aggregated single measure with a single value or into a set of indicators with multiple values (Mitchell, 1996). Ideally, the sustainability indicator, index or metric should reduce a large quantity of data and should express the information in its simplest form while minimizing information distortion (Mitchell, 1996). However, aggregate single measures could be difficult to understand not well supported by the data. In order to develop a composite sustainability metric, typically weighting between categories is applied (Singh et al., 2012). Besides weighting, normalization can be applied to transform different scales of specific indicators to a unique scale of aggregated or composite sustainability metric (Böhringer and Jochem, 2007). Monetary-based metrics have the advantage of overcoming weighting and normalization, as well as solution dimensionality, and are relatively easy to interpret and understand (Zore et al., 2017a). However, even when using monetary-based sustainability metrics, such as Sustainability profit (Zore et al, 2017a) or Sustainability net present value (Zore et al., 2018), specific systems could provide results with orders of magnitude difference between the pillars. This means that for specific systems, one sustainability pillar could be contributing a significant share to overall sustainability, while the other two pillars contribute much less, or one or both could even be negative. Given the different views at the micro- and macro levels and also within each specific level, sustainability pillars could be defined differently for each level (Zore et al., 2016).

In addition to “sustainable development,” an increasingly popular concept is the “circular economy” (Sauvé et al., 2016), which is also attracting more research and political interest (Geissdoerfer et al., 2017). The concept is of paramount importance for sustainable development and sustainability. Circular economy, with its synonyms cradle-to-cradle approach, closed-loop approach or also zero-waste approach, transforms the produced waste into valuable resources. It focuses on the 3R principles, on reducing, reusing and recycling materials (Heshmati, 2017). It enables integration of economic activities, environmental impact and use of resources in a more sustainable way by reducing resource and environmental pressures. Indirectly, it also has a positive impact on the social pillar through, e.g., job creation (Esposito et al., 2017). The circular economy focuses on redesign of processes and recycling of materials (Murray et al., 2017), and thus on supply networks instead of supply chains (linear economies; Andrews, 2015) by comprising life cycle thinking (Kobza and Schuster, 2016). Circular economy is viewed as a way to implement the concept of sustainable development by closing the loops in production and consumption (Ghisellini et al., 2016).

It has been argued that industrial ecology could assist in the transition from a linear to a circular economy (Saavendra et al., 2018). Industrial ecology can be seen as a framework which guides production systems towards more sustainable ones by moving from linear to a closed-loop systems (Lowe and Evans, 1995). The core of the industrial ecology concept is the continuous exchange of energy and materials within and between natural and industrial systems in a sustainable way (Arbolino et al., 2018). The cyclic industrial ecology model represents the ultimate goal of industrial ecology, with circulation of the resources at every phase of the product life-cycle within a supply network and thus with no negative impact on the environment (Leigh and Li, 2015).

However, assessing a production system's circularity performance is not a straightforward task (Saidani et al., 2017). Several circularity indicators have been proposed at the micro, meso and macro levels (Banaité, 2016). Additionally, various definitions of circular economy exist (at least 114) in different dimensions (Kirchherr et al., 2017). No standardized method for measuring circularity of products exists (Linder et al., 2017), and the following question remains (Saidani et al., 2017): "During design or re-design phases, how can we assess the circularity potential of a product, component or material, all along the lifecycle, and throughout the value chain?" Important work in this field has been performed by the Ellen MacArthur Foundation, which published several publications and a series of reports (Geissdoerfer et al., 2017).

A review of the literature shows that the studies performed mainly dealt with "isolated" topics, such as evaluation of sustainability (Strezov et al., 2017), sustainability performance of supply chains (Gómez-Luciano et al., 2018), relevance and importance of a circular economy to sustainable development (Schroeder et al., 2018), policy recommendations regarding sustainability and circular economy (Balanay and Halog, 2016), and applications of sustainability and/or circular economy at a specific level (Franco, 2017). Limited research studies have been performed linking industrial ecology and supply network sustainability development (Leigh and Li, 2015). To the best of our knowledge, no studies to date have addressed the evaluation of production systems from different perspectives considering i) company level, ii) company and country level and iii) individual, company and country level from a sustainability viewpoint comprising all three sustainability pillars and including circularity measures.

In this work an upgraded generalized concept of Sustainability profit (Zore et al. 2017a) is introduced from three different perspectives: the microeconomic (company level), the macroeconomic (company and country/government) and the wider macroeconomic perspective (company, country/government and individuals/employees), together with various combinations between specific sustainability pillars. All the versions of Sustainability profits are composite metrics of sustainability expressed in monetary terms. They are formulated as optimization problems expressed in a single-objective optimization form, and the best sustainable solutions can be obtained with a single run. Alongside the upgraded Sustainability profit, this work incorporates basic circularity metrics to measure the circularity of materials and energy in a production system. The upgraded concept of Sustainability profit is applied on two case studies of production systems. The first illustrative case study is an electricity production supply network, and the case study is a larger-scale supply network for production of biofuels, food and renewable electricity. The features of using the upgraded sustainability metric for solving multi-objective production systems of any scale, by considering various views (company, country and individuals) and circularity of materials and energy are demonstrated.

The proposed generalised concept of sustainability measures comprising all three pillars of sustainability as applied to smaller and larger-scale production systems from a supply network perspective is relevant to both cleaner production and sustainability. It introduces a generalised metric to assess sustainability at different micro and macro levels. It also promotes cleaner production, as it links industrial ecology and supply network sustainability performance with a focus to more cyclic production systems. The proposed concept could be applied as a stand-alone concept or it could be used as a part of mathematical programming, enabling optimality, feasibility, flexibility and integrality of solutions (Kravanja, 2010). In addition, in the proposed Sustainability profit design concept also unburdening effects on the environment are now considered, besides burdening ones. Considering these total effects on the environment opens a new powerful perspective in the designing of more cleaner production which would facilitate achieving the sustainable development faster because solution alternatives that unburden the environment the most would have higher priorities than those burdening the least.

The paper is organized as follows: Section 2 presents the upgraded concept of Sustainability profit from the micro, macro and wider macroeconomic perspectives. Section 3 introduces the circularity of raw materials and energy, which are defined as the share of reused materials and energy in regards to the total amount of material and energy used. Section 4 demonstrates the upgraded metrics of sustainability, together with measuring circularity on two illustrative case studies. The first case study deals with a fixed demand for electricity that could be satisfied from fossil and/or renewable energy sources, and the second case study deals with a supply network producing food, biofuels and bioproducts and renewable electricity from biomass, waste, geothermal, solar and wind. The fourth and final section provides conclusions and prospects for future research.

2. Sustainability profit

Sustainability profit is a composite criterion for measuring sustainability expressed in monetary units and consists of Economic, Eco- and Social profits (Zore et al. 2017a). Sustainability can be evaluated from different micro- and macroeconomic perspectives. In addition to the microeconomic (company) perspective and the macroeconomic (government + company) perspective, as in Zore et al. (2017a), in this work a wider macroeconomic perspective is introduced, which includes the macroeconomic perspective and also the perspective of employees and as such, represents the combined perspective of the company, government and workers.

Fig. 1 shows that Sustainability profit lies at the intersection of Economic, Environmental and Social profits. However, when a certain pillar is not considered, sustainability can be expressed with Viability profit (Economic + Eco), Equitability profit (Economic + Social) or Bearability profit (Eco- + Social). Each of these specific sustainability pillars (Economic, Environmental and Social profit) and combinations of pillars (Viability, Equitability, Bearability and Sustainability profit) can be calculated at the microeconomic (company level) and macroeconomic levels (company + country; and in the case of a wider level, company + country + individual level). A more detailed explanation of each sustainability pillar from each perspective is presented in the continuation. Sustainability could be, like specific profits and their combinations, assessed in terms of net present values (Economic, Eco-, Social, Viability, Equitability, Bearability and Sustainability net present value; Zore et al., 2018).

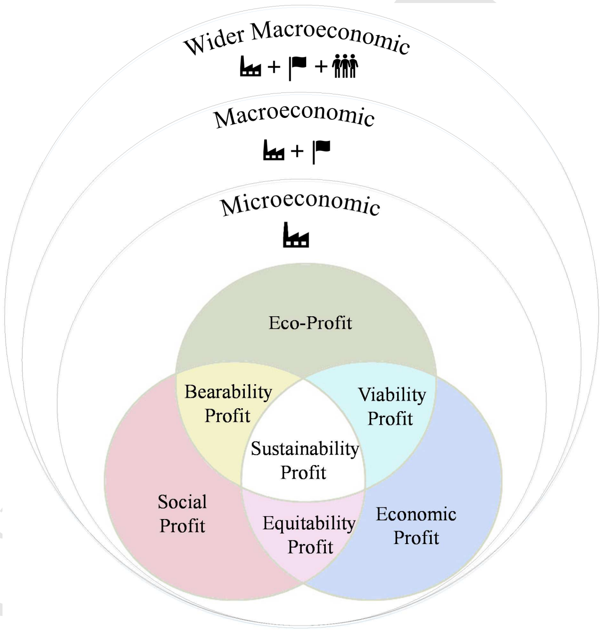


Fig. 1. Different types of profit from various perspectives obtained when considering specific sustainability pillars, pairs of pillars, and all pillars combined (from a representation by Dréo, 2006, modified by Zore et al., 2018).

Sustainability profit (*SP*) represents all the three basic pillars of sustainability - economic, environmental and social ones, which are in *SP* expressed in monetary terms as Economic ($P^{Economic}$), Eco- (P^{Eco}) and Social profits (P^{Social}). Since these individual sustainability indicators are expressed by the same units, they can be directly compared and composed in a single sustainability measurement. A higher value of sustainability or its individual criteria means that the solution obtained is more sustainable, more profitable, environmentally friendly or socially responsible.

