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Towards a Sustainable Future – Life Cycle Management

Challenges and Prospects

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Springer

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ISBN 978-3-030-77126-3 ISBN 978-3-030-77127-0 (eBook)
https://doi.org/10.1007/978-3-030-77127-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Sustainable future – now the dream of poor, middle-income, and rich generations. Therefore, the sustainable development goals are the blueprint for achieving a better and more sustainable future for all. They address the global challenges we face, including environmental degradation and climate change. This book concentrates on issues connected with different aspects influencing environment state and its core idea focused both on the life cycle concept and life cycle management. It includes present contributions on different aspects of making life cycle thinking and product sustainability operational for businesses aiming for continuous improvement, especially striving towards reducing their footprints and minimizing their environmental and socio-economic burdens.

This book presents current scientific and business achievements in the field of life cycle management (LCM), providing methodological and formal development along with practical application, and is the source of theoretical background/knowledge and practical templates. Moreover, some aspects of circular economy–based approaches are highlighted. The book presents new points of view, including regionalities, and it is equipped with the examples coming from around world, especially from all over Europe, including central and eastern European countries.

One of the main ideas of this book is to bring together presentation from the world of science and world of enterprises as well as institutions supporting economic development. This extorts the topics to be more focused on the practical aspects of product life cycle management. The structure of the work is based on five themes. The themes represent different objects and are focused on sustainability and LCM practices mainly related to: products, technologies, organizations, markets, and policy issues as well as methodological solutions.

Undoubtedly, the area of methodological solutions is still of great interest in LCM scientists and practitioners' community. In one chapter, the way in which technology-driven society, facing new environmental challenges, encourages more and more companies' key decision-makers to be committed to limit the impact of their products and services on the environment is presented.

Taking into consideration the fact that ecodesign approaches have shown the potential to increase companies' global value proposition and that the integration of environmental parameters at an early stage of the design process will only be possible if such approach is tailored to a specific sector and customer expectations, the proposal of transposable and replicable action-step methodology facilitating the creation of a common language and enabling the translation of environmental commitments into functional requirements was elaborated and is presented in this work.

At present, an increasing joint use of Life Cycle Assessment and Data Envelopment Analysis (LCA + DEA) as an emerging research field when evaluating many similar entities in the framework of eco-efficiency and sustainability, may be observed. In addition, an interesting attempt to enhance life cycle management through the symbiotic use of data envelopment analysis, showing innovative advances in LCA + DEA analyses, is presented. It reveals the situation within the tertiary sector, exploring the novel advances offered regarding the application of the well-established five-step method for enhanced sustainability benchmarking.

The main interests for LCM practitioners are focused on products area – an interesting example is presented in the chapter showing life cycle assessment benchmark for wooden buildings in Europe. Despite the fact that LCA and the EU-recommended environmental footprints (EF) are well known and accepted tools to measure a comprehensive set of environmental impacts throughout a product's life cycle, the assessment of level of environmental performance of wooden buildings is still a challenge. Based upon the EU recommendations for a benchmark of all kinds of European dwellings, a scenario of a typical European wooden building was developed. The developed benchmark for wooden buildings is a suitable comparison point for new wooden building designs. This benchmark can be used by architects and designers early in the planning stages – when changes can still be made to improve the environmental performance or to communicate and interpret LCA results for customers and other stakeholders.

As usual, there are several chapters focused on sustainability and LCM practices related to different technologies. Some of them concentrated on different aspects of analyses dealing with municipal solid waste management. Among others there is the presentation of framework for the systematic analysis of the material flows and the life cycle environmental performance of municipal solid waste management scenarios. This framework is capable of predicting the response of waste treatment processes to the changes in waste streams composition that inevitably arise in municipal solid waste management systems. The fundamental idea is that the inputs and outputs into or from treatment processes are previously allocated to the specific waste materials contained in the input waste stream. Aggregated indicators like life cycle environmental impacts can then be allocated to waste materials, allowing systematic scenario analyses. The given chapter framework is generic and flexible, and can easily be adapted to other types of assessments such as economic analysis and optimization.

Specific aspects of issues focused on sustainability and LCM practices related to application in different organizations are also presented in several chapters. In one case study, an interesting dilemma, "is environmental efficiency compatible with economic competitiveness in dairy farming?" is considered on the base of study of Luxembourgish farms. The main aim of this study is to investigate both environmental and economic performances of dairy farms in order to assess possibilities and limits of improving economic competitiveness via increasing environmental efficiency. Analysis of four LCA-impact environmental categories and three economic ones shows that a sustainable dairy production with less environmental impact in all considered categories is also of advantage in terms of farm economic competitiveness. The case study proves that a high environmental performance is not only of advantage in terms of economic competitiveness, but is even a necessary prerequisite for best economic performances. Other interesting application of LCM in organization is shown on the example of international non-governmental organization practicing in the social and environmental sector. Thanks to environmental focus considered NGO is interested in assessing the environmental impacts of its own activities throughout the whole value chain and therefore, an Organizational Life Cycle Assessment study had been conducted for one NGO community.

Markets and policy issues are specific field for LCM application. Among others, specific problems generate the fact that wind power generation is weather-dependent and that at a high penetration rate, storage systems such as power-to-gas may become necessary to adjust electricity production to consumption. One chapter presents the environmental life-cycle performance of wind power accounting for the energy storage induced by the temporal variability of weather-dependent production and consumption. A case study in which wind power installations are combined with a power-to-gas system in Denmark to provide electricity according to the national load consumption profile is analyzed. Results highlight an increase, roughly by a factor two, of the carbon footprint coming from both energy storage infrastructure and induced losses, but remain significantly, at least ten times, lower than fossil counterparts.

The content of this monograph is the presentation of various examples of scientific and practical contributions, showing the incorporation of a life cycle approach into decision-making processes at the strategic and operational level. Special attention is drawn to show how to apply LCM to target, organize, analyze, and manage product-related information and activities towards continuous improvement, along the different products life cycle. The panorama of cases presents that LCM is a business management approach that can be used by all types of businesses and organizations in order to improve their sustainability performance. Thus, this book provides a cross-sectoral, present picture in LCM issues area.

The book presents chapters by scientists and researchers working in the field of sustainable development who have engaged in dynamic approaches to implementing widely understood sustainability. It guides the reader to understand the current issues of life cycle management and can be used apply product-related information to ensure more sustainable value chain management. The book encompasses many practical, methodological, and theoretical fields. Recently introduced to the technical and business vocabulary, term "LCM" is about a business management approach that can be used by all types of business and other organizations in order to improve their products' sustainability performance to promote better understanding among students and business professionals in the utility sector and across industries.

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Acknowledgments

This book is a selection of contributions of LCM 2019 conference held in Poznań, Poland. The series of life cycle management conferences is established as one of the leading events worldwide in the area of environmental, economic, and social sustainability. The 2019 conference motto "Towards sustainable future – current challenges and prospects in life cycle management" was chosen to focus on both current challenges and current prospects in the LCM field. In total, 502 abstracts from 41 countries were submitted. High quality of the contributions made it quite a challenge to select 26 papers for this book. They have been organized into five parts.

Due to core contribution of the authors and, in addition, due to the efforts of many colleagues and friends, this book became possible. We are very grateful for the support by members of scientific and business committees, namely acting as a co-chairs of this body: Anna Lewandowska, Joanna Kulczycka, Stefan Trzcieliński, and Zbigniew Kłos, as well as: Can B. Aktas, Stefan Albrecht, Joana Almeida, Martin Baitz, Fritz Balkau, Ligia Tiruta-Barna, Christian Bauer, Sandra Belboom, Catherine Benoit Norris, Alberto Bezama, Jan Bollen, Miguel Brandao, Birgit Brunklaus, Dorota Burchart-Korol, Julie Clavreul, Pierre Collet, Mauro Cordella, Helena Dahlbo, Francesco Del Pero, Andrea Di Maria, Johannes Drielsma, Jim Fava, Matthias Finkbeiner, Göran Finnveden, Matthias Fischer, Zenon Foltynowicz, Michele Galatola, Hans Garvens, Mark Goedkoop, Jeroen Guinée, Karen Hanghøj, Krzysztof Hankiewicz, Aranud Hélias, Almudena Hospido, Christine Roxanne Hung, Diego Iribarren, René Itten, Allan Astrup Jensen, Joanna Kałkowska, Renata Kaps, Kamil Kasner, Robert Kasner, Jędrzej Kasprzak, Regula Keller, Nicola Kimm, Martin Kirchner, Stephan Krinke, Michał Kulak, Martin Kurdve, Karin Lochte, Tim Lohse, Søren Løkke, Antonino Marvuglia, Paulo Masoni, Eric Mieras, Mark Mistry, Tiago G. Morais, Dominik Muller, Magdalena Muradin, Belmira Neto, Hanna Nilsson-Lindén, Mikołaj Owsianiak, Tiina Pajula, Elisabetta Palumbo, Nicholas Perry, Anna Petit-Boix, Marina Proske, Francesca Recanati, Patricia Reis, Emma Rex, Marcin Sadowski, Peter Saling, Roberta Salomone, Liselotte Schebek, Andreas Schiffleitner, Karsten Schischke, Sergiy Smetana, Guido Sonnemann, Dariusz Stasik, Sangwon Suh, Wojciech Sumelka, Nydia Suppen-Reynaga, Marzia Traverso, Georgios Tsimiklis, Sonia Valdivia, Marisa Vieira, Andy Whiting, Pia

Wiche, Joanna Witczak, Joanna Zarebska, Krzysztof Zarnotal, Rosalie Van Zelm, and Stefano Zuin. Their efforts in selecting the right mix of contributions were strongly valuable. Unfortunately the coronavirus disease influenced on the rhythm of preparation of this book, significantly prolonging this process.

We also want to thank two research group members at Poznań University of Technology and one research group member at Poznań University of Economics for all their support. From the very beginning, Krzysztof Koper was deeply engaged in organization of the 9th International Conference; he unfortunately left us before the conference. We also would like to acknowledge the technical support of Michał Trziszka, Krzysztof Hankiewicz, and Grzegorz Musioł.

Lastly, we direct our sincere thanks to our families for their patience and courtesy.

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Part I
Sustainable Products

Ecodesign as a New Lever to Enhance the Global Value Proposition: From Space to Corporate

Kévin Le Blévennec, An Vercalsteren, and Katrien Boonen

Abstract As our technology-driven society is facing new environmental challenges, more and more companies' key decision-makers are committing to limit the impact of their products and services on the environment. While ecodesign approaches have shown the potential to increase companies' global value proposition, the integration of environmental parameters at an early stage of the design process will only be possible if such approach is tailored to a specific sector and customer expectations. To support environmental experts in charge of organizing the integration of such approach in the design process of complex engineering systems, VITO retrospectively analysed a project initiated by the European Space Agency (ESA), from a product strategy perspective. A transposable and replicable action-step methodology facilitating the creation of a common language and enabling the translation of environmental commitments into functional requirements is resulting.

1 Introduction

1.1 Principles of Responsibility Driving Stronger Environmental Commitments

Launched in 2000, the United Nations Global Compact (UNGC) is both a policy platform and a practical framework for companies that are committed to sustainable business practices. It seeks to align business operations and strategies everywhere with ten universally accepted principles in support of achieving the Sustainable Development Goals by 2030. Over 12,000 organizations around the world, including 9953 companies, have joined the UNGC. Principles number 8, 9 and 10, respectively, mention that businesses should support a precautionary approach to environmental challenges, undertake initiatives to promote greater environmental

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_1

responsibility and encourage the development and diffusion of environmentally friendly technologies [1].

Within this global context, the objectives set in the EU's seventh Environmental Action Programme, entitled 'Living well, within the limits of our planet', gave rise to a political focus on the circular economy. The resulting Circular Economy Action Plan includes several measures covering the whole material cycle, from production and consumption to waste management and the market for secondary raw materials. The proposed actions, highlighting the essential role of the private sector, aim to contribute to the transition to a circular economy by 'closing the loop' of product life cycles through an increase of recycling and reuse, benefiting both the environment and the economy [2].

By signing the UNGC, companies are committing to a deliberate, responsible approach to the protection of the environment. It is often reflected in a policy to reduce environmental impacts and risks in various activities of the company. Due to the environmental challenges that our society is facing, new stakeholders such as investors are getting concerned and involved. Not only to comply with this evolving political framework, many key decision-makers have considered their commitment to the UNGC as a driver of ambitious environmental policies shaping new opportunities in their business practices and enhancing their global value proposition. To reinforce their commitment, goals are set in terms of energy, climate, waste, environmental management of the supply chain and increasingly concerning product design. More and more companies are now committing to a responsible approach which aims at limiting the impact of their products and services on the environment.

The role of product design is a key in the transition to a circular economy; the effective implementation of those environmental policies now targeting products could thus accelerate this transition. By recirculating products instead of throwing them out, not only is the value of products and components retained, but also the demand for virgin materials decreases, as do the energy demand and the production of (hazardous) waste. Product design heavily influences a product's life cycle impacts and is crucial for connecting different stages and actors along the life cycle.

1.2 From a Commitment to an Effective Implementation?

In many sectors, the regulatory and normative contexts as well as the pressure of markets are leading more and more companies to deepen a process characterized by the integration of environmental parameters since the design of products. Since the 1990s, engineers and designers, in joint efforts and gradually enriched, have defined an approach to those environmental concerns: ecodesign also defined as design for environment but with the same meaning – 'design with environment' [3].

In many situations, ecodesign demonstrated its effectiveness. By implementing this activity, companies have managed to reduce their costs, access new markets, develop new partnerships and arouse new investors' interest. Not only reducing products environmental impact, it has been proved as a concrete source of industrial competitiveness [4].

While benefits might be multidimensional, many ecodesign approaches also showed some limits. Their integration within existing company practices is key. Only a few organizational tools exist and are with difficulty transposable from one company to another. Integration of environmental parameters needs to be done in a collaborative way and using suitable tools, chosen in function of the company's size, maturity regarding ecodesign and existing design processes. The one-off intervention as well as the development of tools and methods only intelligible by environmental experts has sometimes showed the limit of ecodesign integration within companies. When implementing ecodesign activities, a deep understanding of the current business context has also been listed as a key success factor [5–7].

1.3 Challenges Related to Constrained Engineering Environments

Many authors have emphasized the importance of the business context: the integration of an ecodesign approach is progressive and needs to be tailored to the company's sector and customer expectations. If effective ecodesign approaches have shown their effectiveness in mass-consumer goods producers, the situation is not so advanced in business-to-business industries, even less for companies developing complex engineering systems.

In sectors such as the space and aerospace sectors, many companies are developing and offering a range of solutions along the critical decision chain. Their activities are mainly referring to business-to-business and/or business-to-government with customers oriented towards security, reliability and performance. Those solutions are evolving in a complex environment requiring an integration of an important number of functionalities and constraints to face up to any events and ensuring customers' security. Due to a possible evolving customer demand during the design process or again due to high prototypes costs, concurrent engineering methodologies are applied to ensure the critical dependencies of defined functional requirements. Complexity of those solutions mainly implies that those organizations are characterized by multiple highly specialized experts who infrequently communicate together [8].

Driven by performance and technological considerations, those companies are part of highly competitive markets in which value creation is at the heart of the concerns. The previous limited number of customer requests with regard to ecodesign and the specificity of product development life cycles did not lead most of internal actors to collaborate and anticipate this environmental parameter integration into design processes. While ecodesign approaches have shown the potential to increase companies' global value proposition, the integration of environmental parameters in the design process can still be considered as a constraint by many key actors. The following research question is thus appearing: how to organize the integration of an efficient ecodesign into the current design process of complex engineering systems?

2 Retrospective Analysis of the GreenSat Project

2.1 Objective and Methodological Approach

In order to reduce the risk of inactions of companies evolving in constrained engineering environment which have committed to limit the impact of their products and services on the environment, or again limit divergent or unfinished actions within those companies, the objective of this research is to develop a methodology supporting environmental experts in charge of organizing the integration of an ecodesign approach into the current design process of the solutions developed by their company.

Being the archetype of a constrained engineering environment, a case study within the space sector has been selected. In the GreenSat project initiated by the European Space Agency (ESA), VITO was commissioned (together with QinetiQ) to identify and select ecodesign options for the PROBA-V mission. A brief introduction to this study, focusing on the different steps having enabled the achievement of the project rather than on the results themselves, is provided in Sect. 2.2. Those results were fully described in the final report of the study [9].