The incremental values are considered which represent the difference between new and previous alternatives, see Eq. (1) (Zore et al., 2017a). However, for simplification, in the continuation all the symbols will be written without "Δ".

$$\Delta SP = SP^{\text{New}} - SP^{\text{Old}} = \Delta P^{\text{Economic}} + \Delta P^{\text{Eco}} + \Delta P^{\text{Social}} \tag{1}$$

A trade-off between all three types of profit is obtained with the maximization of Sustainability profit; see also Fig. 1, which shows the individual profits and their combinations. The combination of objectives into a composite one allows us to obtain the most sustainable solutions in one single run from single-objective optimization. For more details relating to the concept of Sustainability profit, readers are referred to Zore et al. (2017a), which introduced this concept.

However, the question arises regarding the conditions necessary for sustainability. Could an alternative be considered sustainable if only the overall *SP* is positive, or should all the pillars (P^{Economic}, P^{Eco}, and P^{Social}) be positive, or at least non-negative for the solution to be sustainable? In the opinion of the authors, a truly sustainable solution is one where, by maximizing the SP, all the pillars are at least non-negative. It is also pointed out by Thwink.org (2014) that "If any one pillar is weak then the system as a whole is unsustainable." The reasoning behind this is that Economic profit should be positive, because no firm would pursue losing invested capital and work; positive Eco-profit is needed to avoid or minimize deterioration of the environment and positive Social profit is needed to ensure at least social stability, if not improving society's well-being. However, in several real-world situations, the condition for all individual profits to be non-negative might not be satisfied, even if production systems are optimised. Examples include novel promising technologies, certain renewable production systems, and systems for treatment of waste and emissions. These production systems might still not be considered unsustainable. Non-negativity constraints for a specific pillar, while maximizing the overall *SP*, are shown in Eq. (2):

$$\begin{aligned} &\max SP = \max P^{\text{Economic}} + P^{\text{Eco}} + P^{\text{Social}} \\ &\text{s.t.} \quad P^{\text{Economic}} \geq 0 \\ &\qquad P^{\text{Eco}} \geq 0 \\ &\qquad P^{\text{Social}} \geq 0 \end{aligned} \tag{2}$$

By applying weightings for individual profits (w^{a}, w^{b} and w^{c}) with values between 0 and 1, a general expression for calculating different profits P^{x} is obtained, see Fig. 1 and Eq. (3). Alongside *SP*, by combining pure pairs of sustainability pillars, the following types of profit are obtained:

- Viability profit, defined as P^{Economic} plus P^{Eco} (previously called also "Total" (Kravanja and Čuček, 2013));
- Equitability profit as P^{Economic} plus P^{Social}, and
- Bearability profit as P^{Eco} plus P^{Social}.

The general formulation for calculating "Sustainability" profit where different weights between 0 and 1 could be specified for each of the sustainability pillars, expressed in monetary terms is shown in Eq. (3) (modified from Zore et al., 2017b):

$$P^{x} = w^{a} \cdot P^{\text{Economic}} + w^{b} \cdot P^{\text{Eco}} + w^{c} \cdot P^{\text{Social}} \quad (3)$$

The reasoning for using weights between the sustainability pillars that are all expressed in the same units (monetary terms) can be laid out due to various views (such as those of companies, governments, and individuals), various preferences (for example, greenhouse gas footprint is of higher importance than water footprint), because of order of magnitude differences between the pillars, unavailability of resources for performing analysis for all the pillars, and several other reasons. For simplification and to avoid subjective weighting, in this study all the weights are set to 1.

Economic profit

Microeconomic level: $\Delta P^{\text{Economic Micro}}$ is defined as revenue (ΔR) plus subsidies ($\Delta R^{\text{subsidy}}$) and reduced by expenditures (ΔE), depreciation (ΔD) and taxes (ΔC^{tax}):

$$\Delta P^{\text{Economic Micro}} = \Delta R + \Delta R^{\text{subsidy}} - \Delta E - \Delta D - \Delta C^{\text{tax}} \quad (4)$$

Macroeconomic and wider macroeconomic level: $\Delta P^{\text{Economic Macro}}$ and $\Delta P^{\text{Economic Wider Macro}}$ are defined as $\Delta P^{\text{Economic Micro}}$ but without taxes and subsidies. They are namely cancelled out as company pays taxes and receives subsidies from the government, while government receives taxes from company and pays subsidies to company. Economic profit is calculated in the same way at both macroeconomic and wider macroeconomic levels as:

$$\Delta P^{\text{Economic Macro}} = \Delta P^{\text{Economic Wider Macro}} = \Delta R - \Delta E - \Delta D \tag{5}$$

Eco-profit

Eco-profit ΔP^{Eco} stands for the difference between the eco-benefit (*EB*) of unburdening the environment and the eco-cost (*EC*) of burdening effects on the environment (Čuček et al., 2012a). Calculation of burdening and unburdening is based on eco-cost coefficients (Delft University of Technology, 2018). Eco-cost coefficients take into account raw materials $(c_{i,tech})$, products $(c_{j,tech})$ and processes with technology *tech*. Index *i* stands for unburdening (R_{UNB}) and burdening (R_B) effects of raw materials and index *j* for the unburdening (P_{UNB}) and burdening (P_B) effects of products on the environment. Index *tech* represents technologies in which raw materials, intermediates or products are involved. Both effects are proportional to mass flows of raw materials $q_{m_{i,tech}}$ and products $q_{m_{j,tech}}$ for a specific technology. Unburdening of any product is further multiplied by its substitution factor $(f_j^{S/P_{\text{UNB}}})$ which is defined as the amount of product to be substituted (*S*) divided by the amount of the resulting product (P_{UNB}). The substitution factor is based on the same performance (e.g. energy value, amount of nutrients) of produced and substituted products (Čuček et al., 2012a).

Microeconomic level: $\Delta P^{\text{Eco Micro}}$ takes into account only the environmental effects that occur inside the companies' gate. The burdening effects (EC^{Micro}) are calculated only for the part of the waste that is not utilised by the company $(q_{m_{i,tech}}^{\text{R}_{\text{B, tot}}} - q_{m_{i,tech}}^{\text{R}_{\text{UNB, consumed}}})$, and for the products produced by the company (Zore et al., 2017a). $\Delta P^{\text{Eco Micro}}$ is thus defined as:

$$\begin{aligned}
\Delta P^{\text{Eco Micro}} &= \Delta EB^{\text{Micro}} - \Delta EC^{\text{Micro}} = \\
&\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{UNB, Micro}}} \Delta q_{m_{i,tech}}^{\text{R}_{\text{UNB, consumed}}} \cdot c_{i,tech}^{\text{R}_{\text{UNB}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{UNB, Micro}}} \Delta q_{m_{j,tech}}^{\text{P}_{\text{UNB, consumed}}} \cdot f_j^{\text{S/P}_{\text{UNB}}} \cdot c_{j,tech}^{\text{S}} \right) - \\
&\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{B Micro}}} \Delta (q_{m_{i,tech}}^{\text{R}_{\text{B, tot}}} - q_{m_{i,tech}}^{\text{R}_{\text{UNB, consumed}}}) \cdot c_{i,tech}^{\text{R}_{\text{B}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{B Micro}}} \Delta q_{m_{j,tech}}^{\text{P}_{\text{B}}} \cdot c_{j,tech}^{\text{P}_{\text{B}}} \right)
\end{aligned} \tag{6}$$

Macroeconomic and wider macroeconomic level: $\Delta P^{\text{Eco Macro}}$ and $\Delta P^{\text{Eco Wider Macro}}$ include all environmental effects of all materials that the company uses or produces (Zore et al., 2017a).

$$\Delta P^{\text{Eco Macro}} = \Delta P^{\text{Eco Wider Macro}} = \Delta EB^{\text{Macro}} - \Delta EC^{\text{Macro}} = \left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{UNB Macro}}} \Delta q_{m_{i,tech}}^{\text{R}_{\text{UNB}}} \cdot c_{i,tech}^{\text{R}_{\text{UNB}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{UNB Macro}}} \Delta q_{m_{j,tech}}^{\text{P}_{\text{UNB}}} \cdot f_j^{\text{S/P}_{\text{UNB}}} \cdot c_{j,tech}^{\text{S}} \right) - \left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{B Macro}}} \Delta q_{m_{i,tech}}^{\text{R}_{\text{B}}} \cdot c_{i,tech}^{\text{R}_{\text{B}}} + \sum_{t \in T} \sum_{j \in P_{tech}^{\text{B Macro}}} \Delta q_{m_{j,tech}}^{\text{P}_{\text{B}}} \cdot c_{j,tech}^{\text{P}_{\text{B}}} \right) \quad (7)$$

Social profit

Microeconomic level: $\Delta P^{\text{Social Micro}}$ at the company level is defined as social cost (SC), representing the contribution of the company to improving the social status of employees (Zore et al., 2017a). It is expressed as follows:

$$\Delta P^{\text{Social Micro}} = -\Delta SC^{\text{Micro}} = -\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot c_s^{\text{Company}} \quad (8)$$

where social cost SC^{Micro} is the average company contribution per employee (c_s^{Company}), multiplied by the number of employees (N_{tech}^{Jobs}). Note that salaries and social security contributions (cost of labour) is not included in $P^{\text{Social Micro}}$ because they have already been considered as part of expenses in $\Delta P^{\text{Economic Micro}}$.