Based on this case study approach and within the framework of its 'design for the circular economy' strategic research activities, VITO has retrospectively analysed this project from a product strategy perspective. The learnings and outcomes are reported in Sect. 2.3.

2.2 Introduction to the GreenSat Project

PROBA (PRoject for On-Board Autonomy) is a family of small satellites developed for ESA by QinetiQ Space and launched in 2013. The PROBA-Vegetation (PROBA-V) mission, an earth observation mission, was selected as a continuation of the Vegetation programme. The main payload of the PROBA-V satellite is the Vegetation instrument. Through the GreenSat project, ESA wanted to evolve from assessment to reduction of environmental impact through the redesign of an existing satellite mission and to check the feasibility of implementing ecodesign in the development of future space missions.

In a first step of the GreenSat project, a life cycle assessment (LCA) has been performed with the following objectives:

1. To identify environmental hotspots of the mission, which was considered as an important starting point to look for ecodesign options.
2. To quantify the environmental impact of the mission, to understand the impacts and the sources, which is a baseline to benchmark the environmental impact of the ecodesigned GreenSat mission and which allows to assess the environmental impact reduction.

Concerning the redesign of the mission, ESA identified initial requirements that would need to be adapted in case of a 'GreenSat' PROBA-V mission. In particular, the system should achieve equivalent function, meaning that the functional requirements should be almost all the same. As a consequence, while functional requirements should not be significantly different, design and operations requirements however could be significantly different.

The functional unit has been defined conforming to the space system LCA guidelines: 'one space mission in fulfilment of the mission's requirements'. The PROBA-V LCA includes all activities in the space and ground segment, but the launch segment was excluded. The life cycle impact assessment (LCIA) for PROBA-V was performed for the environmental impact categories and according to the defined LCIA methods as provided in the LCIA method in the ESA LCA database [10]. Given the relevance of critical materials use in space applications, an additional 'impact category (criticality – weighted)' that assesses the availability of raw materials, taking into account socio-economic constraints, has been defined.

Environmental profile of the PROBA-V mission was thus obtained. The LCA allowed identifying the environmental hotspots for the PROBA-V mission, which were considered most relevant to look at for the ecodesign exercise in the next study phase. Hotspots per mission phase were identified, and a distinction was made between the different levels the hotspot can relate to: materials, equipment and components, manufacturing processes, system, management and programmatic issues and regulation. If an environmental hotspot contributes to more than one impact category, its environmental importance was considered higher (Fig. 1).

As ESA has only little influence in the ground segment activities (e.g. energy use, data processing equipment), it was considered essential, and it has been decided to focus the ecodesign phase of the study on technologies where ESA has impact on. Starting from the identified environmental hotspots, ecodesign options for improving the environmental performance have been defined. For that, an external workshop was first organized at ESA concurrent design facility premises, with a wider group of stakeholders. Then an internal brainstorm was coordinated at QinetiQ Space, with experts specifically involved in the PROBA-V life cycle stages. A long list of ecodesign options was generated for space missions in general and PROBA-V in particular. As only a limited number of ecodesign options could be further developed in the framework of the GreenSat project, a selection process was applied to the full list of options.

As a first step, the analytic hierarchy process (AHP) methodology was used to select the 25 most promising options among the 70+ identified. AHP allows calculating weighting factors for the trade-off criteria, based on input from different

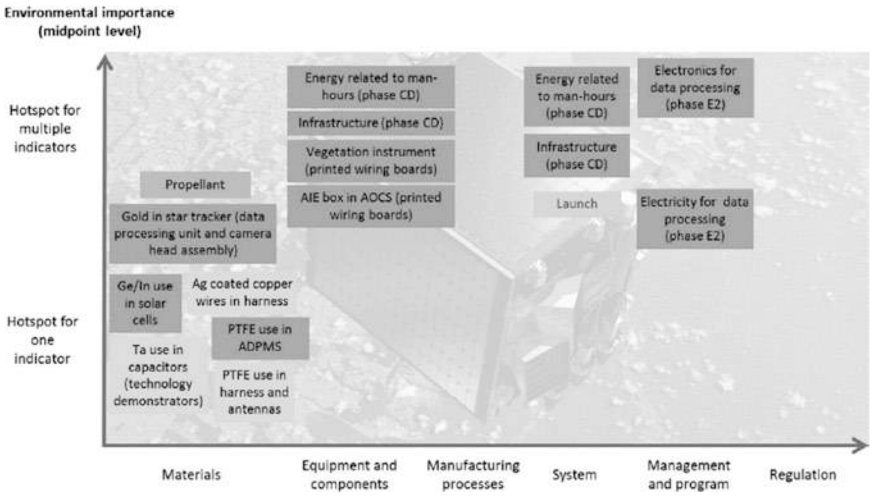

Fig. 1 Hotspots of the PROBA-V mission

stakeholders (brainstorm participants). Scores are then assigned to each ecodesign option by VITO and QinetiQ, which leads to a final ranking of all ecodesign options. This trade-off was based on specific criteria:

1. Solution implementation effort (cost, manhours, means)
2. Duration (time to market/launch)
3. Risk (feasibility, applicability, performance, availability of alternatives, flexibility)
4. Impact (operational cost)
5. Overall environmental impact
6. Reusability of the solution
7. Space relevance (technologies for the space segment, activities related to the space segment and their preparation that differ from other ground activities, system approach)

In a next step, a semi-quantitative analysis was done to assess the potential reduction of each option, leading to the down-selection of ten options. In a third step, an estimate of the required design and development effort and related environmental impact to estimate the risk of burden shifting was initiated, leading to the final selection of six options.

A technical assessment was then performed, and an analysis of the environmental effects was done by LCA. The analysis was done per option, at different levels (e.g. material, satellite production and mission). Finally, a combined analysis of the environmental impacts including the three most promising options, improved data processing, more sustainably produced germanium and optimized electronics, was performed to assess the overall reduction potential of the redesign of the PROBA-V mission.

Overall, it was concluded that the implementation of ecodesign from the start of a space mission design and development process can actually reduce the environmental impact of the space mission significantly. It was recommended to focus efforts in a first instance on the environmental hotspots of a space mission as this leads to the largest improvements. Improvements are related not only to the satellite production but also to the operational phase of the satellite (e.g. data processing). In addition to a final report, the results have been summarized and communicated through an infographic.

2.3 Retrospective Analysis from a Product Strategy Perspective

VITO aims to accelerate the transition towards a circular economy by providing advice to companies. As product design is key for enabling circularity, VITO decided to capitalize on the achievement of the GreenSat project for developing a methodology supporting environmental experts in charge of organizing the integration of an ecodesign approach into the current design process of complex engineering systems. An internal brainstorm session between 'circular economy assessment methods and indicators' and 'design for the circular economy' VITO experts has been organized. The objective of this session was to bring face to face those two research perspectives in order to detect essential factors for the development of the methodology.

Outcomes of this brainstorm session have been summarized (Tables 1 and 2). Elements listed in the project perspective (Table 1) refer to a specific action undertaken during the GreenSat project, as described in Sect. 2.2. Corresponding elements in the product strategy perspective (Table 2) refer to a derived analogy between this specific action and identified key success factors for an effective implementation of an ecodesign approach, as introduced in Sects. 1.2 and 1.3.

3 A Transposable and Replicable Resulting Methodology

The retrospective analysis of the GreenSat project from a product strategy perspective allowed illustrating key success factors for efficiently implementing an ecodesign approach with concrete specific actions undertaken during a project within a constrained engineering environment. Based on those analogies (Tables 1 and 2), the creation of a common language ensuring the compatibility of the stakeholders' different sources of value creation appears to be essential for efficiently implementing an ecodesign approach. Necessary actions facilitating the creation of this common language thus originate from this analysis.

By organizing those necessary actions and generalizing some elements specific to the GreenSat project, the following action-step methodology enabling the creation of this common language has been developed (Table 3).

Table 1 Outcomes of internal brainstorm session bringing face to face two research perspectives – part 1

Element	Project perspective
1.	[…] project initiated by the European Space Agency (ESA), VITO was commissioned by QinetiQ […]
2.	[…] With the GreenSat project, ESA wanted to check the feasibility of implementing ecodesign in the development of future space missions […]
3.	[…] The system should achieve equivalent function, meaning that the functional requirements should be almost all the same […]
4.	[…] Conform to the space system LCA guidelines […], […] ESA LCA database […], […] Given the relevance of critical materials use in space applications, an additional 'impact category' […] has been defined […]
5.	Figure 1 Hotspots of the PROBA-V Mission, […] communicated through an infographic […]
6.	[…] As ESA has only little influence in the ground segment activities (e.g. energy use, data processing equipment), it was considered essential, and it has been decided to focus the ecodesign phase of the study on technologies where ESA has impact on […]
7.	[…] An external workshop was first organized at ESA concurrent design facility premises, with a wider group of stakeholders. Then an internal brainstorm was coordinated at QinetiQ Space, with experts specifically involved in the PROBA-V life cycle stages […]
8.	Analytic Hierarchy Process (AHP) methodology
9.	Specific criteria used for the AHP methodology
10.	[…] Per option, a technical assessment was performed and an analysis of the environmental effects was done by LCA […]
11.	[…] Implementation of ecodesign from the start of a space mission design and development process can actually reduce the environmental impact of the space mission significantly […]

All these actions-steps are further explained:

1. The project was initiated by ESA which wanted to reduce the environmental impact of their product. ESA through the ESA Clean Space initiative supports the UNGC, having a Committee on the Peaceful Uses of Outer Space: 'States and international intergovernmental organizations should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets and that maximize the use of renewable resources and the reusability or repurposing of space assets to enhance the long-term sustainability of those activities' [11]. The commitment of key decision-makers is thus the real starting point of this project. To integrate environmental parameters at an early stage of a design process, it is essential to have the internal support of companies' key decision-makers. To convince them, it will be essential to demonstrate that the ecodesign approach will benefit the company's environmental strategy. Listing all environmental commitments associated with products and services is thus considered as a first step.
2. The GreenSat project reflected an efficient external collaboration between three main stakeholders. Based on identified environmental commitments associated

Table 2 Outcomes of internal brainstorm session bringing face to face two research perspectives – part 2

Element	Product strategy perspective
1.	External collaboration between three stakeholders. ESA being the customer. QinetiQ being the industrial partner collaborating with VITO for their environmental expertise
2.	Description of the project objective showing a customer interested in the implementation of an ecodesign approach
3.	System driven by performance. While having the objective to reduce the environmental impacts, environmental and industrial sources of value creation should be compatible
4.	Tailoring of existing tools (guidelines, database, impact category) to a specific business context, i.e. space sector
5.	Intelligibility of results adapted to interested stakeholders
6.	Focus on customer sources of value creation
7.	Collaboration between highly specialized experts from different fields
8.	Use of a specific methodology for connecting highly specialized experts' inputs
9.	Criteria including parameters being source of value creation for all stakeholders: Customer, industrial, environmental
10.	Ensure the compatibility of industrial and environmental sources of value creation
11.	Early stage integration of environmental parameters

Table 3 Definition of an action-step methodology for organizing the integration of an efficient ecodesign approach

Number	Action step
1	List environmental commitments associated with products and services
2	Identify the right stakeholders
3	Understand individual value creation processes
4	Connect individual value creation processes
5	Deliver efficient messages

with products and services, it is essential to understand what expertise(s) and thus which stakeholder(s) will be required to collaborate for achieving those commitments. For instance, if a commitment refers to the use of a minimum recycled content for materials of specific products, involving the engineering teams, the marketing and/or the purchasing department might be relevant. If relevant expertise cannot be identified internally, involving the right external stakeholders is also determining.

3. The retrospective analysis highlighted that a factor for ensuring an external collaboration between highly specialized experts from different fields, with regard to the integration of environmental parameters, was to ensure the compatibility between different sources of value creation. In this case study, the search of ecodesign options was, for instance, reduced to ESA's scope of actions, and the AHP methodology was integrating parameters' source of industrial competitiveness but also benefiting the environment. Before ensuring their compatibility, it

is thus essential to understand individual ‘business languages’ and how each of the identified stakeholders individually creates value for their company or own departments within an organization. An analysis of individual stakeholders’ value creation processes is thus recommended.

4. Once individual stakeholders’ value creation processes are understood, the objective is to ensure their compatibility. For that, there is a need to develop tailored tools and practices ensuring the creation of a common language between those stakeholders. ESA LCA guidelines and database are a concrete example. The space sector has unique characteristics like low production rates, long development cycles and specialized materials and processes, and the sector’s activities create impacts on environments generally not considered in LCA. Issued in 2016, these guidelines aim to establish methodological rules for performing space-specific LCA. A methodology mostly used by environmental experts is thus tailored to a specific business context thus facilitating the communication and exchange of information with highly specialized engineers.
5. Also shown with the analysis of the GreenSat project, intelligibility of results was considered as determining in this collaborative process. The described matrix (Fig. 1) is, for instance, translating results often only intelligible by LCA experts into clear messages in a language perfectly intelligible for a system engineer. Once tailored tools and practices have been developed, it is thus key to ensure their effective use. The last step of this methodology thus emphasizes the fact that results need to be illustrated and intelligible for non-environmental experts. This last step is also a key for delivering convincing arguments to relevant stakeholders.

By following the different steps of this methodology, the translation of environmental commitments into functional requirements should be facilitated for environmental experts in charge of organizing the implementation of an efficient ecodesign approach into their companies.

4 Conclusion

This case study within the space sector demonstrated that implementing an ecodesign approach could enhance companies’ global value proposition by ensuring a compatibility of stakeholders’ sources of value creation during the integration of environmental parameters at an early stage of the design process. Originating from a retrospective analysis from a product strategy perspective of this space project, an action-step methodology supporting environmental experts in charge of organizing the integration of an ecodesign approach into the current design process of the solutions developed by their company has been defined. While arising from a case study in a constrained engineering environment, this methodology could be replicated in different sectors and applicable to external as well as internal collaborations. In a next applied research step, ‘design for the circular economy’ VITO experts aim to test and validate this methodology with different use cases to finally propose this methodology as a service, in order to support the private sector in accelerating the transition towards a more circular economy.

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The "Environmental Activation Energy" of Modularity and Conditions for an Environmental Payback

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Abstract Similar to the meaning of "activation energy" in physics and chemistry, there is a certain environmental investment needed for some circular design approaches: On the example of modular mobile devices, the additional environmental impact of implementing "modularity" is explained. This additional impact can be overcompensated through lifetime extension effects, if the design and related business models trigger the intended circularity effect. The paper systematically categorizes the different variants of modularity, explained on the example of smartphones. Each modularity approach features specific circularity aspects, including repair, upgrade, customization as a means to not over-spec a product, reuse and repurposing of modules. These life cycle management aspects are discussed on the example of various smart mobile products.

1 Introduction

Activation energy is the energy which must be provided to trigger a chemical reaction. Similarly, to foster a better environmental life cycle performance of a product in most cases, an additional initial manufacturing effort is needed in support of a circular design: Increased reliability might require high-quality materials, better

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_2

robustness can be achieved with higher material intensity, and reparability requires a modular instead of a monolithic design. Also design for recycling might require initially design changes, which do not reduce manufacturing impacts – but are supposed to reduce impacts at end-of-life significantly. Only the use of recycled materials, as a circular design approach, tends to reduce environmental impacts right in the production phase. Figure 1 shows the comparison of an iPad with a mobile computer, which was designed with several circular design strategies in mind, such as:

- Better compatibility with accessories (see the nine-pin serial port and the RJ45 Ethernet connector, which are not found in conventional tablet computers).
- Exchangeable connector blends to allow for a shell reuse in case of changing internal electronics.
- Wood as sustainable material, which does not allow similarly small form factors as metals.
- Reparability and replaceable battery, etc.

For a more comprehensive overview of design features of this mobile computer, see Ospina et al. [1]. What is evident is the significantly larger form factor, more total material use of the circular design approach.

With this in mind, our research suggests the term “environmental activation energy” to illustrate the fact that circular design requires additional efforts – and bears the risk that these additional efforts might not pay off as expected in later product life cycle phases. Our research focusses on several examples of modular

Fig. 1 Mobile computer designed by an SME following circular design principles compared to an iPad (fifth generation)

design, as one prominent circular design approach in support of better reparability, reusability, upgradeability and recyclability.

2 Life Cycle Assessment of Modularity

With a range of examples from latest design research, the environmental impacts of circular design strategies and modularity in particular are explained to road-test our thesis that modular design comes at the cost of an "environmental activation energy".

2.1 Smartphone Modularity

The Fairphone is the most prominent example of a modular smartphone designed for do-it-yourself repairs. The Fairphone 2 launched in 2015 featured larger internal modules, mainly connected with spring-loaded connector arrays. These are robust connectors which can also withstand a rude handling by the user. These gold-coated connectors, additional printed circuit board area for contacts and module housing all resulted in a significantly higher environmental impact than a comparable conventional design [2–4].

Depending on the impact category, the impact share of modularity components is between 2.2% and 12.9% (Table 1). System boundaries are cradle to readily manufactured phone.

These additional impacts need to be compensated by the effect of a longer product lifetime due to enhanced reparability. Proske et al. [4] calculated a significantly improved environmental footprint in case this measure increases the product lifetime from in average 3 years to 5 years. This takes into account also repairs and battery replacements.

The next generation of the Fairphone launched in 2019 [5] addressed this aspect of a modularity overhead by changing the connector concept towards mezzanine strip connectors, which require only a small additional PCB footprint and feature a smaller contact area, thus less gold-coated surface finishes (Fig. 2). Some connections from the core module now had to be made with flex PCBs to bridge distances.

Table 1 LCA results: Fairphone 2 modularity (cradle to gate)

	Fairphone 2	Modularity components
Global warming (kg CO_2e)	35.16	0.77 (2.2%)
Resource depletion (abiotic, g Sb-e)	0.788	0.102 (12.9%)
Resource depletion (fossil, MJ)	139.51	8.05 (5.7%)
Human toxicity (g DCB-e)	8.290	280 (3.4%)
Ecotoxicity (g DCB-e)	110	5.79 (5.3%)

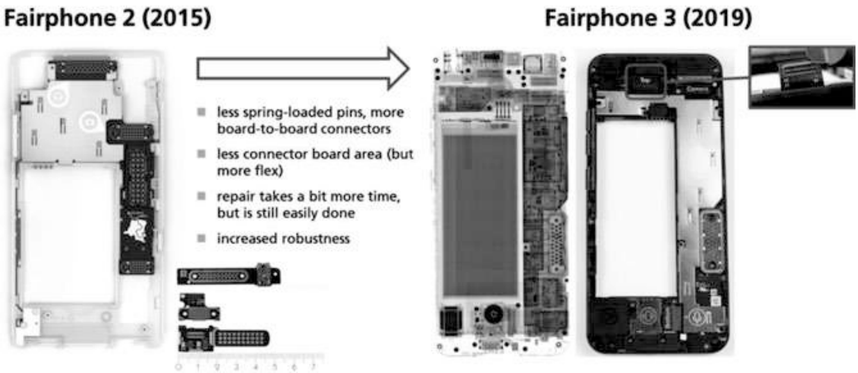

Fig. 2 Evolution from modular fairphone 2 to modular Fairphone 3 and major design changes

This might affect the manufacturing impact adversely. It remains to be seen, by how much these design changes reduce the modularity-related environmental impacts and thus the “environmental activation energy”, but the tendency definitely is positive.

A life cycle assessment study for the Fairphone 3 is currently work in progress. Results are expected mid-2020.

2.2 *Digital Voice Recorder Concept DPM D4R*

Professional digital voice recorders cover a wide range of functions. Not only the basic function “voice recording”, but much more subsequent processing of the recorded files like voice recognition, creating and editing documents, adding and managing additional information and supporting the workflow via cloud solutions are in the focus. Such devices are designed for professional use in the hospital sector, by lawyers or notaries. Enabling those functions, digital voice recorders have a design similar to that of today’s average smart mobile product.

A modular concept of a Digital Pocket Memo (DPM) has been designed together with a new B2B rental service [6]. This intended business model opens the possibility to replace old products with refurbished ones, update or just repair them. This leads to a lifetime extension of the whole product or single modules, and the overall life cycle impact decreases.

With this product concept, a D4R modularity approach (D4R means *design for repair*, *reuse*, *remanufacturing* and *recycling*) was applied. The product’s modules are defined by components with similar end-of-life strategies (Fig. 3).

This circular design approach leads to the following six modules: The shell (mainly made out of recyclable stainless steel) consists of all parts, which are in direct contact to the user. To assure a visually nice product, these parts can only be used once, and the main end-of-life strategy is *design for recycling*. The battery is

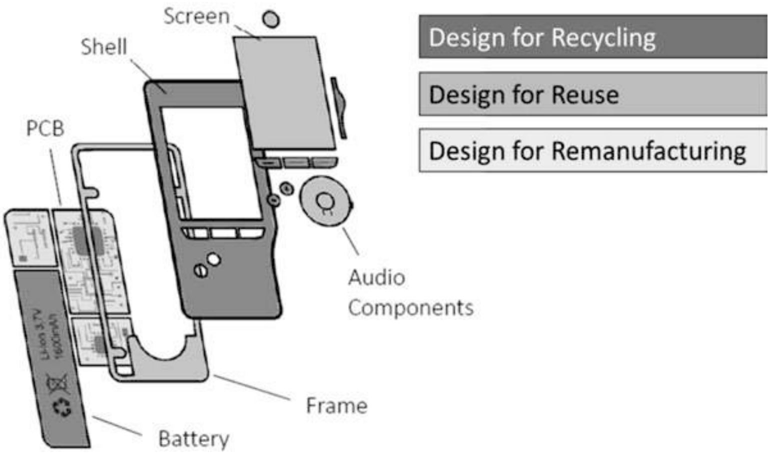

Fig. 3 Design strategies implemented with the digital voice recorder redesign

designed for recycling as the lifetime is relatively short and a certain performance is expected by a new customer. The frame (made out of recycled plastic) is the supporting structure for the PCB modules, the screen and the audio components. The frame is hidden inside (no aesthetic requirements) and meets future requirements of product updates and therefore has to be *designed for reuse*. Also, the audio module and the screen (using detachable connectors) are long lasting and are *designed for reuse*. As the environmental impact of the PCB assembly is very relevant, it should be reused. But due to short innovation cycles, the whole PCB assembly cannot be reused. Instead, the PCB itself is split into functionally grouped modules with the advantage of enabling exchange of single modules during product updates, and the PCB is *designed for remanufacturing*.

Comparing a reference product like the Philips DPM8000 and the concept DPM D4R in a scenario with a linear life cycle with no real circular approach, the impact of the DPM D4R is 12% higher. This “environmental activation energy” is caused by additional manufacturing efforts, mainly the new, modular PCB design, which enables the PCB remanufacturing. If the use time is doubled (by a second user), meaning two life cycles are taken into account (including exchange of shell module and battery, assumptions for repair of broken parts and product update, including transport, etc.), the GWP can be reduced by 21% in comparison to the reference product. If three life cycles can be realised, the GWP is reduced by 35% CO_2 eq. per product cycle [6].

Figure 4 depicts clearly the “environmental activation energy”: Impacts go up with the implementation of circular design strategies and go back down only with extended lifetimes. Then, however, the positive effect can be very significant. The crucial question again is if this extended lifetime is realistic or if other limiting factors, such as component obsolescence, software obsolescence and incompatibility, might limit the possibilities for further use at the end of the first product life.

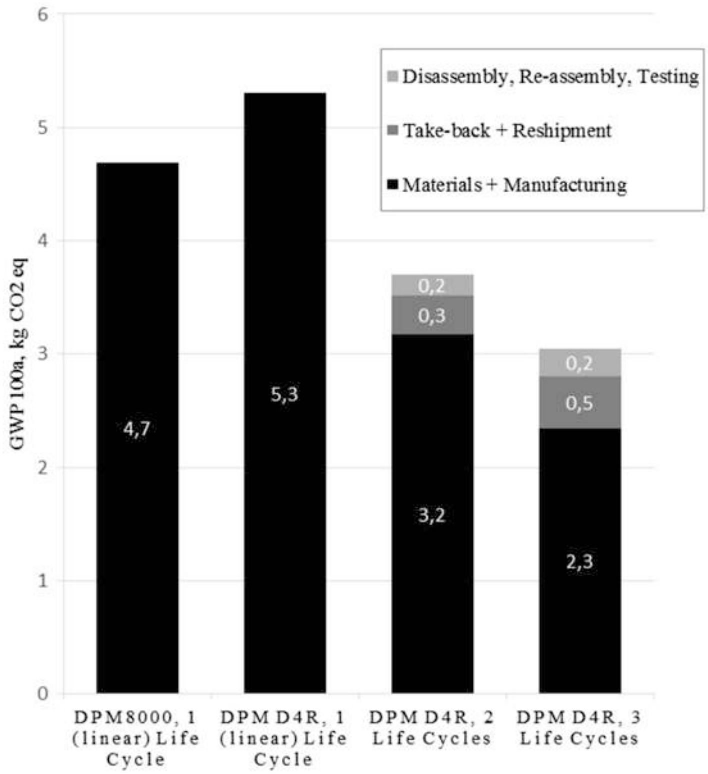

Fig. 4 Life cycle assessment results (GWP) for DVR design variants and lifetime scenarios

2.3 Embedding of Components for a Modular Printed Circuit Board Assembly

The idea of circular design has been advanced even a step further on the example of the digital voice recorder: Embedding is an advanced integration technology, where electronics components are not only placed on the surface of the PCB but are also buried in the PCB substrate. This reduces the needed area footprint for electronics modules. The PCB of the digital voice recorder is split into four distinct modules, the digital signal processor part, the internal power management, the USB connectivity and a backbone board similar to a PC mainboard [7]. The first three modules feature embedded components, and the power and USB module are assembled with non-permanent interconnection technology (screws, spring connectors, ZIF connector). This allows for a repair and refurbishment as indicated in the DVR concept outlined in the chapter before, but now with a miniaturized overall design (Fig. 5).

The image below clearly shows how complexity has been "outsourced" to the modules, featuring embedding. These modules now can be easily exchanged, easing the reuse of either modules or the backbone PCB.

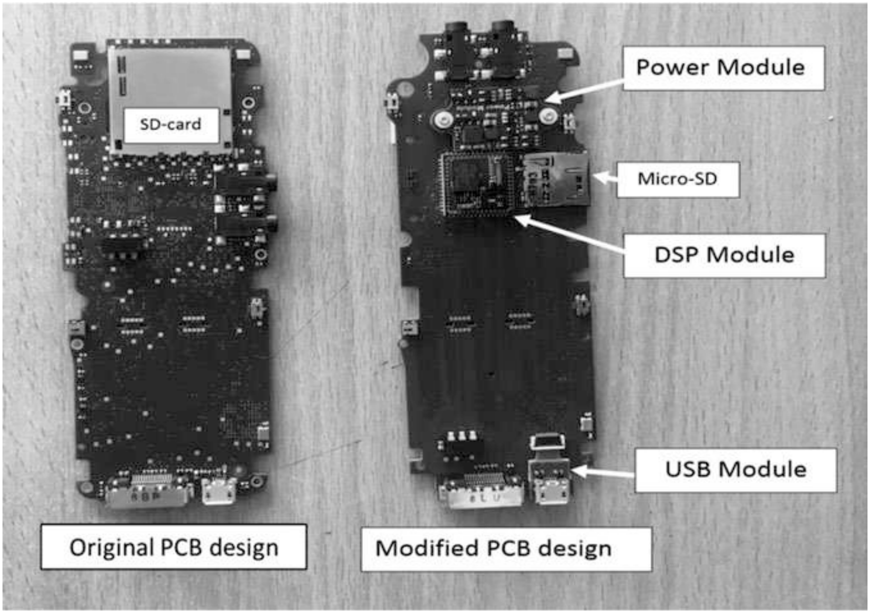

Fig. 5 Printed circuit board design changes towards modularity with embedded components

Table 2 LCA results: Digital voice recorder PCB assembly variants (cradle to gate, components excluded)

	Carbon footprint (kg CO_2 eq.)		
	Standard design	Six-layer backbone with three modules	Four-layer backbone with three modules
PCB/ backbone	1.01	1.01	0.90
USB module	–	0.17	0.17
Power module	–	0.32	0.32
DSP module	–	0.16	0.16
Connectors	–	0.007	0.007
Totals	1.01	1.67	1.57

Although Kupka et al. [8] identified a positive environmental effect of embedding as such, this does not materialize in the given design study [9]: The environmental impact is driven by the additional surface area of backbone and modules, which are – except for the DSP module – electroless-nickel/gold finishes with a high contribution to overall impacts (Table 2). Although not implemented, it seems feasible to reduce the layer count for the backbone from six to four layers. As the backbone board was not miniaturized, but defined by the existing physical dimensions of the handset, the potential of embedding is not fully exploited in this case.

As with the other examples, modularity comes at an initial environmental investment, which is likely to pay off only through lifetime extension of the device as a whole or at least high-impact key components. In mobile electronics, these high impacts in most cases are related to processors and memory (RAM or flash).

3 Design Rules for Modularity

The findings from the modularity assessments indicate how important it is to implement a circular design in a thought-through way and that modularity serves a well-defined (circularity) purpose.

Usually, smart mobile devices get defective caused by a failure or damage of only one single part, although all other parts are still working. These parts could serve more than one product lifetime. To continue the reuse of those parts, mixing different end-of-life strategies in one product is needed; the product's modules are defined by its components with similar end-of-life strategies.

The following design guideline (as proposed in detail by Pamminger et al. [6] and depicted in Fig. 6) shows roughly how to design a modular product that meets the needs of circular economy using the D4R modularity approach.

Task 1 – Definition of the Product's CE-Strategy
The first task is to find an adequate main CE-strategy. There are four end-of-life strategies (repair, reuse, remanufacturing, and recycling) to close the circle. The choice depends on different aspects like how does the current business model look like and what are the customer's needs and does my product contain valuable parts

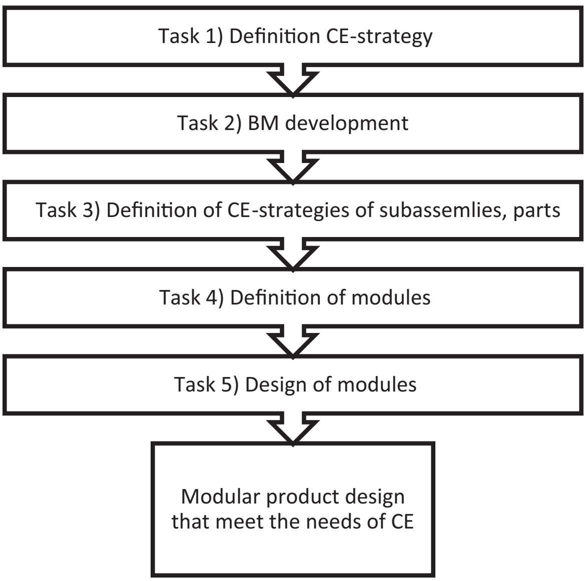

Fig. 6 Stepwise design approach for modular product designs

from an environmental perspective or product lifetime vs. product use-time considerations. By defining the main CE-strategy, a general direction is set for the second task, the business model development.

Task 2 – Business Model Development

A circular product design can only realise its full potential with an appropriate business model. A linear business model, which might represent the status quo, needs to be adopted to fulfil supplementary needs: reverse logistic, additional products like spare parts, new services, new activities, etc.

Tools like the CE Strategist [10] offer great help in developing circular business models.

Task 3 – Definition of CE-Strategies of Subassemblies and Parts

In the third task, the product is investigated at the component level. Depending on attributes like environmental impact, value, function, size or lifetime, the main components and parts can be identified.

For each of the main components or parts, an end-of-life strategy has to be defined, similar as with the main end-of life-strategy of the product (Task 1), but with the additional requirement, that those sub-strategies have to serve of course the product's main strategy.

Influencing factors for selecting the right strategy are the lifetime and wear, the environmental impact and the value. They are also caused by the previously defined circular business model. As with the product's main end-of-life strategy, the hierarchy of CE-cycles should receive attention.