Macroeconomic level: $\Delta P^{\text{Social Macro}}$ at the combined governmental and production sectors' level is defined as a sum of social security contributions (SS^{Macro}) and social unburdening (SU^{Macro}) minus social cost (SC^{Macro}) (Zore et al., 2017a):

$$\Delta P^{\text{Social Macro}} = \Delta SS^{\text{Macro}} + \Delta SU^{\text{Macro}} - \Delta SC^{\text{Macro}} = \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \left(s_{tech}^{\text{Gross}} - s_{tech}^{\text{Net}} \right) + \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot c_s^{\text{UNE, State}} - \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot (c_s^{\text{EMP, State}} + c_s^{\text{Company}}) \quad (9)$$

Social security contributions are defined as the difference between gross $(s_{tech}^{\text{Gross}})$ and net salaries (s_{tech}^{Net}) for all new employees. Social unburdening is defined as the product between the average state social transfer for an unemployed person $(c_s^{\text{UNE, State}})$ and the number of new jobs/employees (N_{tech}^{Jobs}). Social cost is social support from the government and company and is calculated as the product of N_{tech}^{Jobs} and the sum of the average social transfer by the government $(c_s^{\text{EMP, State}})$ and company (c_s^{Company}) (Zore et al., 2017a).

Wider macroeconomic level: $\Delta P^{\text{Social Wider Macro}}$ at the combined governmental, company and employee level integrates the macroeconomic level along with the employee perspective. From the employee's view, the income or social benefit (SB^{Employee}) corresponds to his/her net salary (s_{tech}^{Net}), and all the social benefits that are provided to him/her by the government and the employer/company $(c_s^{\text{EMP, State}} + c_s^{\text{Company}})$. The outcome or social cost (SC^{Employee}) corresponds to the loss of unemployment support from the government $(c_s^{\text{UNE, State}})$. The social benefits and cost from the employee perspective are multiplied by the number of employed persons in a company.

The wider Social profit after most of its parts cancel each other out becomes simply an employee's gross salary $(s_{tech}^{\text{Gross}})$ multiplied by the number of employees (N_{tech}^{Jobs}):

$$\begin{aligned}\Delta P^{\text{Social Wider Macro}} &= \Delta SS^{\text{Macro}} + \Delta SU^{\text{Macro}} - \Delta SC^{\text{Macro}} + \Delta SB^{\text{Employee}} - \Delta SC^{\text{Employee}} = \\ &\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \left(s_{tech}^{\text{Gross}} - s_{tech}^{\text{Net}}\right) + \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot c_s^{\text{UNE, State}} - \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot (c_s^{\text{EMP, State}} + c_s^{\text{Company}}) + \\ &\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot s_{tech}^{\text{Net}} + \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot (c_s^{\text{EMP, State}} + c_s^{\text{Company}}) - \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot c_s^{\text{UNE, State}} = \\ &\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot s_{tech}^{\text{Gross}}\end{aligned} \quad (10)$$

Sustainability profit overview

Sustainability profit from the different perspectives can now be defined based on the corresponding Economic, Eco- and Social profits.

The Microeconomic or company perspective comprises the following:

- Economic profit – the company's economic performance; subsidies and taxes are included in the annual cash flow.
- Eco-profit – ideally achievable under assumption of a zero-waste concept by the company. All the emissions originating from raw materials, processes, products and waste that occur from company's activities are taken into account.
- Social profit – social security contributions paid by the employer/company to the employees.

ΔSP^{Micro} is defined (Zore et al., 2017a):

$$
\begin{aligned}
\Delta SP^{\text{Micro}} &= \Delta P^{\text{Economic Micro}} + \Delta P^{\text{Eco Micro}} + \Delta P^{\text{Social Micro}} = \\
&\Delta R + \Delta R^{\text{subsidy}} - \Delta E - \Delta D - \Delta C^{\text{tax}} + \\
&\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{UNB Micro}}} \Delta q_{m_i,tech}^{\text{R}_{\text{UNB, consumed}}} \cdot c_{i,tech}^{\text{R}_{\text{UNB}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{UNB Micro}}} \Delta q_{m_j,tech}^{\text{P}_{\text{UNB, consumed}}} \cdot f_j^{\text{S/P}_{\text{UNB}}} \cdot c_{j,tech}^{\text{S}} \right) - \\
&\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{B Micro}}} \Delta (q_{m_i,tech}^{\text{R}_{\text{B, tot}}} - q_{m_i,tech}^{\text{R}_{\text{UNB, consumed}}}) \cdot c_{i,tech}^{\text{R}_{\text{B}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{B Micro}}} \Delta q_{m_j,tech}^{\text{P}_{\text{B}}} \cdot c_{j,tech}^{\text{P}_{\text{B}}} \right) - \\
&\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot c_s^{\text{Company}}
\end{aligned}
\tag{11}
$$

The Macroeconomic perspective combines the company's and the government's wishes:

- Economic profit – a function of market prices; annual cash flows of the company and the government where subsidies and taxes cancel each other out.
- Eco-profit – ideally achievable under a zero-waste policy from an overall perspective. Alternatives with greater unburdening and less burdening effects are preferred.
- Social profit - combines social security contributions paid by the employer/company to the government, social support from the government for employees, and reduced social support for unemployment.

ΔSP^{Macro} is defined (Zore et al., 2017a):

$$
\begin{aligned}
\Delta SP^{\text{Macro}} &= \Delta P^{\text{Economic Macro}} + \Delta P^{\text{Eco Macro}} + \Delta P^{\text{Social Macro}} = \\
&\Delta R - \Delta E - \Delta D + \\
&\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{UNB Macro}}} \Delta q_{m_i,tech}^{\text{R}_{\text{UNB}}} \cdot c_{i,tech}^{\text{R}_{\text{UNB}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{UNB Macro}}} \Delta q_{m_j,tech}^{\text{P}_{\text{UNB}}} \cdot f_j^{\text{S/P}_{\text{UNB}}} \cdot c_{j,tech}^{\text{S}} \right) - \\
&\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{B Macro}}} \Delta q_{m_i,tech}^{\text{R}_{\text{B}}} \cdot c_{i,tech}^{\text{R}_{\text{B}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{B Macro}}} \Delta q_{m_j,tech}^{\text{P}_{\text{B}}} \cdot c_{j,tech}^{\text{P}_{\text{B}}} \right) + \\
&\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \left(s_{tech}^{\text{Gross}} - s_{tech}^{\text{Net}} \right) + \sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot c_s^{\text{UNE, State}} - \\
&\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot (c_s^{\text{EMP, State}} + c_s^{\text{Company}})
\end{aligned}
\tag{12}
$$

The Wider macroeconomic perspective that is newly introduced in this paper combines the views of the company, the government and individuals (employees):

- Economic profit is equal to that from a macroeconomic perspective.
- Eco-profit is also the same as that from the macroeconomic view.

- Social profit – besides social profit from the macroeconomic perspective, this also includes cash flow that represents employee income. The incomes are net salary and social benefits, while the outcomes are the loss of unemployment support from the government. In comparison with the macroeconomic perspective the wider macroeconomic perspective prefers those alternatives with a higher number of employers (represents employability) with higher salaries (represents technological level or better paid work). Also, gross salaries cancel out from this perspective, since they represent a cost for the company but a benefit for employees and the government.

$\Delta SP^{\text{Wider Macro}}$, which is considered to represent the ideal viewpoint for employees, companies, a nation or wider community, is defined:

$$\begin{aligned}\Delta SP^{\text{Wider Macro}} &= \Delta P^{\text{Economic Wider Macro}} + \Delta P^{\text{Eco Wider Macro}} + \Delta P^{\text{Social Wider Macro}} \\ &= \Delta P^{\text{Economic Macro}} + \Delta P^{\text{Eco Macro}} + \Delta P^{\text{Social Wider Macro}} \\ &= \Delta R - \Delta E - \Delta D + \\ &\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{UNB Macro}}} \Delta q_{m_{i,tech}}^{\text{R}_{\text{UNB}}} \cdot c_{i,tech}^{\text{R}_{\text{UNB}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{UNB Macro}}} \Delta q_{m_{j,tech}}^{\text{P}_{\text{UNB}}} \cdot f_j^{\text{S/P}_{\text{UNB}}} \cdot c_{j,tech}^{\text{S}} \right) - \\ &\left(\sum_{tech \in Tech} \sum_{i \in R_{tech}^{\text{B Macro}}} \Delta q_{m_{i,tech}}^{\text{R}_{\text{B}}} \cdot c_{i,tech}^{\text{R}_{\text{B}}} + \sum_{tech \in Tech} \sum_{j \in P_{tech}^{\text{B Macro}}} \Delta q_{m_{j,tech}}^{\text{P}_{\text{B}}} \cdot c_{j,tech}^{\text{P}_{\text{B}}} \right) + \\ &\sum_{tech \in Tech} \Delta N_{tech}^{\text{Jobs}} \cdot s_{tech}^{\text{Gross}}\end{aligned} \quad (13)$$

3. Circularity indicator

Circularity can be assessed from various perspectives, at the micro-, meso- and macro levels (Zhu et al., 2011). However, there is a lack of criteria for how to assess the measures for improving circularity of products and economies (Haas et al., 2015). Various circularity metrics exist, such as a circularity indicator based on material flow analysis (MFA), the Material Circularity Indicator (MCI), the Eco-efficient Value Ratio, the Circular economy index and many others (Linder et al., 2017). Moreover, different types of units are used (e.g. mass, energy) to quantify product-level circularity (Linder et al., 2017).

One of the main circularity indexes is MCI (The Ellen MacArthur Foundation and Granta Design, 2015). The MCI gives a value between 0 and 1, where a higher value indicates greater circularity (The Ellen MacArthur Foundation and Granta Design, 2015). Because of the complexity of the MCI, especially for larger scale supply networks with numerous technologies, process and products, the indicators used in this work have been simplified. The focus of this work is on material and energy (heat and electricity) circularity.