Task 4 – Definition of Modules

This task represents the original idea of modularisation. Components, parts and subassemblies have to be clustered to modules with similar properties, end-of-life strategies, technical possibilities (interfaces, etc.) and requirements derived by the products use or the business model. A reasonable granularity should be achieved without a too detailed modularity, since a too detailed modularity will cause negative effects regarding product design, environmental impact, assembly, all sort of costs and failure susceptibility.

Task 5 – Design of Modules

The last task includes creating the module's technical structure. Questions which arise at this stage are, for example, how are the modules connected to each other, or how do the electronic interfaces look like? Can an easy and non-destructive separation of modules, which are meant for reuse or remanufacturing, be realised? Focus on design rules like "Design for Manufacturing" and "Design for Assembly" helps achieving an appropriate design. Also, automated disassembly will reduce costs with the right quantities. Include possibilities for failure detection to ensure that modules which will be reused work properly. So they can be taken again for a second life without any concerns, a convenient quality can be achieved. For a non-destructive disassembly, easy separation of modules for reuse or remanufacturing is important. In contrast, modules "designed for recycling" could be possibly removed in a destructive way (e.g. milling the housing or drilling clips or screws). When designing modules for recycling, select proper material combinations which ease the recycling process, or enable a good separability.

4 Conclusions

The comparison of modularity approaches shows the broad variety circular design strategies can have even for a rather narrow product segment: smart mobile devices.

The "environmental activation energy" is higher for those products which are built for end-user interaction, such as the DIY repair approach of the Fairphone 2 or a mix-and-match approach of functional modularity, than for those which follow, e.g. the serviceability approach only [2], where connectors do not need to withstand laymen's interaction. The potential environmental payback however is the highest, where the product remains in the hands of the end-user for a repair or even upgrade. However, also business models, which are built on modularity in a business-to-business market, can yield significant environmental savings over the lifetime. Some modularity concepts are at risk not to contribute to circularity at all, but have an adverse environmental impact over the full product life cycle: Where modularity is likely to trigger major rebound effects, the overall life cycle impact is likely to increase on top of the "environmental activation energy" of modularity. It is therefore of high importance to get clarity on the circular economy strategy and to implement appropriate design strategies stepwise, as outlined in this research.

This discussion on modularity and related environmental life cycle impacts is meant to contribute to a better understanding of the right drivers for more sustainable product concepts and factors fostering those developments.

Acknowledgement This research is part of the project sustainablySMART (www.sustainably-smart.eu) which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 680640.

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Quantitative Environmental Impact Assessment for Agricultural Products Caused by Exposure of Artificial Light at Night

Yoko Kurahara and Norihiro Itsubo

Abstract Increase in artificial lighting at night adversely affects human activities, wild animals, plants, agricultural crops, and livestock. The Ministry of the Environment defines such adverse effects as "light pollution." Rice is an agricultural crop subject to the influence of light environment. We used LED lighting rice plants ("Koshihikari" cultivar) grown in a paddy field owned by professional farmers for illumination during the night and evaluated its impact on the rice's heading and yield by actual measurement. We also factored in the roadway light installed in the paddy field's vicinity and evaluated its effects on yield. Damage coefficients of light pollution for rice cultivation were developed, 18.9 g/m^2/lx (equivalent to 0.046 US$/m^2/lx) for natural white lighting and 16.4 g/m^2/lx (equivalent to 0.039 US$ /m^2/lx) for light bulb-colored lighting.

1 Introduction

The increased use and scope of night illumination reportedly resulted in an annual 2% expansion of the outdoor area illuminated by artificial lighting around the world over 16 years from 2012 [1].

According to the Ministry of the Environment, the term "light pollution" is defined as an impediment caused by light leakage from outdoor illumination or other forms of lighting and collectively the adverse effects resulting from such an impediment. Reportedly, light pollution affects human activities, wild flora and fauna, and agricultural crops in various ways. Rice is a crop subject to the influence of light pollution [2].

Rice is a short-day crop that promotes flowering beyond a certain critical dark period. Conversion of light receptor phytochrome B (phyB) between Pr-type (red

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_3

light-absorbing type) and Pfr-type (far-red light-absorbing type) is known to be involved in the expression of *heading day 3a (Hd3a)*, a flower induction gene in rice. Normally, plants in places without outdoor illumination absorb red light by photoreaction during day to induce conversion to Pr, thus increasing Pfr amount. Conversely, Pfr decreases at night, promoting *Hd3a* expression. However, it is evident that illumination by outdoor lighting and other light sources during night prevents Pfr from decreasing. Consequently, *Hd3a* expression is suppressed at the transcription level, resulting in delay in or inhibition of heading [3]. For rice of the "Hinohikari" cultivar, illumination above 2 lux (lx) caused a delay in heading; the impact was more prominent when fluorescent mercury lighting, rather than LED lighting, was used, thus suggesting differences in effects depending on the type of light source [4].

Presently, no studies have evaluated the effects of light pollution by the methodology of life cycle assessment (LCA). However, in recent years, the following items have been added as new LCA impact assessment indices: "light pollution," "ecological light pollution," and "artificial light emission." This highlights the importance of evaluating the impact of these new items on the ecosystem and human health [5, 6]. Cucurachi et al. [5] discussed the functional units of light pollution in life cycle impact assessment (LCIA) model. Given the aspects of biodiversity, they reported that not only illuminance (common measurement unit: lx) at a certain place but also light intensity and wavelength are important factors in the functional unit. Therefore, they recommended that joule (J) factoring in electrical power per unit time (watt [W]) be used as the elementary flow and argued that LCIA may be applicable to impact assessment [5].

In Japan, many papers have been published regarding the quantitative assessment results of studies targeting rice. These studies have demonstrated that an increase in the illuminance of night illumination (lx) undoubtedly adversely affects rice yield. Cucurachi et al. [5] reported the possibility of developing a model for further endpoint type damage assessment.

In this study, we evaluated the impact of night LED illumination on the heading and yield of "Koshihikari" rice grown in rice paddies owned by professional farmers. Additionally, factoring in the influence of light leakage from roadway lights installed in the vicinity of the paddy field, we evaluated the effect of light on yield and developed damage coefficients of light pollution for rice cultivation. These findings should serve as a ground for determining how to design and where to install lighting to suppress light pollution.

2 Methods

2.1 Development of a Method for Assessing Light Pollution Impact on Rice Cultivation

2.1.1 Procedures for Assessing the Impact of Light Pollution on Rice Cultivation

Referring to the impact assessment method by Itsubo et al. [7], we developed a calculation flow for light pollution damage factors based on the impact [7]. Coefficients were calculated for each of the following three categories: inventory, impact, and damage analysis. Inventory (*Inv*) was the illumination per unit of area relative to emission from one of the light source units such as outdoor lighting. Influence coefficient (*EF*) was the delay (days) in heading by increased illuminance and the impact on yield caused by the delay. Damage coefficient ($DF_{\text{light pollution}}$) was the decrease in yield and loss of profits by increased illuminance. This allows the damage on yield to be quantified when a new light source is added (Fig. 1).

$$\text{Light pollution impact} = \Sigma\,\text{inventory}\left(\text{lx}/\text{m}^2\right) \times \text{damage coefficient}\left(\text{US\$}/\text{lx or g}/\text{lx}\right) \tag{1}$$

2.1.2 Effect Analysis

At night, rice of the "Koshihikari" cultivar was illuminated with bulb-colored and natural white LED lights, and their effects on heading and yield were evaluated. Based on the actual measurement data, the correlations between the "illumination and delay in heading" and the "delay in heading and yield of unpolished rice" were quantified to calculate the *EF*. The cultivar used was the "Koshihikari" (*Oryza sativa* L. cv. "Koshihikari"). To explore the impact under a more realistic environment, we conducted the experiment in an approximately 20-a paddy field owned by a professional farmer in Joso, Ibaraki Prefecture, in Japan. On April 30, 2019, rice seedlings were mechanically transplanted at a cultivation density of 18 bundles per m-2 (one bundle comprising four to six seedlings). For fertilization, only basal fertilizer was applied (nitrogen, 3 kg/10 a; phosphate, 3 kg/10 a; and potassium, 3 kg/10 a). No additional fertilizer was applied, and the rice was cultivated in a conventional manner. Six light units were used (three natural white LED lights and three bulb-colored LED lights, LDR11N-W 9 and LDR11L-W 9, respectively, Ohm Electric, Tokyo, Japan). The illumination period lasted from May 4 after transplantation to September 8, the day of harvest, during which the rice was continuously illuminated during night from sunset to sunrise.

The delayed time of heading was macroscopically determined. The date when all rice plants in the plot had more than 50% of valid stalks bearing ears was regarded

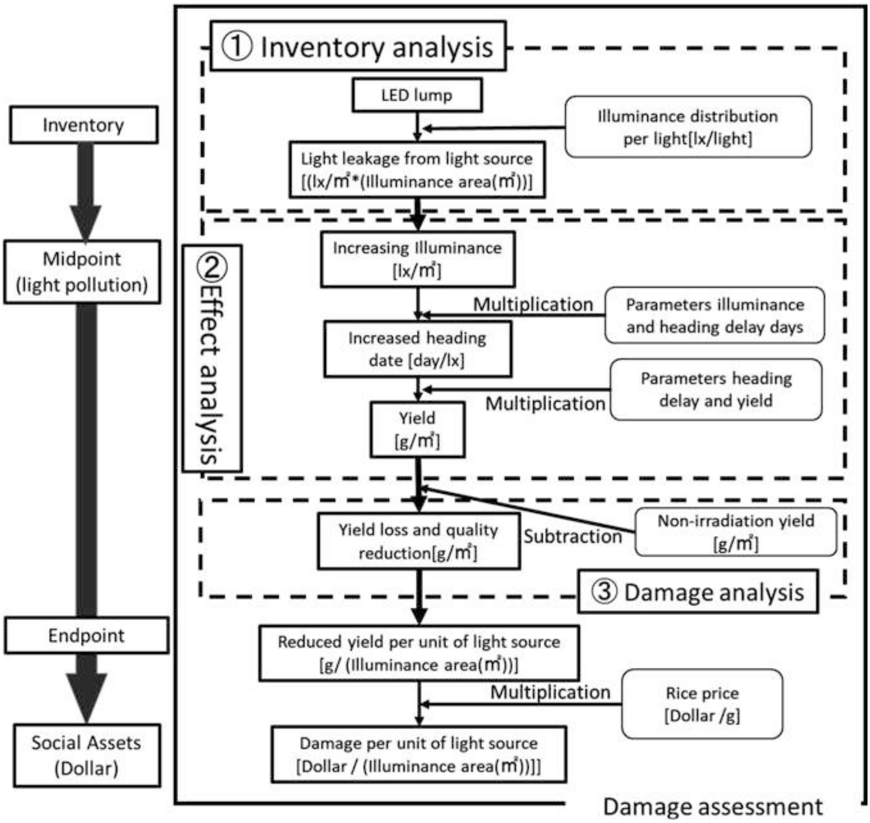

Fig. 1 Damage to rice cultivation due to light pollution

as the date of heading. The rice plants were harvested on September 8 to coincide with the harvesting period of the non-illuminated plot (Fig. 2).

2.1.3 Damage Analysis

Based on the *EF*, a relational expression for illuminance and yield decrease was calculated, which was multiplied by the relative transaction price of rice to calculate the *DF* unit [8].

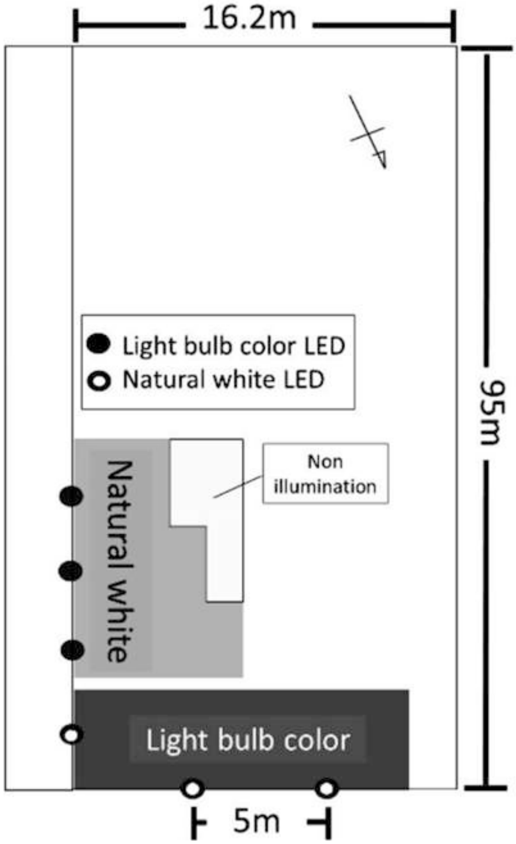

Fig. 2 Lighting position and irradiation range

2.2 *Case Study Using One Unit of Outdoor Lighting*

2.2.1 Assessment Method

A case study was conducted using the damage coefficient developed in Sect. 2.1. The impact of light pollution when outdoor lighting was installed in the vicinity of the paddy field was assessed. The light used was one unit of outdoor lighting equipment (e.g., roadway/street lamps). Calculation scenario was set according to the illumination design and placement conditions satisfying the Japan Industrial Standard “JISZ 9111 Road Lighting Standard.” The situation was assumed in which a roadway/street lamp is installed near the paddy field so that crops are most susceptible to light pollution [9]. Some street lamps were inverted cone type, and others were ball-shaped, thus different in shape.

Table 1 Lighting equipment and installation conditions

Inventory data items		Unit	Street light (Inverted cone type)	Street light (ball-shaped)
Lighting equipment	Instrument luminous flux	lm	5955	6625
	Power consumption	W	60	60
	Color temperature	K	5000	5000
	Color rendering index	Ra	70	70
Installation conditions	Light height	m	4.5	4.5
	Mounting angle	°	0	0
	Maintenance rate		0.64	0.64
	Distance from object	m	0	0

2.2.2 Inventory Analysis

The *IF* was the illuminance distribution emitted per one light source unit. The illuminance distribution was calculated using three-dimensional illuminance calculation software "DIALux" [10]. The items necessary for calculating the illuminance distribution were treated as the inventory analysis parameters. Therefore, the adopted parameters were as follows: light source specifications (luminous flux [lm], power consumption [W], and color temperature [K] or color rendering properties [Ra]) and installation conditions (lamp height [m], installation angle [°], maintenance rate, and distance from the object affected by light pollution [m]) (Table 1).

3 Results

3.1 Development of Impact Assessment Methods

3.1.1 Correlation Between Illuminance and Heading Delay

Figure 3 shows the correlation between illuminance and delay in heading. The delay in heading refers to the number of days by which heading was delayed compared with the date of heading in the non-illuminated plot, which was July 26, 2019. As the illuminance increased, the date of heading was delayed. In both natural white illumination and bulb-colored illumination plots, a strong correlation was observed ($r^2 = 0.85, 0.97$). This result was consistent with that reported by Harada et al. [11]. Figure 4 shows the heading delay caused by the experiment. It is affected in a circle along the illuminance distribution. The center of the circle is irradiated with about 300 lx.