The circularity of raw materials in the supply chain (F^{Material}) is upgraded from that in Zore et al. (2017b) and is defined by Eq. (14). The alternatives with the lowest fractions of virgin feedstocks are preferred. Other symbols in Eq. (14) are as follows: $q_{m_i}^{\text{Total Feedstock}}$ represents the total amounts of feedstocks used in the production system and $q_{m_i}^{\text{Circulated Feedstock}}$ stands for recycled, reused or recovered feedstocks or waste.

$$F^{\text{Material}} = \frac{\sum_{i \in R} q_{m_i}^{\text{Circulated Feedstock}}}{\sum_{i \in R} q_{m_i}^{\text{Total Feedstock}}} \cdot 100\% \qquad (14)$$

For the calculation of circularity of energy (F^{Energy}), representing heat, cold or electricity the following similar relation defined by energy flows is proposed in this paper, see Eq. (15):

$$F^{\text{Energy}} = \frac{\sum_{i \in R} Q_i^{\text{Reused energy}}}{\sum_{i \in R} Q_i^{\text{Total energy}}} \cdot 100\% \qquad (15)$$

In the case of heating or cooling energy, the circularity indicator is denoted as F^{Heat} and for electricity it is $F^{\text{Electricity}}$. Circularity of energy is related to process integration (Klemeš, 2013), such as utilisation of waste heat (Arsenyeva et al., 2016) or power generated from waste heat (Matsuda, 2014), and use of renewable energy sources for the production of heat, cold or electricity. However, closed-loops of material, energy, waste, and emissions are generally impossible. Systems would still require non-renewable resources and will produce some waste (Kobza and Schuster, 2016), although it is expected that with constant innovation the loops will become gradually closer.

4. Illustrative Case Studies

The proposed concept of micro-, macroeconomic and wider macroeconomic perspective, with and without additional non-negativity constraints for specific sustainability pillars is demonstrated on two case studies. The first case study is a hypothetical illustrative example of electricity production from various fossil and renewable-based sources and is used for a straightforward demonstration of the upgraded metric. The second case study presents a larger scale heat-integrated biorefinery and renewable electricity supply network with coproduction of food (Čuček et al., 2014). Both case studies were computed using the GAMS modeling system (GAMS Development Corp. and GAMS Software GmbH, 2018).

The first case study is formulated as a nonlinear programming (NLP) model consisting of approximately 50 constraints and 55 single variables. It was solved on a personal computer with an Intel® Core™ i3 CPU @ 2.93 GHz processor with 4 GB of RAM. The second case study is formulated as a mixed-integer linear programming (MILP) model. The model includes approximately 600,000 constraints, 225,000,000 single variables, and 7,100 binary variables. This model was solved with a server because of its higher RAM (768 GB). The server is an HP DL580 G9 CTO with 4 processors (32 core) Intel® Xeon® CPU E5-4627 v2 @ 3.30 GHz. Solution time was between 20 and 40 minutes with the optimality gap set to a maximum of 5 %.

4.1. First case study – electricity production from various sources

The first illustrative study presents a hypothetical case of electricity production (modified from Zore et al., 2018). The study covers the renewable technologies, photovoltaics, wind turbines, geothermal sources, waste incineration and anaerobic digestion (AD) with cogeneration (CHP), and the fossil technologies are coal power plants and combined cycle gas turbines (CCGT). Feedstocks for AD comprise manure (30 %) and corn silage (70%), and feedstocks for waste incineration are wood residue (50 %) and municipal waste (MSW) (50 %). Total available feedstocks for AD are limited to 20 Mt/y (as in Zore et al., 2017a) and total available amount of wood residue and municipal waste is limited to 2 Mt/y each. Constraints on installed power are selected in such a way that none of the individual technologies can satisfy the demand on its own.

The market price of electricity is assumed to be 42.30 €/MWh (Borzen, 2018). Demand for electricity is assumed to be 1,500 MW. The upper limit of installed capacity for each technology is 1,000 MW, except for geothermal where it was set to 500 MW, for AD where the actual availability of feedstocks is up to 806 MW and for waste incineration, where up to 865 MW is available based on the available feedstock amounts. For calculation of power output and efficiency of a specific technology, see Eqs. (10) – (12) in Zore et al., 2017a. Additionally, an interest rate of 3 %, a lifetime of 20 y and a tax rate of 17 % on the profit were selected.

Using manure and municipal waste to produce electricity rather than transporting them to a landfill represents an unburdening of the environment, and their coefficients (in €/kg) become eco-benefit coefficients. Eco-cost and eco-benefit coefficients for biomass and waste shown in Table 1 are calculated based on the ratio of feedstocks. The electricity mix to be replaced is assumed to be generated 50 % from coal and 50 % from natural gas. Table 1 presents the assumed data for the demonstration case study. The new data related to technologies not presented in Zore et al. (2017a) were obtained from the U.S. Energy Information Administration (2016). For making projections of price changes for various technologies, data from the U.S. Energy Information Administration (2013) were used. For the remaining data related to technologies, see Zore et al. (2017a). Also, for calculation of Social profit the same assumptions are made as in Zore et al. (2017a).

For calculation of circularity, the virgin feedstocks considered are corn silage used for AD and natural gas and coal, while manure used for AD and municipal waste and forest residue used for waste incineration are defined as reused materials or waste. Water for the geothermal plant is not taken into account.

Table 2 shows the main results from optimizations applying different maximization criteria. The objective values in the corresponding columns are shown in bold.

Table 1. Data for demonstration case study.

	Solar	**Wind**	**Biomass**	**Wood residues and MSW**	**Geothermal**	**Coal**	**Natural gas**
Investment cost (M€/MW)	2.112	1.564	4.154	6.927	3.635	2.705	0.815
Fixed maintenance and operating cost (€/MWh)	18,167	33,083	91,667	327,350	83,333	31,500	9,167
Variable maintenance and operating cost (€/MWh)	0.00	0.00	3.50	7.29	0.00	3.73	2.92
Subsidy for producing electricity (€/MWh)	29.99	50.36	101.45	52.85	113.55	0	0
CO_2 emissions (kg/MWh)	0	0	0	0	0	820	490
f_t - Capacity factor (%)	21	35	85	85	65	80	85
Maximum installed power (MW)	1,000	1,000	806**	865**	500	1000	1000
Eco-cost coefficient for electricity (€/MWh)	30.00	9.84	39.66	216.28	1.73	165.28	79.17
Eco-cost coefficient for raw materials (€/kg or €/m^3)	0	0	$4.49\cdot10^{-3}$	$4.74\cdot10^{-2}$	0	0.0554	0.129
Eco-benefit coefficient for raw materials (€/kg or €/m^3)	0	0	$3.34\cdot10^{-3}$	$5.90\cdot10^{-2}$	0	0	0
Number of jobs for construction (MW^{-1})	5.99	1.47	0.4	0.4	9.46	0.27	0.25
Number of jobs for maintenance (MW^{-1})	3	0.27	1.41	3.85	0.24	0.74	0.7
η_{tech} - factor of energy content in energy source and efficiency* (kWh/kg or kW/m^3)	/	/	0.3	1.41	/	2.68	4.32

*40 % efficiency of electricity generation is assumed

**based on the available feedstocks

Table 2 shows that the same results are obtained when maximizing $P^{\text{Economic Micro}}$ and SP^{Micro}. The economic pillar is positive, while the environmental and social pillars are negative. By considering the principle that the project is truly sustainable if all the pillars are non-negative, the company should sacrifice 16.9 M€/y to the prevention of environmental damage and 1.7 M€/y to cover social loss. The technologies selected are all renewable technologies except solar, and are set to their upper limits, while waste incineration fills the gap to fulfil the demand. All the selected technologies perform well economically with subsidies included, and at the same time they only slightly burden the environment since all of them are renewable. Photovoltaics was not selected due to social perspective, as it employs the highest number of employees per installed MW and it would burden the social part of the company budget too much. In terms of circularity, 32.6 % of materials used are reused and 100 % of the electricity comes from renewable sources. Altogether 5,597 employees are selected to be employed from the microeconomic perspective.

Table 2. Results when maximizing different types of profit for the electricity production supply chain.

	Maximization criteria				
Economic items	**Microeconomic perspective** (company)		**Macroeconomic perspective** (company + government)		**Wider macro perspective** (company + government + employees)
	$P^{\text{Economic Micro}}$	SP^{Micro}	$P^{\text{Economic Macro}}$	SP^{Macro}	$SP^{\text{Wider Macro}}$
$P^{\text{Economic Micro}}$ (M€/y)	**838.6**	838.6	194.2	783.0	726.6
$P^{\text{Eco Micro}}$ (M€/y)	-16.9	-16.9	-339.6	-21.2	-19.1
$P^{\text{Social Micro}}$ (M€/y)	-1.7	-1.7	-0.4	-1.9	-2.0
SP^{Micro} (M€/y)	820.1	**820.1**	-145.8	759.9	705.5
$P^{\text{Economic Macro}}$ (M€/y)	-205.7	-205.7	**275.6**	-172.9	-193.5
$P^{\text{Eco Macro}}$ (M€/y)	1,088.4	1,088.4	-226.5	1,312.6	1,320.7
$P^{\text{Social Macro}}$ (M€/y)	65.6	65.6	19.6	72.1	77.8
SP^{Macro} (M€/y)	948.3	948.3	68.7	**1,211.8**	1,205.0
$P^{\text{Economic Wider Macro}}$ (M€/y)	-205.7	-205.7	275.6	-172.9	-193.5
$P^{\text{Eco Wider Macro}}$ (M€/y)	1,088.4	1,088.4	-226.5	1,312.6	1,320.7
$P^{\text{Social Wider Macro}}$ (M€/y)	172.5	172.5	50.6	190.2	205.3
$SP^{\text{Wider Macro}}$ (M€/y)	1,055.2	1,055.2	99.7	1,329.9	**1,332.5**
Installed power (MW)					
- solar	-	-	-	667	1,000
- wind	1,000	1,000	-	1,000	1,000
- biomass	806	806	-	806	724
- waste incinerator	165	165	-	-	-
- geothermal	500	500	-	500	500
- coal	-	-	813	-	-
- gas	-	-	1,000	-	-
- total	2,471	2,471	1,813	2,973	3,224

Power output (MW)	1,500	1,500	1,500	1,500	1,500
$F^{Material}$ (%)	32.6	32.6	0	30	30
$F^{Electricity}$ (%)	100	100	0	100	100
Number of employees	5,597	5,597	1,464	6,260	6,762

At the macro level, different results are obtained when maximizing $P^{Economic\ Macro}$ and SP^{Macro}. From the pure market perspective (subsidies and taxes are excluded) when maximizing $P^{Economic\ Macro}$, the only technologies selected are those based on non-renewable sources, where natural gas is preferred over coal. Their production costs are lower in comparison with renewable-based sources and as a result, renewable sources are subsidised (Nicolini and Tavoni, 2017). This alternative shows the only positive $P^{Economic\ Macro}$ and also the only negative $P^{Eco\ Macro}$ among all alternatives displayed in Table 2. This alternative also exhibits the lowest $P^{Social\ Macro}$, the lowest number of employees (1,464) and the lowest SP^{Macro} among all the alternatives. Both circularity indicators are equal to 0, since only virgin materials are used and electricity is produced only from non-renewable sources. It should be noted that the solution when maximizing $P^{Economic\ Macro}$ could differ from country to country, since market prices for electricity are different.