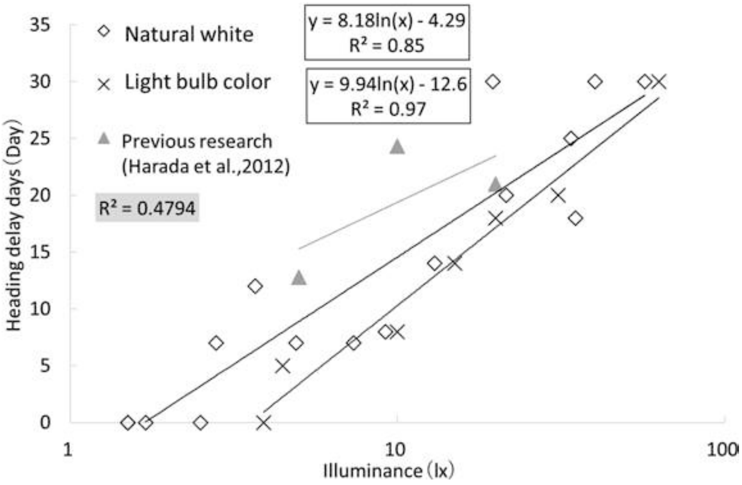

Fig. 3 Relationship between illuminance and heading delay days

Fig. 4 Paddy field affected by light on August 26

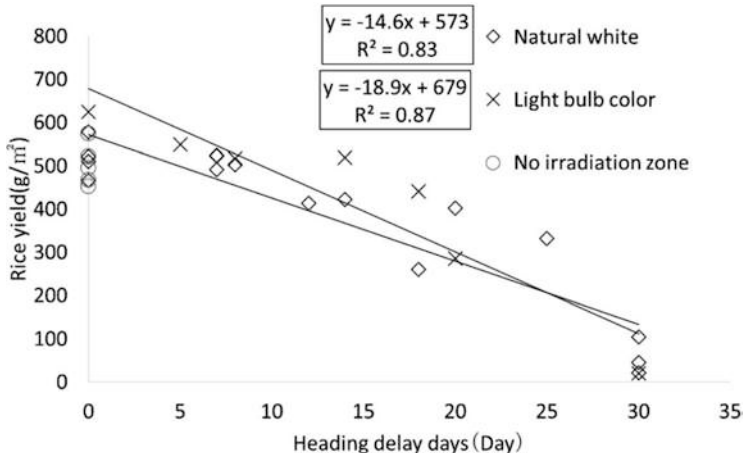

Fig. 5 Relationship between heading delay days and rice yield

3.1.2 Correlation Between Heading Delay and Yield

Figure 5 shows the correlation between heading delay and yield. The yield of polished brown rice decreased as the delay in heading increased, thus exhibiting a strong correlation ($r^2 = 0.83, 0.87$). In particular, the delay beyond 10–15 days considerably reduced the yield. Compared with the non-illuminated plot ($p = 503$), both illuminated plots (natural white and bulb-colored) exhibited a significant difference at a significance level of 1%.

3.2 Damage Factor Results

3.2.1 Correlation Between Illuminance and Yield

Figure 6 shows the correlation between illuminance and yield decrease. Consequently, the following damage coefficients were obtained: (i) natural white *DF*, 18.9 g/lx, and (ii) bulb-colored *DF*, 16.4 g/lx. Decrease in yield was observed from approximately 2 lx with natural white light and approximately 4 lx with bulb-colored light. Given the average yield in Ibaraki Prefecture ($p = 524$), the illuminance that results in zero yield was calculated to be approximately 28 lx with natural white light and approximately 32 lx with bulb-colored. Because this slope has different effects depending on the illuminance, overestimation may occur under approximately 5–15 lx, which is a limitation of this study.

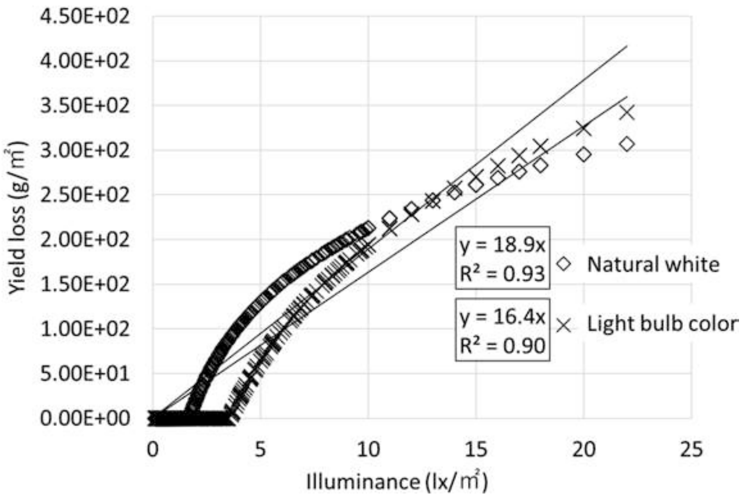

Fig. 6 Relationship between illuminance and yield

3.3 Case Study Results by One Outdoor Lighting Unit

3.3.1 Illumination Distribution in the Paddy Field

The illumination distribution in the paddy field was calculated. The values in the paddy field signified the illuminance per mesh per 1 m^2 (lx/m^2). The maximum illuminance of inverted cone-type street lights exceeded 20 lx and that of the ball-shaped street lights was around 6 lx. The spread of the illuminance greatly varied depending on the shape (Figs. 7, 8).

3.3.2 Endpoint Calculation Results

Figure 9 shows the decrease in the yield (damage amount) per light annually. When installed in the vicinity of the paddy field, the inverted cone-type street lights reduced the yield by 23 kg, whereas the yield reduced by the ball-shaped street lights was 10 kg. Both types of light exhibited light pollution effects. However, the effects varied depending on the distance from and the shape of the light source (due to differences in luminous flux beneath the light source). Therefore, places/situations susceptible to light pollution require countermeasures, such as installation of light shielding plates and changes in illumination position (Fig. 9).

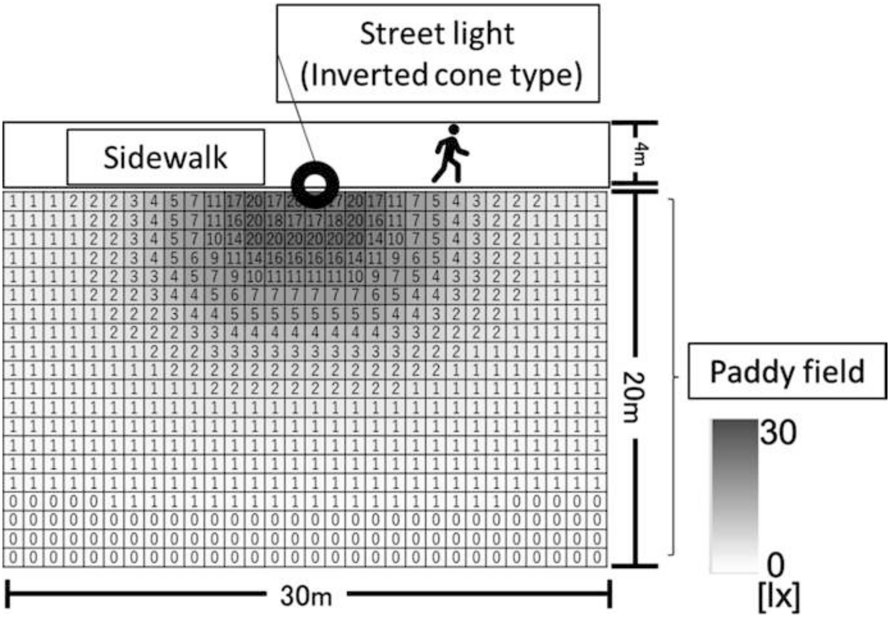

Fig. 7 Illuminance distribution result of street light (inverted cone type)

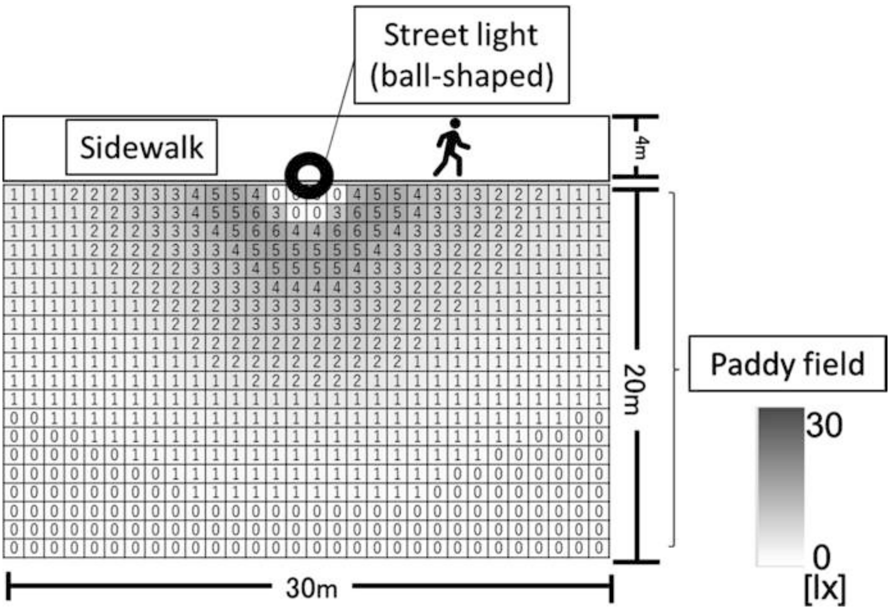

Fig. 8 Illuminance distribution result of street light (ball-shaped type)

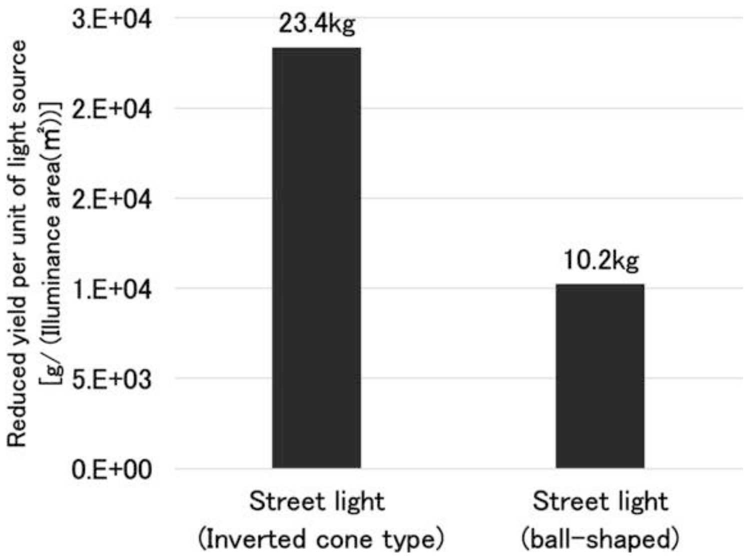

Fig. 9 Result of yield reduction per light/year

4 Conclusion

This study has proposed a framework for light pollution assessment. Additionally, we developed damage coefficients intended for assessing the impact of LED lighting on rice cultivation. Based on these damage coefficients, we conducted a case study of outdoor illumination installed in the vicinity of a paddy field. By actual measurement, a delay in heading occurred with approximately 5 lx of light. When the heading delay exceeded 10–15 days, the yield was greatly affected. Because we used data obtained from experiments, the representativeness of these results may be low. In the future, damage coefficients for assessing the ecosystem and human health should be developed.

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City Air Management: LCA-Based Decision Support Model to Improve Air Quality

Jens-Christian Holst, Katrin Müller, Florian Ansgar Jaeger, and Klaus Heidinger

Abstract Siemens has developed an emission model of cities to understand the root cause and interactions to reduce air emissions. The City Air Management (CyAM) consists of monitoring, forecasting and simulation of measures. CyAM model aims to provide formation on air pollution reduction potential of short-term measures to take the right actions to minimize and avoid pollution peaks before they are likely to happen. The methodology uses a parameterized life cycle assessment model for transport emissions and calculates the local impact on air quality KPIs of individual transport measures at the specific hotspot. The system is able to forecast air quality and by how it is expected to exceed health or regulatory thresholds over the coming 5 days.

In this paper, the LCA model and results from selected cities will be presented: Case studies show how a specific combination of technologies/measures will reduce the transport demand, enhance traffic flow or improve the efficiency of the vehicle fleet in the vicinity of the emission hotspot/monitoring station.

1 Introduction

According to the World Health Organization (WHO), almost 90% of the world's urban population breathe air with pollutant levels that far exceed the recommended thresholds. Approximately seven million people die each year from the effects of air pollution, which, according to the WHO, makes it a greater global health threat than Ebola and HIV [1].

City leaders are under pressure to meet these challenges and define strategies for sustainable, clean and smart growth. However, they often lack sufficient data or

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_4

digital tools necessary to make the best decisions. Additionally, continuous urbanization has resulted in population growth, sprawling land use and changes in mobility behaviour. Despite public transit investments, congestion is worsening globally. The sheer volume of inter- and intra-urban transportation has outpaced improvements in and customer uptake of clean transport technology. As a result, air quality has deteriorated in many cities, large and small, and city leaders are accepting that, at its core, poor air quality is an issue of public health and wellbeing [2].

As trusted global partner for sustainable city development, Siemens has developed a complete, cloud-based software suite to overcome the challenges of poor air quality using artificial neural networks and LCA-based decision support methodology. The City Air Management Tool visualizes air quality data recovered from municipal measuring stations in real time. In addition, it forecasts air pollution levels for the next 3–5 days with up to 90% accuracy and also simulates the impact of short-term measures on air quality. Combining air quality forecasts with the simulation of the effectiveness of planned measures and technologies helps cities in the first instance to activate short-term measures; however, it will also foster long-term air quality improvement measures in the upcoming years, such as the implementation of low emission zones or increased e-mobility.

2 City Air Management: Solution and Methodology

The process of CyAM is depicted in Fig. 1. The system starts with data collection from measuring station at hotspots in cities [3]. Then a simulation predicts the degree of air pollution several days in advance. Based on its analytical capacities, the main drivers for air pollution are identified and monitored continuously in order to improve the prediction capabilities. The software aims to give cities the information needed to minimize and avoid pollution peaks before they are likely to happen.

The main technical specifications of the CyAM are as follows:

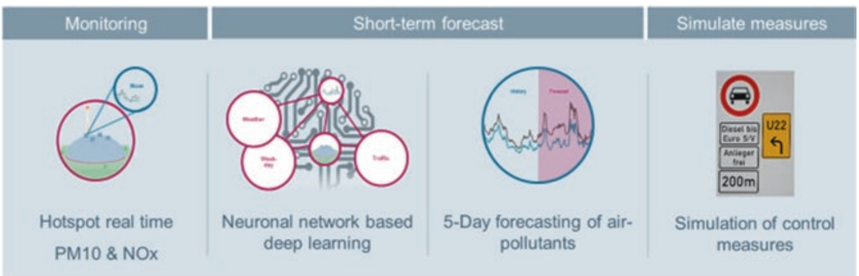

Fig. 1 City air management process: monitoring of air quality KPIs, forecast and simulation of applicable measures

- Monitor the citywide, hotspot emissions of all environmental sensors which have been integrated in the tool, focusing primarily on PM2.5, PM10 and NOx. Data is shown for each sensor on an hourly basis.
- Forecast air quality and inform city leaders through a dashboard about where and by how much air quality is expected to exceed health or regulatory thresholds over the coming 3 days with 90 per cent accuracy and up to 5 days at a level of 75–80%.

Cities/counties/states operate their own air pollution sensor networks in order to prove their compliance with national or international regulations [4, 5] . This data is gathered on central severs and publicly available in most parts of the world. The city would need to provide air quality sensor data, historic and real-time air quality data streams of all available measurement stations from a central database using standard database data interfaces. The CyAM has an API, which allows this data to be pulled from these servers or pushed to the CyAM as soon as the data is available. This is depicted in Figs. 2 and 3.

The dashboard shows the three air quality KPIs, NO2, PM10 and PM2.5, over a timeline. Potential transportation-related measures to improve the air quality are shown on the right-hand side. The data for the individual measurement stations are visualized, categorized and benchmarked against the legal thresholds in the dashboard. It provides an immediate evaluation of the current situation and information on whether it is necessary to act. The latest history is also available for review, as well as the gliding annual average (Fig. 3).

There are two options to do forecasting for air pollutants, domain models and artificial intelligence [6].

Domain models are models which fully understand the physical and chemical processes of emission source behaviour and the atmospheric processes during transmission of pollutants. Their main disadvantage is that there are a vast variety of emission sources in and around a city. It is very expensive and time consuming to

Fig. 2 Dashboard of measuring stations and potential measures to reduce emissions for KPIs like NOx and PMx

Fig. 3 Dashboard of actual air pollution data for NO2 and PM10

assess them in real time. The modelling of the transmission (distribution plus the physical and chemical processes of the pollutants in the air) is time consuming and requires high computing capacities.

CyAM uses artificial intelligence (AI) to forecast air pollution concentrations at individual air quality measurement stations [7]. It takes few available parameters which are available as forecasts and builds an empiric model based on historic data. CyAM uses air pollution measurement data, weather data/weather forecast data, calendric data and special events. The AI finds correlations and patterns in this data to predict air pollution for individual measurement stations. It doesn't contain any knowledge about the physical and chemical processes, responsible for these concentrations. Based on real-time data and forecasts of weather – and calendric/event data – a 5-day forecast is provided. The Advantage is a model which has a high precision, takes little computing power during operation and requires few data points.