On the other hand, when maximising SP^{Macro}, all the sustainability pillars perform better in comparison to maximizing SP^{Micro} because they are now viewed jointly from the company and government perspectives. The only negative pillar, from a macroeconomic perspective, is $P^{Economic\ Macro}$ since subsidies are now excluded and the foremost renewable sources are selected. If the market price for electricity produced were 55.5 €/MWh or higher instead of 42.3 €/MWh (Borzen, 2018), the solution would be sustainable, even from a macroeconomic point of view. In Eco-profit, the products and waste outside company borders are also considered, i.e. electricity sold to the grid is also considered in Eco-profit, besides that used in the company. In Social profit, the unburdening of the state budget due to more employees and some state cost as investments into employees are also now included. It can be seen that more workers are employed (6,260 vs. 5,597), and also different technologies are chosen for producing electricity. Instead of waste incineration, photovoltaics is now preferred, because of the higher unburdening effect of produced electricity sold to the grid and a higher number of employees.

When comparing the Social profit, it can be seen that at the micro level, it is always slightly negative, at the macro level, which includes relieving of social transfer from the government budget owing to additional new employees, it becomes positive, and at the wider macro level including the employer perspective (net salaries and social benefits reduced by support for unemployment), the Social profit is the highest of all the alternatives.

Finally, when comparing the results at the macro and wider macro level, all the solutions except economics are better in terms of profits and number of employees. The solution is shifted towards technologies which require more employees with higher salaries. Technologies that run on wind, solar and geothermal power are preferred over AD that only fulfils the demand, while waste incineration and coal and gas power plants are not selected.

Table 3 shows all the profits obtained from a wider macroeconomic perspective, when they are optimised separately. It shows the preferred solutions in terms of individual pillars (economic, eco- and social) and overall sustainability. It should be noted that the only difference between the macro level and the wider macro level lies in the calculation of the Social profit, while maximization of $P^{\text{Economic Macro}}$ and $P^{\text{Economic Wider Macro}}$, and $P^{\text{Eco Macro}}$ and $P^{\text{Eco Wider Macro}}$ yields the same results.

Table 3. Main results when maximizing different profits from the wider macroeconomic perspective.

Economic items	Maximization criteria			
	$P^{\text{Economic Wider Macro}}$	$P^{\text{Eco Wider Macro}}$	$P^{\text{Social Wider Macro}}$	$SP^{\text{Wider Macro}}$
$P^{\text{Economic Wider Macro}}$ (M€/y)	**275.6**	-193.5	-608.2	-193.5
$P^{\text{Eco Wider Macro}}$ (M€/y)	-226.5	**1,320.7**	126.8	1,320.7
$P^{\text{Social Wider Macro}}$ (M€/y)	50.6	205.3	**275.6**	205.3
$SP^{\text{Wider Macro}}$ (M€/y)	99.7	1,332.5	-205.8	**1,332.5**
Installed power (MW)				
- solar	-	1,000	1,000	1,000
- wind	-	1,000	-	1,000
- biomass	-	724	270	724
- waste incinerator	-	-	865	-
- geothermal	-	500	500	500
- coal	813	-	-	-
- gas	1,000	-	-	-
- total	1,813	3,224	2,635	3,224
Power output (MW)	1,500	1,500	1,500	1,500
F^{Material} (%)	0	30	56.1	30
$F^{\text{Electricity}}$ (%)	0	100	100	100
Number of employees	1,464	6,762	8,580	6,762

From the $P^{\text{Economic Wider Macro}}$ viewpoint, again only fossil-based sources are selected for electricity production, as subsidies and eco taxes are not considered. When maximizing $P^{\text{Eco Wider Macro}}$ and $SP^{\text{Wider Macro}}$, the same solutions are obtained with a significant contribution from the environmental part, compared to the economic and social parts. This solution presents the best possible trade-off between $P^{\text{Economic Wider Macro}}$, $P^{\text{Eco Wider Macro}}$ and $P^{\text{Social Wider Macro}}$. When $P^{\text{Social Wider Macro}}$ is maximised, the highest number of employees (8,580) is obtained since the optimization criteria favor a higher number of employees, possibly with higher salaries. The selected technologies are those that need a higher number of employees per MW installed. Such technologies are solar, geothermal, waste incineration and AD that is used to fulfil demand.

From the results in Table 3, it can be seen that $SP^{\text{Wider Macro}}$, compared with $P^{\text{Economic Wider Macro}}$, reduces economic performance by 469.1 M€/y to gain a 1,547.2 M€/y higher Eco-profit and a 154.7 M€/y higher Social profit.

4.2. The second case study - a biorefinery and renewable electricity supply network

This case study represents the upgraded sustainability criteria applied to a multi-period MILP optimization model of a larger-scale energy supply network at the Central EU level. The model represents the reduced size of the one presented in Zore et al. (2018), which was applied at the level of the EU. Central EU is represented by Austria, Czech Republic, Germany, Hungary, Lichtenstein, Poland, Slovakia and Slovenia (Central Intelligence Agency, 2018). The model includes the concept of a System-Wide Supply Network (SWSN) superstructure (Zore et al., 2018; motivated by Marquardt et al., 1999) that combines a heat-integrated biorefinery supply network, a renewable electricity supply network and a food supply network, see Fig. 2. Corn and wheat are feedstocks that can be used for food production. Electricity can be produced from solar, wind and geothermal sources. The main products are food, bioethanol and green gasoline as gasoline substitutes, biodiesel and Fischer-Tropsch (FT) diesel as diesel substitutes, hydrogen and electricity. Possible technology routes are presented in Fig. 2.

The superstructure is based on four layers, L1-L4 (Čuček et al., 2010) including harvesting sites at L1, storage, pre-processing of raw materials to intermediate products and production of electricity at L2, bio-refineries at L3, and demand locations at L4 (Zore et al., 2018).

Each layer is divided into 33 zones across the Central EU (after Širovnik et al., 2016). It is assumed that locations of sites are at zone centers. Transportation is calculated within and between zones. For reducing the size of the model it is assumed that the distances for the transportation of biomass and waste, energy and products are limited (Lam et al., 2011). For solar, wind and geothermal energy, it is assumed that they cannot be transported until they have been transformed into electrical energy. Up to 10 % of the total area of each zone is assumed that can be devoted to satisfying food and biofuel demand and up to 1 % to producing electricity from renewable sources (Zore et al., 2018). Note that almost 8 % of land in Europe is already used for corn and wheat production (FAOSTAT, 2018).

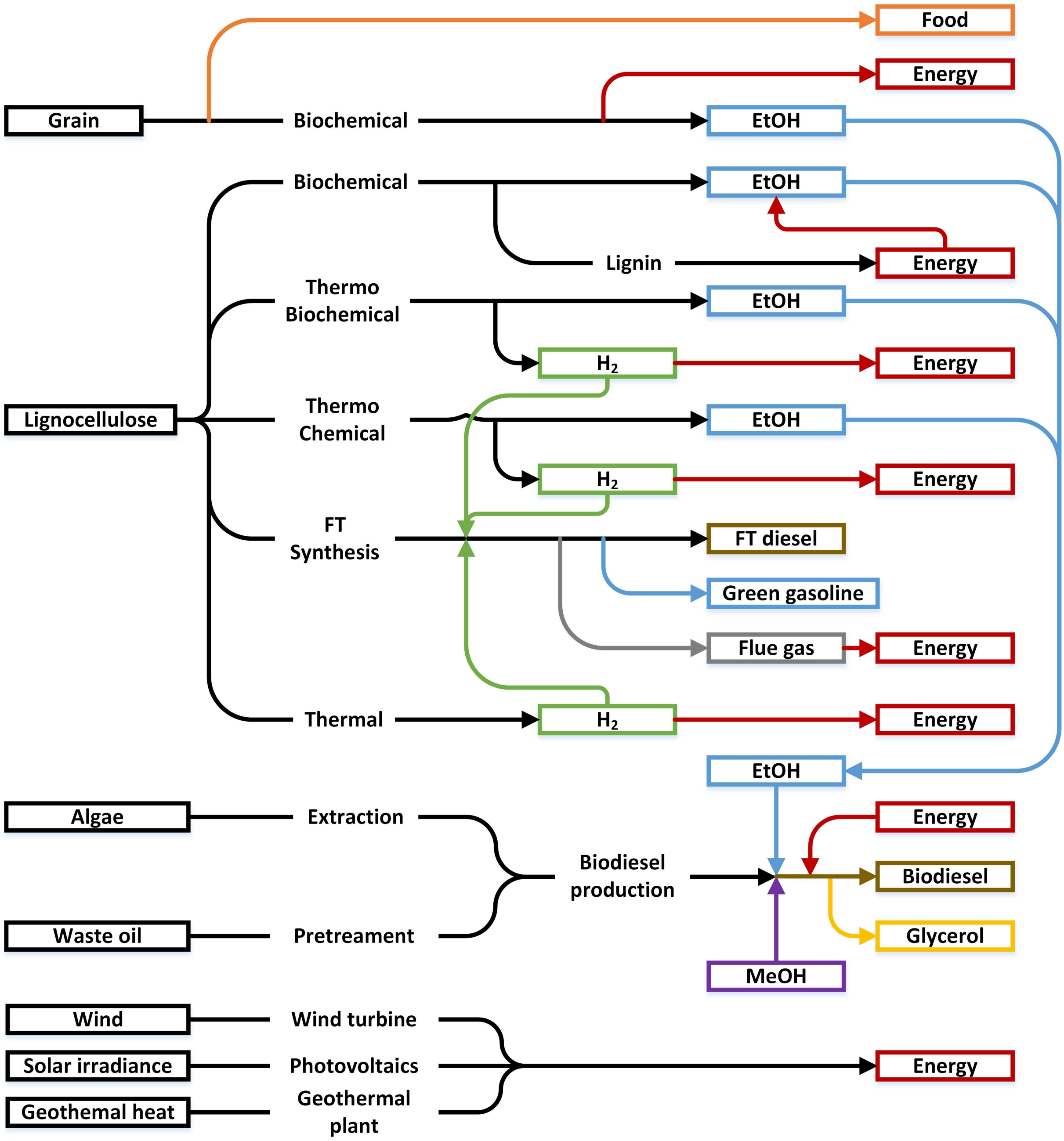


Fig. 2. Integration possibilities in renewable energy supply network (after Zore et al. 2018).

The model is a multi-period model which considers monthly time periods for biomass, food and biofuels, and hourly time periods for solar, wind, and geothermal energy and electricity (Čuček et al., 2016). Due to larger computational time, the number of periods has been reduced to 6 periods per month and 4 periods per day (see Zore et al., 2018). The monthly patterns for wind speed are assumed from Cedar Lake Ventures (2017) and for solar irradiation from the JRC European Commission (2017). The daily patterns for wind speed are obtained from Mędrek et al. (2014) and for solar from Lockwood (2015). Finally, hourly patterns are obtained from Kaonga and Ebenso (2011) and Arif et al. (2013) for wind and solar. For geothermal energy, it is assumed that the available energy is constant. All the patterns are the same as in the model used for the continental-size supply network by Zore et al. (2018).

The demand for food and fuel is assumed that is constant, while the demand for electricity varies with time. The monthly patterns for electricity consumption are taken from Energy Cents (2010) and hourly patterns from Electropaedia (2005). Daily patterns for electricity consumption are assumed to be the same, and thus electricity demand patterns are assumed to be the same in each specific month. It is also assumed that all the zones in a specific country have the same demand for food, biofuel, and electricity. The demand for food (corn and wheat) should be satisfied in each country and at least 10 % of transportation fuels and a 20 % or larger share of electricity produced from renewable sources across the central EU should be satisfied.

Data for the biorefinery and food supply network are taken from Čuček et al. (2014), while for the electricity supply network they are obtained from the U.S. Energy Information Administration (2016), and for the sake of price change projections also from the U.S. Energy Information Administration (2013), as for the first case study. All other data are the same as in Zore et al. (2018). All the results are based on a 3 % interest rate and a 20 year lifetime.

Table 4 shows the main results when maximizing Economic and Sustainability profits at the micro, macro and wider macro levels. Additionally, the results at the macro and wider macro levels are shown where non-negativity constraints on the economic part in SP^{Macro} and $SP^{\text{Wider Macro}}$ are imposed (Economic > 0), so that the solutions obtained are truly sustainable from all three perspectives of sustainability. Note also that the solution at wider macro level possesses positive Economic profit at the micro level (24,914 M€/y) which is close to the one obtained when Economic profit at the micro level was maximized (31,944 M€/y). The main objective values are shown in bold.

From Table 4, it can be seen that from the microeconomic perspective, Economic profit is always positive and Eco- and Social profits negative. The considerably negative $P^{\text{Eco Micro}}$ shows that distribution and production of food, biofuel and renewable electricity in the Central EU from a company perspective is highly environmentally unsustainable. When SP^{Micro} is maximized, company profit decreases by 22 % (for 6,974 M€/y), but at the same time, $P^{\text{Eco Micro}}$ is increased by 28 % (for 9,044 M€/y) and $P^{\text{Social Micro}}$ by 7 % (for 61 M€/y).

Enforcing non-negative constraints on Eco- and Social profits cannot make them positive (the obtained solution is infeasible), since burdening the environment exceeds the unburdening when considering environmental effects only inside the company's line, and since producing biofuels and renewable electricity requires a larger number of employees, which represents a cost for the companies (Zore et al., 2017a).

Table 4. Results when maximising Economic and Sustainability profits for the second case study.

Economic items	**Maximization criteria**						
	Microeconomic perspective (company)		**Macroeconomic perspective** (company + government)			**Wider macroeconomic perspective** (company + government + employees)	
	$P^{Economic}_{Micro}$	SP^{Micro}	$P^{Economic}_{Macro}$	SP^{Macro}	$SP^{Macro}_{Economic>0}$	SP^{Wider}_{Macro}	$SP^{Wider\ Macro}_{Economic>0}$
$P^{Economic\ Micro}$ (M€/y)	**31,944**	24,970	31,695	2,169	26,419	-16,628	24,914
$P^{Eco\ Micro}$ (M€/y)	-31,520	-22,476	-31,397	-42,721	-34,254	-45,794	-34,108
$P^{Social\ Micro}$ (M€/y)	-855	-794	-856	-26,943	-2,816	-48,468	-9,703
SP^{Micro} (M€/y)	-432	**1,700**	-558	-67,495	-10,651	-110,890	-18,897
$P^{Economic\ Macro}$ (M€/y)	14,710	10,003	**14,930**	-52,788	0	-75,456	0
$P^{Eco\ Macro}$ (M€/y)	17,721	22,622	18,277	115,261	44,017	108,000	37,263
$P^{Social\ Macro}$ (M€/y)	1,086	1,004	1,083	28,955	5,704	42,123	9,095
SP^{Macro} (M€/y)	33,517	33,630	34,290	**91,427**	**49,720**	74,667	46,358
$P^{Economic\ Wider\ Macro}$ (M€/y)	14,710	10,003	14,930	-52,788	0	-75,456	0
$P^{Eco\ Wider\ Macro}$ (M€/y)	17,721	22,622	18,277	115,261	44,017	108,000	37,263
$P^{Social\ Wider\ Macro}$ (M€/y)	3,622	3,375	3,624	99,712	10,860	178,642	36,166
$SP^{Wider\ Macro}$ (M€/y)	36,053	36,000	36,831	162,185	54,876	**211,187**	**73,429**
Circularity (%)							
- material	36.09	42.73	36.20	35.38	36.14	35.39	36.16
- heat	24.70	30.80	21.80	19.90	20.90	20.20	21.40
- electricity	20.00	20.00	20.00	100.00	40.74	100.00	36.22

By maximizing Economic and Sustainability profit at the macro level, all the results are positive, except for Economic profit when maximizing SP^{Macro}. Therefore, additional columns are added which include the non-negativity constraint on $P^{Economic\ Macro}$. If an additional constraint is specified for Economic profit to be non-negative ($P^{Macro\ Economic\ >0}$), $P^{Economic\ Macro}$ drops to the lower limit of 0 M€/y, while $P^{Eco\ Macro}$ and $P^{Social\ Macro}$ remain positive. Both Eco- and Social profits are decreased; however, truly sustainable solutions can be obtained while achieving non-negative Economic profit. When comparing the results of maximizing $P^{Economic\ Macro}$ and $SP^{Macro,\ Economic>0}$, it can be seen that by reducing $P^{Economic\ Macro}$ from 14,930 M€/y to 0 M€/y, $P^{Eco\ Macro}$ increases by 25,740 M€/y (from 18,277 M€/y to 44,017 M€/y) and $P^{Social\ Macro}$ by 4,621 M€/y (from 34,290 M€/y to 49,720 M€y).

When comparing the results obtained from optimizations at the macro and wider macro levels, it can be seen that slightly worse levels of Economic and Eco-profits are obtained and significantly better levels of Social profit at a wider macro level, since at this level the social part has a greater impact. Additionally, it includes individuals; see also Fig. 1. In both cases Economic profit is negative, while both Eco- and Social profit are positive. If in addition a non-negativity constraint on Economic profit is set (last column in Table 4), Economic profit becomes 0, while both Eco- and Social profit are significantly reduced; however, again the obtained result is truly sustainable.

For all the alternatives, Social profit is negative at the micro level and positive at the macro and wider macro levels. The greatest Social profits are always obtained at the wider macro levels when taking into account the employee perspective that considers their salaries.

The circularity indicator for materials is in the range of approximately 35-43 %, for heat it is in the range of about 20 to 31 % and for electricity between a lower limit of 20 % up to 100 %. The greatest material and heat circularity is obtained when maximizing SP at the micro level, and the highest electricity circularity (electricity produced from renewable sources) when maximizing SP at the macro level.

Table 5 further shows the main results in terms of area used, percentage of demand satisfied, raw materials and technologies used.