In the air pollution forecasting system, recurrent neural networks are used, which are well suited for this task. They also make it easier to uncover a great deal of previously unobserved, latent information about air pollution-causing factors from traffic, industries, agriculture, etc., in the internal dynamical model of the environment, which is built up during the training of the network. Based on all of the resulting data, as well as seasonal and immediate weather forecasts, the neural network has to learn how to predict the degree of air pollution. During the city-specific training process of the system, which includes hundreds of iterations, the program steadily reduces the difference between its forecasts and the actual levels of pollutants measured in the city's atmosphere by changing the weightings of individual parameters (Fig. 4).

In order to calculate impacts of individual measures, a domain model is inevitable [8]. The key to success is to only model the share of emission and concentrations, which can actually be impacted by interventions. This reduces the data requirements and complexity to a minimum, using forecasting values for different measurement stations, provided by the AI. Depending on their location, they represent certain emission sources, as indicated in Fig. 5. If the measurement station at

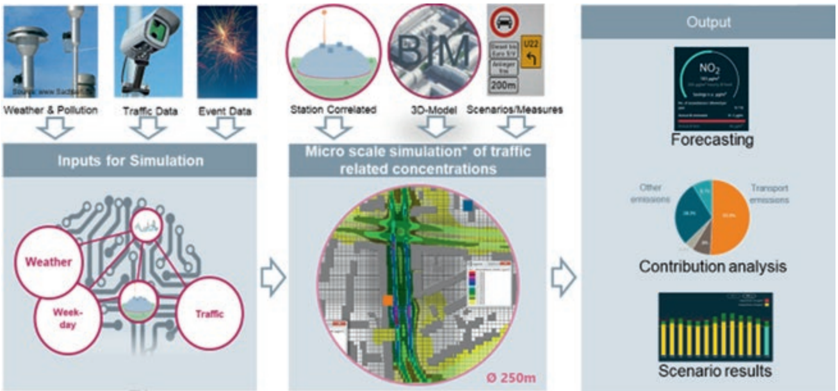

Fig. 4 Forecasting of air pollution is realized by domain models or artificial intelligence; CyAM uses the second

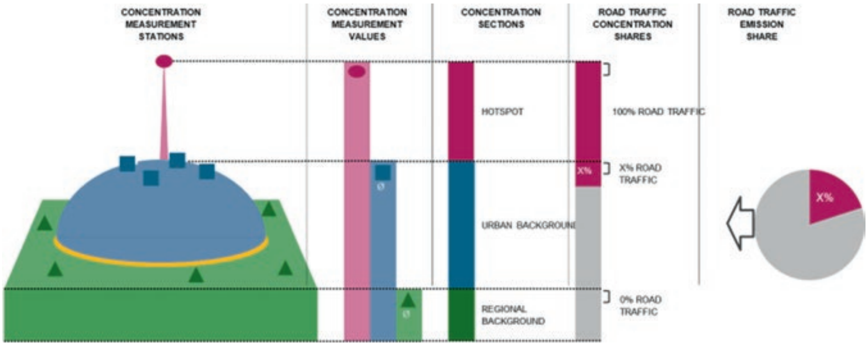

Fig. 5 Urban emission concentration profile for PM or NOx

the roadside (referred to as hotspot) and the one representing the local background are located well, they can be used to estimate the local road traffic-based concentration in a street canyon in front of the roadside measurement station. It is a simplified concentration contribution analysis, singling out local traffic-related air pollution concentration.

In parallel, a domain model is used to perform an emission contribution analysis of different vehicles and vehicle categories from the overall local transport emissions. These are based on information such as how many vehicles of which vehicle category and exhaust gas emission class are passing by the measurement station. Temperature, slope and congestion level are represented as well. The combination of the contribution model from roadside emissions and the concentration contribution analysis based on correlating forecasted air quality sensor data provides a full view of which vehicles are responsible for a certain air pollution concentration [9]. This process is executed for any hour of the forecasting period individually. The domain model for traffic emissions also contains a variety of location-specific scenarios, representing different intervention options. These interventions can be selected short term in order to reduce local emissions and thus local concentrations. There are 17 short-term levers that could be simulated within the CyAM standard model – depending upon the needs of the city. These measures include reducing the price of public transportation and encouraging public transport use, requiring that all buses in that area be electric or encouraging residents to work from home when possible. The selected 17 measures are depicted in Fig. 6.

Triggering any of these interventions results in an emission reduction of one or several modes, what is modelled and translated in concentration reductions at the roadside measurement station via contribution analysis. The result is an hour-by-hour forecast of the saving potential for the modelled interventions within the next 5 days.

To understand the underlying methodology, we use the lever of temporary driving ban for diesel cars. In case of exceeding emission limits, a diesel driving ban is announced and enforced. All diesel cars are restricted to enter the city region. A licence plate recognition system will be installed around city boundaries and near emission hotspots to check the potential driving permission [10].

The LCA model and the mechanism of demand shift are depicted in Fig. 7. After a diesel car ban is in effect, the available additional capacity at peak time will be used by increasing capacity utilization of public transport, shift to bicycle, to carpooling and even absolute reduction of car pkm due to home office, etc.

In the LCA model, passenger kilometre (pkm) of diesel cars is shifted using four different mechanism step-by-step to public transport, to bicycles, to carpooling or ride-hailing and if required to absolute pkm reduction due to home office, work shifting/vacation, etc.

From the 17 levers of our model, the two main impacts of air quality emission reduction are modal shift (from private cars to public transport, taxi and zero emission vehicles) and improved traffic flows by capacity shifting [9].

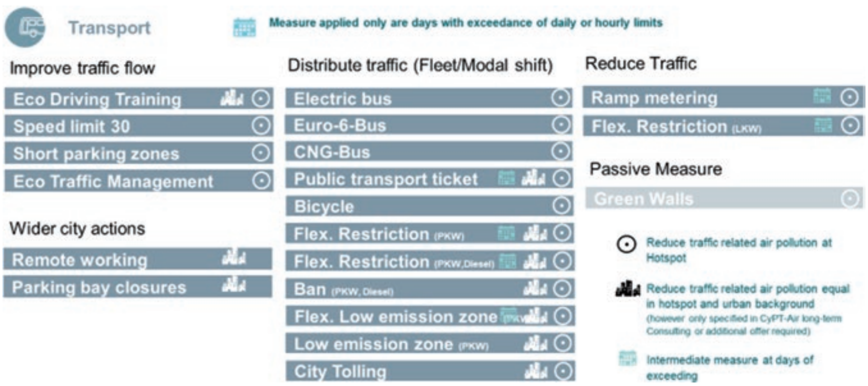

Fig. 6 Seventeen transportation measures to reduce air pollution at hotspot

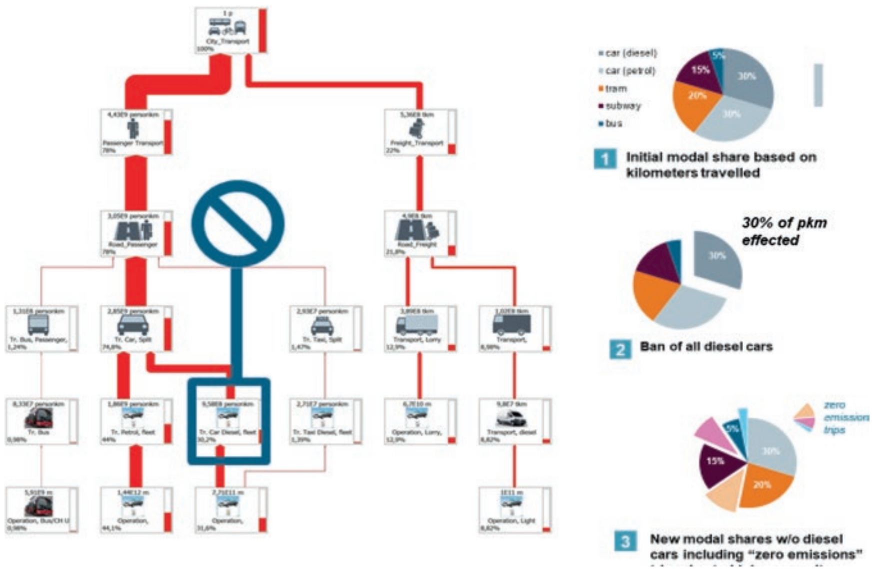

Fig. 7 Example for LCA model of urban transportation: diesel car ban reduces the emissions by modal shift and improved traffic flow

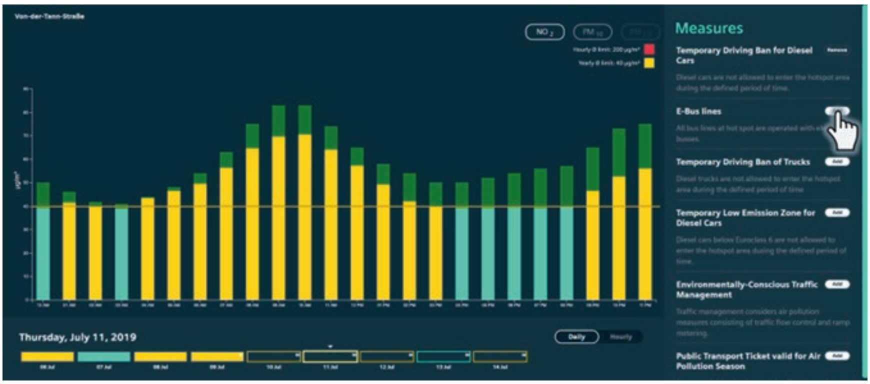

Fig. 8 Quantification of reduced NO2 value at hotspot by applying diesel ban as a measure; temporal behaviour from forecast is also shown

3 Results and Discussion

From Fig. 8, we can understand the decision support function of the CyAM system. The forecast of the emission value for hours and days will be combined with the impact evaluation of the system. By applying different levers, one can see the reduction of certain KPIs for different time scales. The shown example displays a diesel car traffic ban over certain time and the respective NO2 reduction at the hotspot. CyAM can support cities to conduct knowledge-driven decisions to avoid exceeding set limits and combine different measures to increase impact analysis and outlook for set mid- and long-term measures. The system can also be used for other applications, i.e. adjust means of private transportation by using dynamic traffic zones or restrict to electric cars, control the production of factories and power plants and monitor the air pollution nearby, plan time and location of sports and social events to ensure a good air quality and monitor air pollution close to hospitals, schools, kindergartens and living communities for early announcements or change of time and location.

In summary, CyAM can be applied to reshape communication about air quality in your city by improved information quality, transparency, measure polling and/or data-based decision support. It also provides possibilities for short-term measures and real-time management of air quality, i.e. by peak shaving or temporal modal shift.

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Is Environmental Efficiency Compatible with Economic Competitiveness in Dairy Farming? A Case Study of 80 Luxembourgish Farms

Rocco Lioy, Caroline Battheu-Noirfalise, Aline Lehnen, Roman Reding, and Tom Dusseldorf

Abstract The aim of the study was to investigate both environmental and economic performances of Luxembourgish dairy farms in order to assess possibilities and limits of improving economic competitiveness via increasing environmental efficiency. In the environmental field, four LCA impact categories (carbon footprint, energy consumption, acidification, eutrophication) were analysed, while in the economic field, costs, incomes and profit of the farms were investigated. A main result was that a sustainable dairy production with less environmental impact in all considered categories is also of advantage in terms of farm competitiveness. The most efficient farms reach also the highest profit. The case study proves that a high environmental performance is not only of advantage in terms of economic competitiveness, but is even a necessary prerequisite for best economic performances.

1 Introduction

The case study was carried out in the frame of the Interreg VA Program of the European Union (Project AUTOPROT). This project aims to investigate if and to which extent an increase of protein self-sufficiency (autarky) can lead to a better competitiveness of dairy farms and to a reduction of their environmental impact as well. After the abolition of the milk quota system in the European Union at the end of March 2015, dairy farms were forced more than ever to increase production efficiency as a precondition to improve their own competitiveness. Thus, in the frame of this study, a combined environmental and economic analysis of dairy farms was

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_5

carried out in order to highlight possibilities and limitations of a conciliation of environment and competitiveness in dairy farming.

2 Material and Methods

2.1 The Investigated Farms and the Protein Autarky

The investigation refers to a sample of 80 Luxembourgish dairy farms supervised in the years 2014, 2015 and 2016. The figures of crop production and animal husbandry of the investigated farms (Tables 1 and 2) as well as all the figures presented in this study refer to the average of the three investigation years. The farms (ca. 11% of all dairy farms of the land) cover the different dairy production systems in the country and are representative of dairy production in Luxembourg.

A very important indicator for the farms is the self-sufficiency degree of protein in dairy farms, in subsequently called protein autarky. There are two possibilities to express protein autarky. The first one refers to the performance of farm crop production to deliver protein for the herd. In case of crop production, the autarky is the amount of on-farm produced protein in relation to the total protein fed [1]. The other indicator of protein autarky refers to the performance of animal production to valorise protein fed. This figure takes into account the protein need based on need Tables [2] and considers as valorised the difference between needed and purchased (with concentrate and roughage) protein. The purchased protein is estimated based on feed protein Tables [3]. A detailed description of this figure is shown in [4].

2.2 The LCA Methodology Applied and Economic Indicators Used

The investigation of environmental impact was carried out on four LCA midterm impact categories (carbon footprint, energy consumption, acidification and eutrophication). The carbon footprint takes into account not only emissions deriving from production means, animal husbandry and crop production but also carbon credits deriving from humus storage into arable soils and via renewable energies

Table 1 Main figures of crop production

Figure	Average	St. dev.
Farm size (dairy production)	87.08 ha	45%
Cereals	8.25 ha	78%
Maize silage	16.39 ha	54%
Grassland (permanent + temporary)	61.89 ha	46%
Other feed plants	0.55 ha	328%

Table 2 Main figures of animal husbandry

Figure	Average	St. dev.
Animal density	1.56 LAU/ha	19%
Dairy cows	84 (n)	55%
Production intensity	7.550 kg ECM/ha	29%
Dairy performance	7.847 kg ECM/year	15%
Concentrate use	6.33 kg/cow/day	26%
Concentrate efficiency	0.29 kg/kg ECM	21%

LAU Large animal unit, ECM Energy-corrected milk

Table 3 Sources of emission and credit factors for carbon footprint

Emission or credit post	Source
Production means (manufacturing and transport)	Ecoinvent 2009 [5]
Enteric fermentation and manure management	IPCC 2006 [6]
Indirect soil emissions	IPCC 2006 [6]
Mineral nitrogen fertilisation	IPCC 2006 [6]
Fuel (manufacturing and combustion)	Ecoinvent 2009 [5]
Humus balance of arable land	Leithold et al. 1997 [7]
Electricity from biogas	Ecoinvent 2009 [5]

(Table 3). This means that the carbon footprint results in a net balance of CO2-equivalents.

In the case of humus balance of arable soils [7], the balance results in an emission if negative, and in a credit, if positive. The global warming factors used for carbon footprint were 25 for methane and 298 for dinitrogen oxide, according to [6]. The allocation between milk and meat was carried out following their protein content.

The energy consumption (no renewable energy) was estimated by taking into account not only direct energy (fuel and electricity) but also the indirect energy for manufacturing and transport of used production means and investments (buildings and machinery). The source of these energy consumptions was the Ecoinvent databasis [5].

Acidification takes into account the SO2-equivalents deriving from SO2, NH3 and NOx. The sources for the emission factors for the three gases were in the case of used production means [5] and in the case of livestock and crop production [8] for NH3 and [6] for NOx (as NO). The characterisation factors for NH3 and NOx (as NO) were derived from [9].

Finally, in the case of eutrophication, the estimation of nitrate leaching was made as difference between the nitrogen balance at farm gate and the sum of all emission of N-species as well as the N-storage into the soil, in analogy to [10]. The PO4-equivalents coming from phosphorous emission are estimated based on farm gate balance for phosphorus. Even in the case of eutrophication, characterisation factors for PO4-equivalents from different eutrophication sources were derived from [9].

As shown by [11] and [12], the behaviour of carbon footprint when expressed in function of product (kg ECM) or farm size (ha) is contradictory. Thus, to avoid misunderstandings in interpretation of results, for all investigated impact categories, both functional units (per kg ECM and per ha) were used.

In this study, the incomes without subsidies, the production costs for a kg ECM as well as the profit (as a difference between the first two) were used as economic indicators.

2.3 The Principle of Farm Segregation and Statistics Analysis

In order to analyse result variability, according to [13], the investigated farms have been divided into groups by crossing the X and the Y axis in the average value of carbon footprint per ha (11.2 t CO2eq) and per kg ECM (1.32 kg CO2eq) (see Fig. 1).

This allows the segregation of farms into four groups, which are well differentiated in terms of production intensity and efficiency of production mean use (as will be clear more below, Fig. 4). In particular, the farms with only one indicator of carbon footprint better than the average are farms with the highest or lowest production intensity. The farms of the other two groups (with both values of carbon footprint better or worse than the average) are farms with a middle-intensive production intensity, when compared with the other two groups. Figure 1 also shows the used denomination of the four farm groups.

Concerning the statistic methodology, the analysis was carried out by using the program "R", which is freely available on the Internet [14]. ANOVA test was used for determining the significance of selected figures in the whole pool, while Tukey post hoc test was used among the segregated farm groups. The conditions of

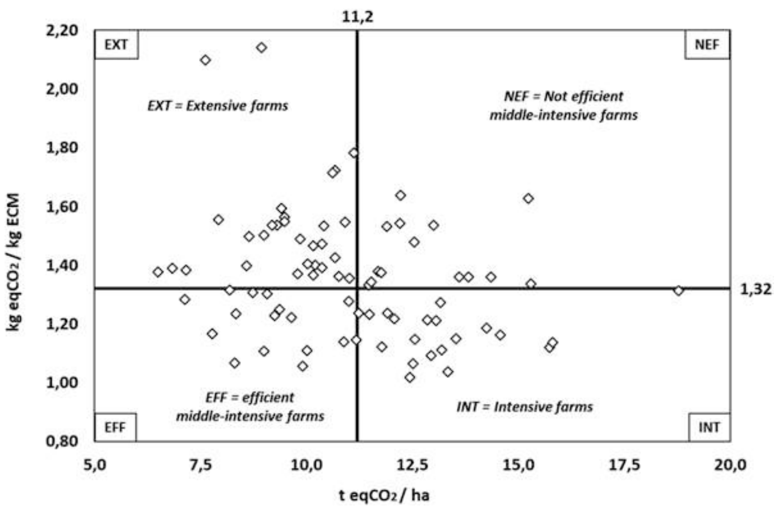


Fig. 1 The segregation and the denomination of the four farm groups

application of the ANOVA test, homogeneity and homoscedasticity, were tested using the Shapiro test and the Bartlett test, respectively. An exhaustive description of ANOVA test can be found under [15].

3 Results and Discussion

The value of protein autarky of crop production of investigated farms (Table 4) shows that two thirds of the protein fed were produced on farm, and the other third was purchased. In the case of animal production, on average the farms show a valorisation of the on-farm produced protein of 49%.

This means that roughly one half of the on-farm produced protein is lost. These losses are problematic, because they result in higher emissions (especially NH3, [16]) and in a higher import of feed (with consequent higher energy consumption and carbon footprint). In terms of variability, the purchased protein shows the maximum value. As we will see below (Fig. 5), the protein purchase plays a key role in explaining differences among the farms.

The results of LCA impact categories show a very high variability both in product (Table 5)- and in surface (Table 6)-related figures. The largest spread between minima and maxima values can be found in the eutrophication figures. The calculated figures for dairy farming in Luxembourg are consistent with the range of values from literature [17–19] concerning all product-related figures as well as surface-related figures of carbon footprint and energy consumption. Only in the case of surface-related figures of acidification and eutrophication, it was not possible to find values in the literature because relating these figures to the farm area is unusual.

In the case of economic results (Table 7), there is an evident difference between incomes and costs on the one hand and profit on the other hand. Indeed, the variability of the first two parameters is clearly lower than those for the profit, which varies very largely among the farms. In any case, on an average, the farms are capable of reaching only a very low profit, if subsidies are not considered.

Table 4 Figures of protein autarky of investigated farms

Protein autarky	Value	St. dev.
On-farm produced protein (1)	966 kg CP/ha	54%
Purchased protein (2)	497 kg CP/ha	81%
Total protein fed (3) = (1) + (2)	1.462 kg CP/ha	60%
On-farm protein autarky = (1) / (3) * 100	66%	14%
Needed protein by dairy herd (4)	982 kg CP/ha	62%
Valorised protein (5) = (4) – (2)	485 kg CP/ha	58%
CP-autarky (anim. prod.) = (5) / (4) * 100	49%	29%

CP Crude protein

Table 5 Product-related impact of farms in the investigated LCA categories

Impact category	Functional unit: 1 kg ECM	St. dev.	Min.	Max.
Carbon footprint	1.32 kg CO2eq	16%	1.02	2.14
Energy consumption	4.8 MJ	19%	3.3	8.0
Acidification	17.3 g SO2eq	21%	12.0	36.3
Eutrophication	11.7 g PO4eq	36%	6.1	29.4

Table 6 Surface-related impact of farms in the investigated LCA categories

Impact category	Functional unit: 1 ha	St. dev.	Min.	Max.
Carbon footprint	11.2 t CO2eq	21%	6.5	18.8
Energy consumption	41 GJ	27%	19	65
Acidification	148 kg SO2eq	23%	80	230
Eutrophication	99 kg PO4eq	33%	35	196

Table 7 Economic figures of investigated farms (*incomes are without subsidies*)

Economic figures	€-cent/kg ECM	St. dev.	Min.	Max.
Incomes	39.7	9%	34.3	55.7
Costs	38.8	20%	23.1	63.2
Profit (incomes-costs)	0.9	822%	−24.6	19.9

Table 8 LCA figures of segregated farm groups and range of results

LCA figure	EFF	Range	EFF	Range	EFF	Range	EFF	Range
Kg CO_2eq/kg ECM	1.2	2	1.17	1	1.51	4	1.45	3
t CO_2eq/ha	9.2	1	13.9	4	9.5	2	12.6	3
MJ/kg ECM	4.4	2	4.3	1	5.3	4	5.1	3
GJ/ha	34	2	51	4	34	1	45	3
g SO_2eq/kg ECM	16.6	2	15.4	1	19.5	4	18.9	3
Kg SO_2eq/ha	127	2	182	4	123	1	164	3
g PO_4eq/kg ECM	10.5	2	9.7	1	14.1	4	13.3	3
Kg PO_4eq/ha	81	1	115	3	88	2	116	4
Sum of ranges	–	**14**	–	**19**	–	**22**	–	**25**

The farm segregation allows ranging the results among farm groups. As can be seen in Table 8, the middle-intensive farms with a high efficiency (EFF) show the lowest environmental impact, if all the ranges in the eight impact categories are added up. In the hierarchy of the range, the group EFF is followed by the intensive farms (INT), then by the extensive (EXT) and finally by the middle-intensive farms with a low efficiency (NEF). In the case of product-related emissions, the farm group INT each times reaches the best performances, but this situation inverts when the results are related to the ha of the farm. In that case, the intensive farm group shows the weakest results in the range with only one exception (kg PO4eq/ha).

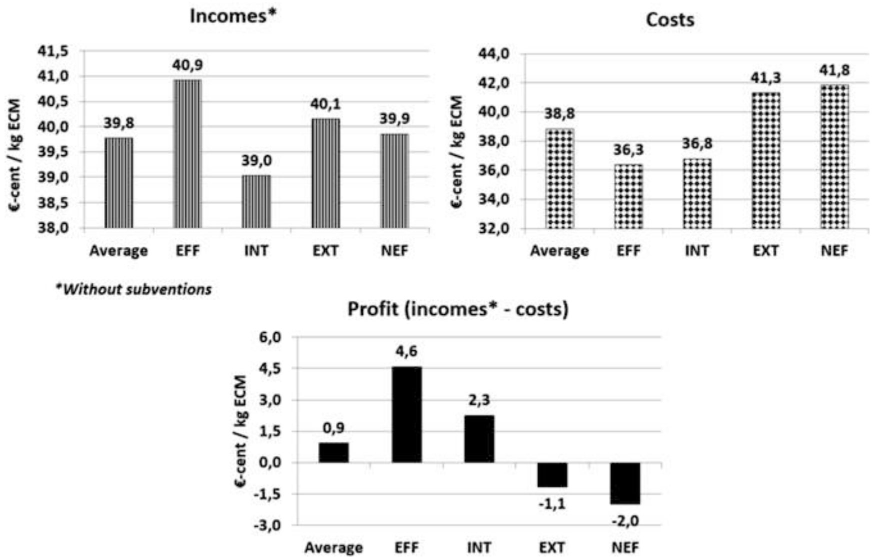


Fig. 2 Economic figures of segregated farm groups

The situation of the extensive farm group (EXT) is inverse to the intensive farms. This suggests that the farm structure is important in order to influence the range of result.

This hierarchy in environmental results among the farm groups is found to be the same also as in the case of economic results. As shown in Fig. 2, the farm group EFF reaches the best profit per kg ECM, followed by the groups INT, EXT and NEF.

It should also be noted that the farms of the group EFF have the highest value in terms of incomes and the lowest value in terms of costs, which explains the higher profit in comparison with the other groups. It is also interesting to observe that intensive farms are able to keep the costs low, but in terms of income, they reach the lowest rates. The other two groups (EXT and NEF) are not able to reach a positive profit, if subsidies are not taken into consideration.

In order to explain this hierarchy in the results, it is helpful to show the figures linked to the structure (Fig. 3) as well as to the management of the farm groups (Fig. 4). The figures of animal density as well as production intensity confirm that the groups INT and EXT have respectively the highest and the lowest production intensity and that the other two groups (EFF and NEF) are located in between, with NEF showing on average a higher intensity than EFF. The EFF group shows the lowest value in the farm area and the second lowest value in terms of number of dairy cows, very close to the lowest value of EXT group. This is a first hint that the farms of the EFF group try to capitalise maximally their own resources because these are limited in comparison with other groups. It appears consistent with the figures of animal density and production intensity that intensive farms (INT) show the highest values in farm size as well as in number of cows.

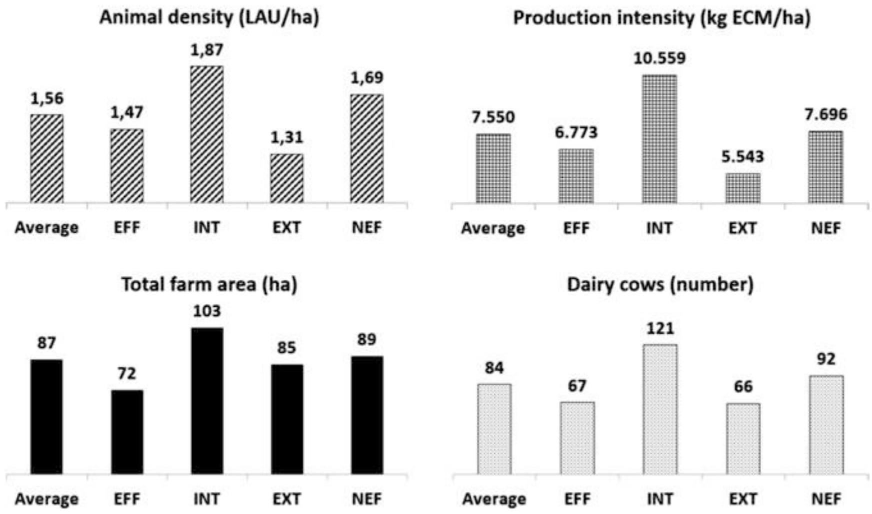


Fig. 3 Main figures of farm groups related to the farm structure

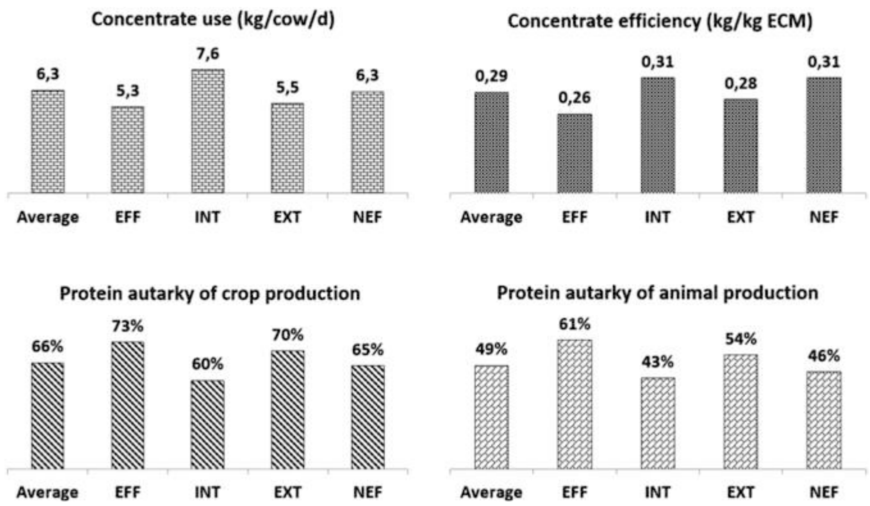
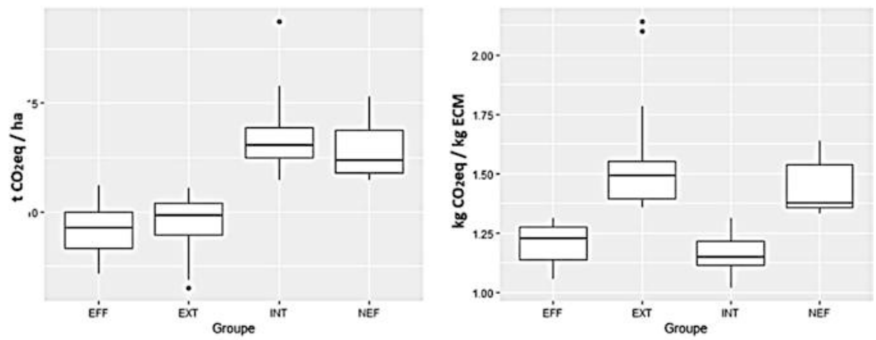


Fig. 4 Main figures of farm groups related to the feeding management

A second important point concerns the influence of management quality on the environmental impact of farm groups. As can be observed in Fig. 4, the most efficient farms (EFF) show also the best values not only in concentrate management but also in protein autarky. This is consistent with observation of other authors [20, 21], who stressed that feed management has a huge impact on the environmental result in livestock/dairy production in general and on carbon footprint in particular.



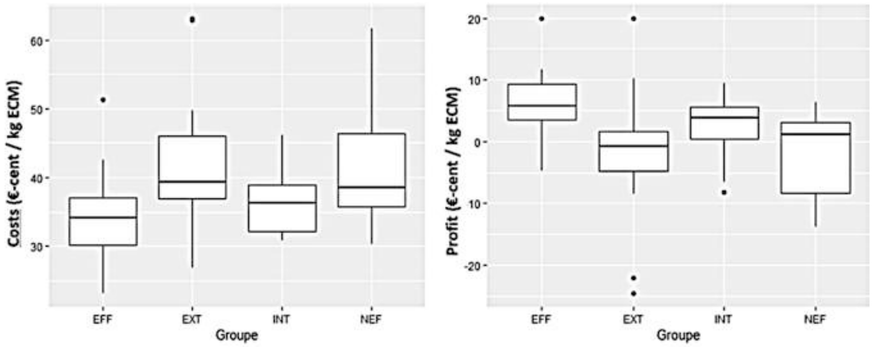
Variable	Significance [ANOVA]	EXT-EFF	INT-EFF	NEF-EFF	INT-EXT	NEF-EXT	NEF-INT
t CO_2eq / ha	0,0000	ns	0,0000	0,0000	0,0000	0,0000	ns
kg CO_2eq / kg ECM	0,0000	0,0000	ns	0,0000	0,0000	ns	0,0000

Fig. 5 Statistics of carbon footprint for the farm groups (*ns* not significant)

Further, it is interesting to point out that the hierarchy in feed management, as shown in Fig. 4, is more similar to the figures of surface-related impacts (Table 8) than to those of product-related ones. Indeed, if results are expressed per ha, extensive farms score better than intensive ones, and the latter show the worse result, which also is the case in Fig. 4. The highest level of milk production of intensive farms is evidently capable of concealing deficits in important management sectors such as feeding and providing better figures for these farms, if results are expressed related to the kg ECM.