From Table 5 it can be seen that all of the available area (11 %) is used for the production of food, biofuels and renewable electricity. Additionally, a certain percentage of the area is usually suggested to be afforested (0.004 %) except when SP^{Micro} is maximized (1.22 %) or when SP^{Macro} and $SP^{\text{Wider Macro}}$ (0 %) are maximized. For the additional land area used for biofuel production (up to 2 %), an eco-cost coefficient of 0.5 €/m^2 is assumed (Hendriks and Vogtländer, 2004). If afforestation is selected, it represents an unburdening of the environment (an eco-benefit). Afforestation could thus yield additional Eco-profit.

Another interesting observation is obtained when maximizing SP^{Macro} and $SP^{\text{Wider Macro}}$. In these cases, the entire demand for electricity is satisfied, owing to the high eco-benefit from solar and wind energy. Besides the comparatively higher Eco-profit, significantly higher Social profit is also obtained, given the higher number of employees needed (2,857,206 and 3,862,142) and their higher salaries in the electrical sector than in the agricultural one; see also Table 4.

Table 5. Main results for the second case study in terms of raw materials, technologies and products.

Supply network items	Maximization criteria						
	Microeconomic perspective (company)		**Macroeconomic perspective** (company + government)			**Wider macroeconomic perspective** (company + government + employees)	
	$P^{Economic}_{Micro}$	SP^{Micro}	$P^{Economic}_{Macro}$	SP^{Macro}	$SP^{Macro}_{Economic > 0}$	$SP^{Wider\ Macro}$	$SP^{Wider\ Macro}_{Economic > 0}$
Area used (%)	11.00	11.00	11.00	11.00	11.00	11.00	11.00
afforested (%)	0.004	1.22	0.004	-	0.004	-	0.004
Food demand satisfied (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Fuel demand satisfied (%)							
gasoline	44.75	33.22	40.58	38.72	39.73	38.92	40.38
diesel	12.11	10.00	15.24	14.59	16.25	14.43	15.66
Electricity demand satisfied (%)							
produced total	20.00	20.00	20.00	100.00	40.74	100.00	36.22
from wind	20.00	20.00	20.00	22.20	20.98	-	17.36
from solar	-	-	-	70.80	19.76	100.00	18.86
from geothermal	-	-	-	-	-	-	-
Raw materials (kt/y)							
corn stover	14,862	14,862	14,862	14,862	14,862	14,862	14,862
wheat straw	37,970	37,970	37,970	37,970	37,970	37,970	37,970
miscanthus	34,322	11,080	33,747	34,500	34,091	34,456	34,024
forest residue	0.495	125	0.422	-	0.495	-	0.495
algae	-	-	-	-	-	-	-
cooking oil	1,556	1,556	1,489	-	1,556	-	1,556
Technologies*:							
hydrogen[1]	●		●		●		●
dry-grind process[2]							
syngas fermentation[3]	●	●	●	●	●	●	●
catalytic synthesis[4]							
FT synthesis[5]	●	●	●	●	●	●	●
WCO methanol[6]	●	●	●		●		●
WCO ethanol[7]							
algae methanol[8]							
algae ethanol[9]							
photovoltaics (km^2)	-	-	-	3,061	710	4,257	760
wind turbines	34,432	34,432	34,342	40,542	36,916	-	27,880
binary cycle geothermal plants	-	-	-	-	-	-	-
Food (kt/y)							
corn grain	24,769	24,769	24,769	24,769	24,769	24,769	24,769
wheat	37,226	37,226	37,226	37,226	37,226	37,226	37,226
Biofuels (kt/y)							
ethanol	18,000	13,293	15,453	14,226	14,884	14,350	15,298
green gasoline	1,253	974	1,682	1,931	1,801	1,909	1,723
et-diesel**	-	-	-	-	-	-	-
me-diesel***	1,493	1,493	1,430	-	1,493	-	1,493
FT-diesel	4,714	3,665	6,329	7,265	6,775	7,182	6,483
hydrogen	1,467	1,367	1,449	1,425	1,441	1,439	1,445
Number of employees	101,309	91,816	100,403	2,857,206	742,500	3,862,142	771,591

*technologies:

[1]gasification and lignocellulosic hydrogen production (Martín and Grossmann, 2011a),

[2]dry-grind process (Karuppiah et al., 2008),

[3]gasification and syngas fermentation and [4]gasification and catalytic synthesis of lignocellulosic biomass (Martín and Grossmann, 2011b),

[5]gasification, FT synthesis and hydrocracking (Martín and Grossmann, 2011c),
[6]biodiesel production from waste cooking oil with methanol, and [7]ethanol, and from [8]algal oil with methanol (Martín and Grossmann, 2012), and [9]ethanol (Severson et al., 2013);
**biodiesel produced using ethanol and ***methanol as alcohol.

All the criteria prefer production of gasoline substitutes, which ranges between 33.42 and 44.75 % of the demand, and also between 10 and 16.25 % of the demand for biodiesel substitutes is satisfied. From a purely economic standpoint, higher substitution of gasoline should be implemented (from 40.58 % to 44.75 %), while from a sustainability viewpoint, the production of gasoline substitutes is slightly lower (from 33.22 % to 40.38 %). Diesel substitutes are preferred from overall sustainability viewpoints (up to 16.25 %) and also from the economic viewpoints (up to 15.24 %). Only when maximizing SP^{Micro} is the production of diesel substitutes set to its lower limit (10 %). The reasons for such choices are the prices of the products and on the environmental side the eco-cost coefficients (see Zore et al. 2018). Note that the differences in the shares of biofuels substitution are comparatively lower than in the shares of renewable electricity production. From these results, it can be seen that 100 % of the food demand, 10 % substitution of fuel demand and 20 % of the renewable electricity share are more than satisfied by only adding about 3 % of the area.

The share of renewable electricity production ranges between the lower and upper limits (20 and 100 %). From microeconomic perspectives and pure economic viewpoints, renewable-based electricity is produced at the lower limit. On the other hand, from sustainability criteria at the macro and wider macro levels, renewable electricity produced is set at the upper limit, because electricity produced from renewable energy sources has significant unburdening effects as it substitutes for the conventional electricity production mix (Čuček et al., 2012b) and it employs a larger number of workers. When non-negativity constraints on Economic profit are imposed, the share of renewable electricity produced is between 36.22 and 40.75 %. Results vary significantly with the price of electricity. The market price of renewable electricity is considered to be 50 €/MWh, and the electricity price with included subsidies is 100 €/MWh (Zore et al. 2018).

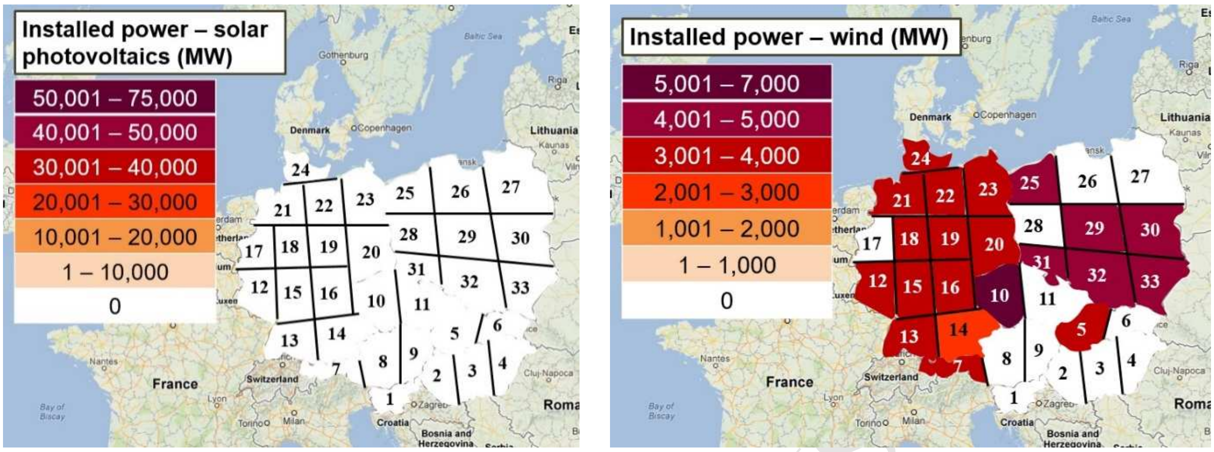
Electricity generated from wind turbines is preferred over photovoltaics and especially over geothermal energy, which is not selected, mainly on account of its lower energy potential, since only electricity without thermal production is considered (see also Zore et al., 2018). The number of wind turbines selected is similar regardless of the optimization criteria (between 34,432 and 40,542); only when maximizing $SP^{\text{Wider Macro}}$ can a larger drop be noticed. This drop occurs because solar energy requires a larger number of employees for construction and maintenance than wind energy and is therefore preferable from the employee perspective (for the data relating to number of jobs per MW see Table 1) . The area of photovoltaic panels selected can be up to 4,257 km^2 in a case where none of the wind turbines is selected. Using this area, 100 % of the electricity required could be produced.

In regards to the raw materials used, it can be seen that the amount of corn and wheat grains is the same for all the alternatives and is such as to satisfy the demand for food. Consequently, corn stover and wheat straw could also be used for biofuel production. It can be seen that they are set at their upper limits of availability (related to grains used). The differences between the alternatives, on the other hand, occur in the amounts of miscanthus, forest residues and cooking oil in use. Miscanthus is used in similar amounts (around 34,000 kt/y) except in the alternative where a higher percentage of area is suggested to be afforested (when maximizing SP^{Micro}). Forest residue is used in the amounts needed for afforestation in only those alternatives where afforestation is selected. Cooking oil is also used in similar amounts (around 1,500 kt/y) except for the alternative where SP is maximised at the macro and wider macro levels. Algae are not selected either from the economic viewpoint or from the sustainability viewpoint.

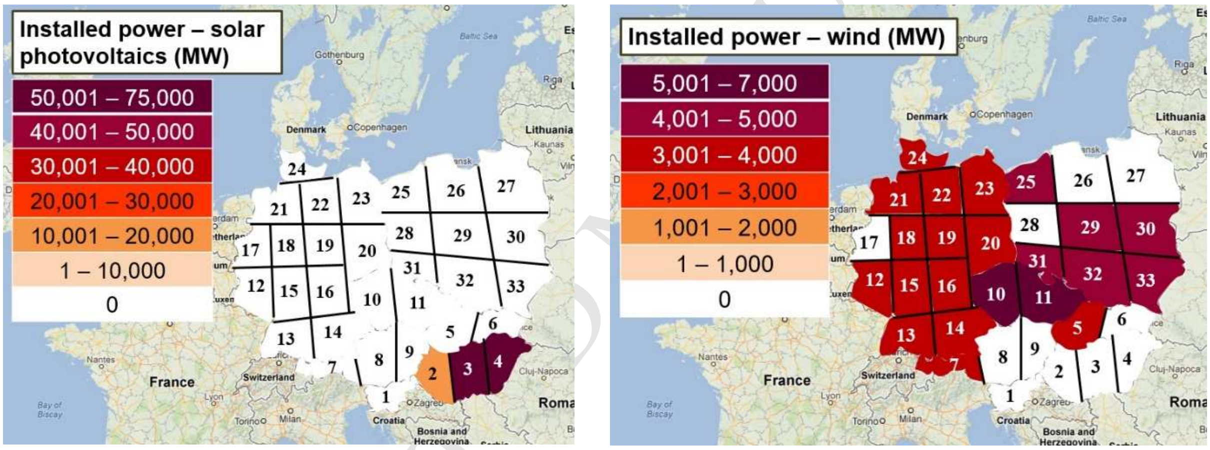
Most of technologies for producing biofuels have been selected except the dry-grind process, lignocellulosic biomass gasification and catalytic synthesis and algae transesterification. Waste cooking oil is suggested to be treated by transesterification by using methanol as a catalyst. Fewer technologies are selected when maximizing SPs at all micro, macro and wider macro levels. If Economic profit is forced to be non-negative, the supply network is more constrained, and in these alternatives, all the technologies are selected which would otherwise be selected.

Maximization of *SP* from:

a) Microeconomic perspective (company)



b) Macroeconomic perspective (company + government)



c) Wider macroeconomic perspective (company + government + employees)

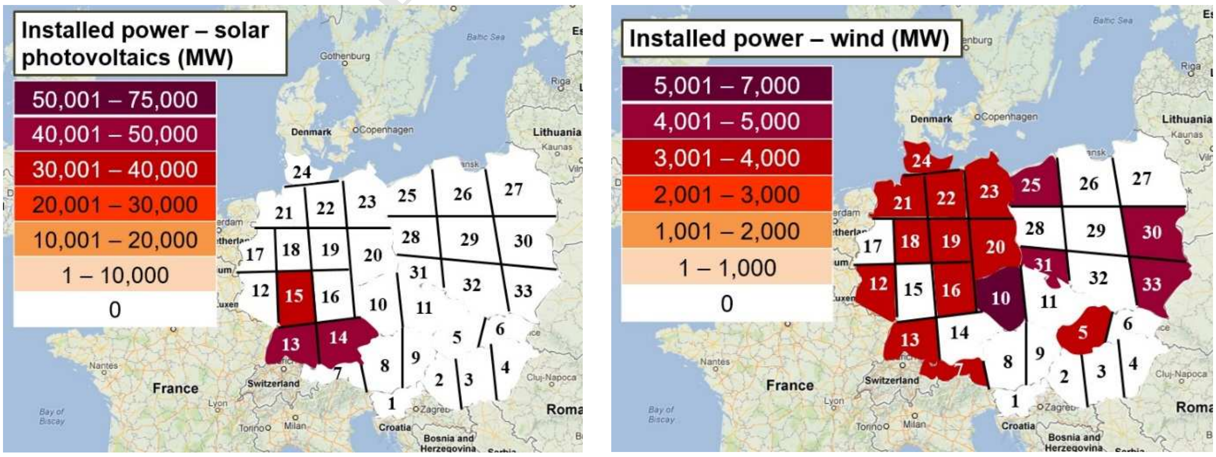


Fig. 3. Distribution of installed photovoltaic panels and wind turbines across Central EU.

From Table 5, it can be seen that the number of employees differs significantly. The lowest number of employees is suggested at the micro level and also at the macro level from the economic viewpoint. On the other hand, the number of employees increases by an order of magnitude when looking from the sustainability perspective at the macro and wider macro levels. When restricting Economic profit to being at least non-negative, the number of employees selected is in between. Results suggest that only 92,000 employees could satisfy the demand. From the sustainability viewpoint, up to 3,862,142 employees could find new jobs.

Fig. 3 further represents the locations of selected installations of solar photovoltaics and wind turbines, when maximizing *SP*, from all three perspectives.

Solar photovoltaics is only selected from the macroeconomic and wider macroeconomic perspectives (see also Table 5). At the macro level the most sustainable locations are in Hungary, while at wider macro level, the selected locations are in southern Germany, especially in Bavaria, owing to the larger number of employees with higher salaries.

Fig. 3 also shows that more locations are suitable for wind turbines than for the solar installations. Wind power is selected at all levels across most zones in the Central EU, except in eastern Austria, eastern Czech Republic, Hungary, northeast Poland, eastern Slovakia, and Slovenia. As mentioned earlier and seen in Table 5, geothermal energy is not selected.

Maximizing *SP* largely promotes a circular economy and renewable electricity production. The results indicate that even despite some negative values, “green technologies” are still a sustainable solution. The economic criteria prefer solutions which are less friendly to the environment and community, and when maximizing *SP*, such alternatives are preferred that are environmentally more unburdening and less burdening.

5. Conclusions

In this paper, the concept of Sustainability Profit (SP) was upgraded to the level that includes the views of: i) company, ii) company and country (government) and now additionally iii) company, country (government) and individuals (employees). Additionally, the general formulation of calculating SP based on weights for specific pillar has been presented and the formulation of Sustainability profit based on non-negativity constraints for all the pillars. As before, SP is composed of Economic, Eco-, and Social profit and is expressed in monetary units that are easily understandable by the wider population. Besides SP, circularity indicators were included which measure the fraction of circulated feedstocks and energy in the total amounts of feedstocks and energy. Note that the circularity indicator for energy has been proposed in this paper.

A comparison between the different perspectives (micro, macro, and wider macro) and different views on sustainability (maximum SP, maximum SP with non-negativity constraints on $P^{Economic}$, P^{Eco} and P^{Social}) and their influence on the final results have been demonstrated on two case studies: hypothetical electricity production from various sources and a larger-scale food, biofuel and renewable electricity supply network.

The first case study shows that using technologies such as solar, wind, biomass and geothermal energy are the most sustainable. The *SP* was always positive, while the Economic profit had a negative value from a macroeconomic perspective, showing that financial support or higher market prices for electricity could be justified. Circularity indicator for material has been around 0.3 when all the renewable sources were selected (due to corn silage used in biogas plant) and 0 in case of fossil sources selected. The indicator for electricity has been either 1 for alternatives where all the electricity was produced from renewable sources or 0 where electricity was produced from natural gas and coal.

The second case study represents a supply network for the production of food, biofuels and renewable electricity production at the level of the Central EU. Currently around 8 % of land is used for production of corn and wheat in the EU (FAOSTAT, 2018), and by using an additional 3 % of the land, 100 % of food, a significant amount of biofuel (almost 41 % of gasoline and more than 16 % of diesel substitutes) and almost 41 % of the electricity (see Table 5) could be sustainably produced.

However, for most of the technologies used in the second case study, several barriers exist to becoming widely used for mass production of biofuel. Most of the technologies for biofuel production are second and third generation technologies that have not yet been commercialized (Karimi and Chisti, 2015); moreover, several barriers exist in terms of the availability and cost of raw materials such as algae (Oh et al., 2018). It should also be noted that in real world, such efficiencies might not be attained. Additionally, since several mitigation technologies for reducing environmental burdens do exist, system specific eco-cost and eco-benefit coefficients might provide more accurate and optimized results. This issue will be dealt with in future works.

The proposed generalised concept of Sustainability profit at different levels can contribute to more sustainable thinking regarding production systems. As the proposed concept integrates industrial ecology, circular economy and supply network perspective, it offers a practical tool for more sustainable business decisions. The aggregate monetary-based single measure of sustainability based on different views (company, government plus company, government plus company plus individuals), including the possibility of selecting suitable weights between the sustainability pillars, will be an efficient supporting tool for decision-making. The second case study clearly indicates that considering sustainability from the wider macro perspective (government plus company plus individuals) would enable obtaining solutions that are significantly more sustainable than those from micro (company) perspective (211,187 M€/y vs. 36,053 M€/y), which would allow governments to plan efficient subsidy schemes for enhancing cleaner production at zero or close to zero waste. However, it should be noted that more work should be performed relating to the data for Eco- and Social profit calculations.

Additionally, the circularity measures within the closed-loop supply networks which provide the levels of sustainable (re)use of energy and materials can assist in contributing to increased circular economy in practice. Future studies should be oriented towards combining Process Integration principles and supply network synthesis in order to obtain truly sustainable production systems. Finally, more detailed circularity assessment in supply chain networks should be performed to account for the time and value dimension of energy and waste recovery and material recycling.

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Highlights

- Sustainability Profit has been upgraded for a wider macroeconomic perspective.
- Employee perspective is added to the company and government perspectives.
- Sustainability Profit is studied in relation to energy and mass circularity indicators.
- It is applied to the synthesis of a large scale, renewable energy supply network.
- Sustainable solutions exhibit high sustainability profits and high circularity indicators.