A last consideration concerns statistical significance of differences in results among farm groups. As shown in Fig. 5 (for reasons of space, the analysis refers only to carbon footprint, but with few differences to the other three impact categories), the major part of differences among the groups are significant, although only in two situations (NEF-EFF and INT-EXT), the significance is given for both product- and surface-related indicators, which could be expected because of the kind of segregation. Further, the most efficient farms (EFF) show a behaviour that is closer to the extensive one, if the result is related to the surface, and to the intensives, if the result is related to the product. This suggests that these farms are best capable of combining a higher level of efficiency with a low level of environmental impact.

In the case of economic figures, the significance is only given for the groups EXT-EFF and NEF-EFF (Fig. 6). In the case of the pair EFF-INT, there is no significance in economic results, despite the fact that in the average the profit of the farm group EFF is higher than the group INT (Fig. 3). Nevertheless, the fact that in comparison with the other two groups (EXT and NEF) the results of the EFF group are better underlines that a better management also results in better economic figures.



Variable	Significance [ANOVA]	EXT-EFF	INT-EFF	NEF-EFF	INT-EXT	NEF-EXT	NEF-INT
Sum of costs (€)	0,0023	0,0062	ns	0,0231	ns	ns	ns
Profit without subventions (€)	0,0098	0,0113	ns	0,0322	ns	ns	ns

Fig. 6 Statistics of economic parameters for the farm groups (*ns* not significant)

4 Main Conclusions

- The use of product- and surface-related functional units allows a better understanding of differences in results among the farms.
- In particular, differences among intensive and extensive farms are mostly due to the farm structure, those among middle-intensive ones mostly to the efficiency in farm management.
- Although not always supported by statistics, there is evidence that efficient middle-intensive farms show better performance both environmentally and economically. Their environmental efficiency allows best economic performance.
- Based on this study, the conclusion that intensive farms always show better performance because of better product-related results cannot be confirmed.
- In times of liberalisation of milk quota, a smart feed management (especially of feed protein) seems to be a key lever for realising best performances both environmentally and economically.

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Dynamic and Localized LCA Information Supports the Transition of Complex Systems to a More Sustainable Manner Such as Energy and Transport Systems

Florian Ansgar Jaeger, Cornelia Sonntag, Jörn Hartung, and Katrin Müller

Abstract The paper gives a snapshot of the potential of LCA (life cycle assessment) data-based optimizations in control systems. The environmental burden of existing infrastructure can be significantly reduced during use phase. Four Siemens' applications in different fields with different lead indicators show how LCA assessments can be adapted to fulfil the requirements of such applications. The applications are power and air quality management use cases in the field of eMobility, building management, industrial process control and traffic management. The main methodological challenge solved is the provision of the necessary temporal and special resolution, as well as forecasting of parameters for scheduling of processes.

1 Introduction

Life cycle assessment (LCA) methodology has become common to assess products and services and even found its way into strategy processes of planning infrastructure to convert our cities into sustainable urban areas [1]. Infrastructure has very long life cycles. Our time to cope with global warming is running up quickly, and there is little doubt that we need to speed up our climate actions as humanity. But to reduce emissions in markets with long life cycles, where inefficient assets can't quickly be replaced with sustainable ones, proves slow. We therefore propose to use LCAs of infrastructure during operation to improve the environmental performance of these infrastructures. To integrate environmental target functions into control systems and reducing or shifting consumption can increase environmental performance compared to conventional, solely monetarily or functionally optimized control algorithms. The goal is to make LCAs fit for control systems.

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_6

2 Four Applications

The four case studies used as examples to show the potential of embedding environmental target functions into control systems are building, energy and transport cases:

- Smart charging for bus depots: A use case using flexibility in charging time of buses during their stay in bus depots in order to charge at times, where the grid mix has low average emissions. The analysis is part of the Mobility2Grid project and funded by the German Ministry for Education and Research.
- Smart cooling: A campus air conditioning system, which uses an ice storage in order to shift power consumption for cooling aggregates to times, where the grid mix has low average emissions. The analysis is part of the EnBA-M project and funded by the German Federal Ministry for Economic Affairs and Energy.
- Smart chemistry, methanol from steel mill gases: A case study using flexibility in power consumption, making an otherwise highly emitting process reduces GHG emissions. The analysis is part of the Carbon2Chem project and funded by the German Ministry for Education and Research.
- City Air Management: An online service operative in Nuremberg which is used to forecast events of high air pollution on a 5-day horizon at a street site measurement station. It simulates different interventions for this period to select them at times of maximum efficiency.

The methods described are a combination of conventional LCA, executed in LCA software and conventional control systems including forecasting algorithms and optimization algorithms. From a pure LCA prospective, they are based on comparative LCA, since the optimizer, no matter if machine or human operator, has to select between different scenarios. Not all assessments cover the full life cycle.

3 Smart Charging for Bus Depots

To guarantee operations of electric bus depots, charging infrastructure is slightly oversized in order to compensate for high demand events such as very cold or hot weather, delayed buses, maintenance and many other inconveniences. This necessary flexibility creates times at which buses are not charged and the grid connection is not fully utilized. This case study is an ex post analysis of the potential of this flexibility to reduce carbon emissions by charging at times, where the grid provides power of low CO2e emissions. Three scenarios are analysed:

- Plug and charge: The buses are connected to the charger and start charging at full power, as soon as they are parked after returning to the depot and going through their daily routine.
- Cost-optimized: The buses are charged at max. Power during the period where the cost for power at the day-ahead market is the lowest without exceeding the grid connection.

- GHG-optimized: The buses are charged at max. Power during the period where the average GHG emission per kWh is the lowest without exceeding the grid connection.

The energy demand and schedules of the bus operation are based on real data from 140 Berlin diesel buses. Due to range restrictions, many buses are assumed to opportunity charge on the route. This increases the flexibility in depots.

3.1 Method

All three scenarios have the same hardware requirements, which is why only the power consumption during operations is part of the assessment. Only bidirectional charging or regulating the charging power based on battery wear would result in the necessity of expanding the system boundary to include the battery production and end of life. To calculate the optimum charging times based on an economic and a GHG target function, dynamic prices or emission functions for power are necessary. The spot market provides economic cost. Taxes and T&D (transmission and distribution) are not included. The dynamic country-based GHG emission factors per kWh are calculated on a time resolution of 15 min for Germany. T&D and upstream emissions are included. The grid mix is known for this time resolution, and each share of each energy carrier is multiplied with its respective energy carrier, as common for annual emission factor aggregates for countries too.

Combined with the bus schedules, dynamic emission factors feed into an optimizer, which defines at which time the buses are charged. The optimizer is set to optimize according to the target functions of the three scenarios stated above (view Fig. 1 Optimization Problem). The secondary constraints are the times the bus is available for charging, 100% state of charge when leaving the depot, the charging power and the grid connection limit of the depot. GHG emissions and cost for power are added up according to the resulting charging schedules of the three scenarios.

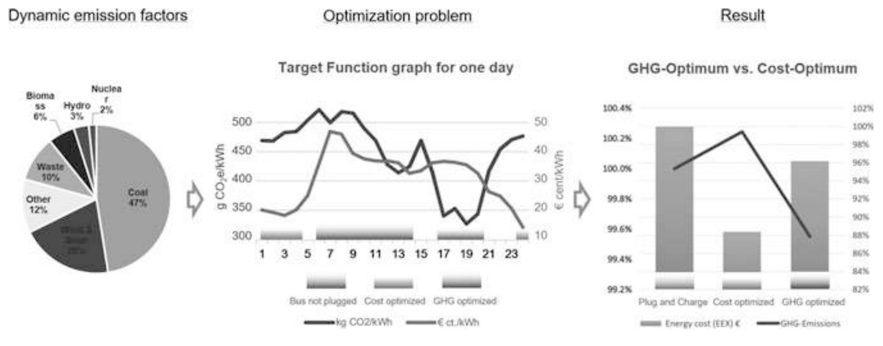

Fig. 1 Smart charging use case process

3.2 Results

The results show that the cost-optimized charging schedule does reduce the cost for power purchase at the energy market by almost 12% compared to a non-optimized plug and charge scenario. This results in a small increase in GHG emissions per kWh. The GHG-optimized charging schedule reduces GHG emissions by less than 0.5% and reduces cost by 4% compared to the plug and charge scenario (Fig. 1 on the right, GHG optimum vs. cost optimum).

3.3 Interpretation

The flexibility to shift charging times of buses is small. The shifting is only possible in the range of a few hours at maximum. The flexibility is almost exclusively available at night. There is almost no flexibility during daytime. But GHG emissions of the German grid mix don't frequently change drastically in short periods during the night, since there is no PV (photovoltaic power) at night and low-pressure zones for wind are moving slowly. This combination results in a marginal GHG saving potential of this application. In order to facilitate cost savings, however, the flexibility is relevant. Power prices at the power markets change more quickly at night, since the demand side has a larger impact. Cost-saving algorithms don't necessarily reduce GHG emissions as to be seen when looking at the results of the cost-optimized scenario.

4 Smart Cooling

Air conditionings are flexible loads. They are rarely running on full power, and any building has a certain thermal inertia, which can be used to store thermal energy. For this project, the thermal storage for the air conditioning was increased by adding a large ice storage to the system. The ice storage increases the temporal flexibility for power consumption. It can be charged independent of the demand of the building and discharged independent of the heat pump. This allows load shifting to provide similar services as smart charging. But in this case, the flexibility is much larger in the sense that power consumption can often be delayed or consumed ahead of time for several days. Additional complexity is added to the system compared to battery charging. The COP (coefficient of performance) and therefore the efficiency of the system differ significantly depending on the spread between the ambient temperature and the temperature of the thermal storage. These two parameters, plus the losses of the storage at high spreads over time, impact the overall power demand of the system. Since this system sets schedules in operation, the optimization is based on forecasted parameters for weather, power cost and emissions. The three scenarios and control mechanisms tested were similar to the smart charging case:

- Reference Scenario: System running without making use of the storage.
- Cost-optimized: The ice storage is filled at times with the best ratio of low power cost and high COP.
- GHG-optimized: The ice storage is filled at times with the best ratio of low relative GHG emissions for power and high COP.

As an additional indicator, the overall electricity demand is plotted.

4.1 Methodology

Even though the ice storage is not necessary for the operation according to the first scenario, production and end of life of the storage are not assessed. The storage was already available, but not in use, since cheap night rates for power had been abolished. The methodology of generating the environmental cost functions is the same as for bus charging above. But the data is based on forecasts for ambient temperatures, cooling demand of the buildings, cost and GHG emissions per kWh. The weather forecast is a commercially available API, and the other parameters are forecasted based on historical data of cooling demand and power generation mixes and day-ahead forecasts on renewable power generation and electricity load on the grid.

4.2 Results

Cost- and GHG-optimized operations are compared with the reference scenario. The cost-optimized operation shows a little reduction in power consumption of 0.2%, the GHG emissions increase by the same amount and the cost for power reduces by 4% (only cost at the power market). The GHG-optimized operation increases power consumption by 4% but reduces GHG emissions by 6%. Cost for power increases by almost 2% compared to the reference operation (Fig. 2: On the right).

4.3 Interpretation

It appears contradictory that the GHG-optimized operation leads to a higher power consumption. Figure 2 shows in the magnifier in the middle that the GHG-optimized operation leads to high power consumption in the middle of the day. This is due to the high availability of PV. The PV drives down the relative GHG emissions of the power mix at noon. This overcompensates the poor COP at daytime where ambient

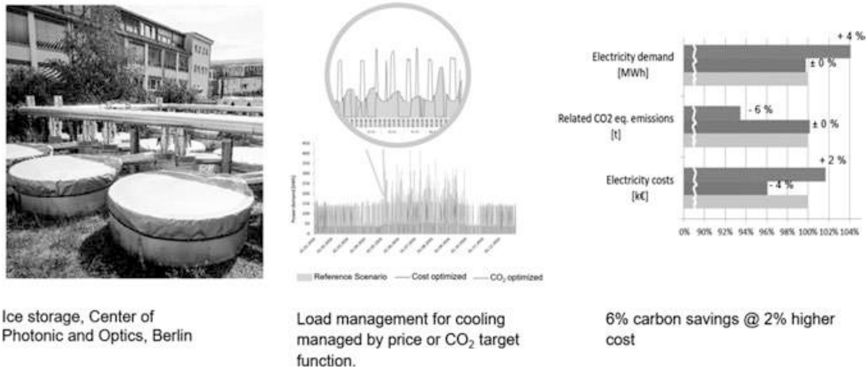

Fig. 2 Smart cooling use case process

temperatures are high and the temperature spread between the ice storage and heat exchanger outside is high. Power cost is more demand driven; thus, cost can also be low at night, where the COP is more favourable. The case shows once again that cost- and GHG-optimized operations can lead to opposing results and create conflicts of interest.

5 Smart Chemistry, Methanol from Steel Mill Gases

The concept of carbon capture and use is to use CO_2 emissions from industrial processes and to reduce them with hydrogen in order to create basic chemicals such as methanol. This project uses electrolysis of water for the production of hydrogen. The target is to draw power when the load on the grid is lower than production in order to minimize curtailment of electricity from renewable energy sources. Using the fossil-based methanol production process as a benchmark, it was determined that, in addition, the power for electrolysis has to stay below 0.2 kg CO_2 eq./kWh with its GHG emissions to generate carbon savings.

5.1 Methodology

The methodology in use is very similar to the first two applications. Since it takes a long time to set up such a large-scale system, forecasting becomes inevitable even to determine the environmental performance of the first year of operation. A power scenario with an hourly resolution with times and volumes of excess energy is created in a multi-model scenario approach. It is based on publicly available plans and policies for the development of installed capacities of German power plants by energy carrier and the net structure in 2030, combined with appropriate

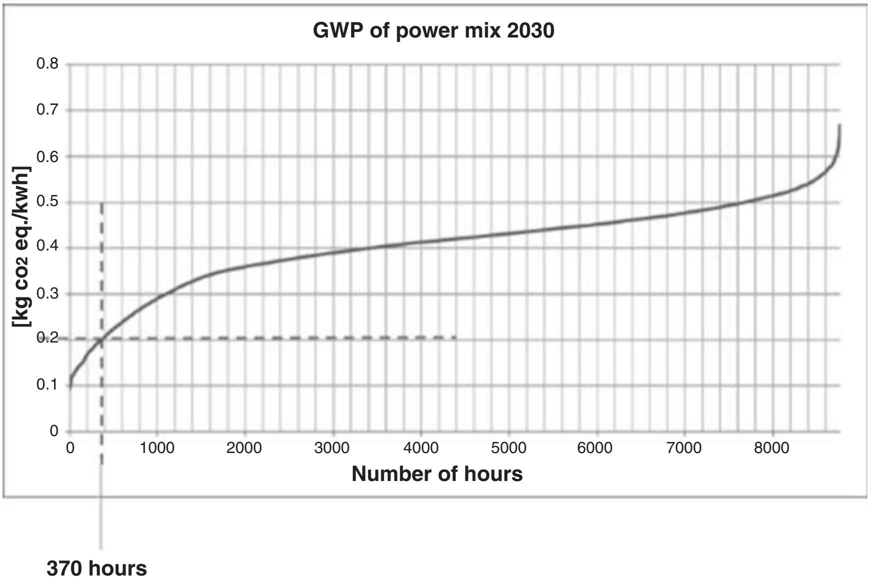

Fig. 3 GWP distribution of power

meteorological data. For the resulting power production profile, the greenhouse gas intensity of power production is calculated on an hourly base.

5.2 Results

For the underlying assumptions regarding the share of installed renewable energy sources, which results in a share of 47 per cent on gross power production, only 370 hours per year fulfilled the criteria of being below 0.2 kg CO_2 eq./kWh (Fig. 3). During these 370 h, the share of renewables in the power mix accounts for at least 70 per cent (Fig. 4). All these time periods coincide with periods of excess energy.

5.3 Interpretation

The analysis indicates that for the underlying assumptions on the share of renewables in power production, only few operating hours meet the criteria of low enough greenhouse gas emissions. A fluctuating electrolysis therefore would require immense capacities for electrolysis and hydrogen storage which cannot be implemented in practice due to economic reasons and required space. Moreover, hydrogen storage would lead to additional environmental impacts, not covered by this

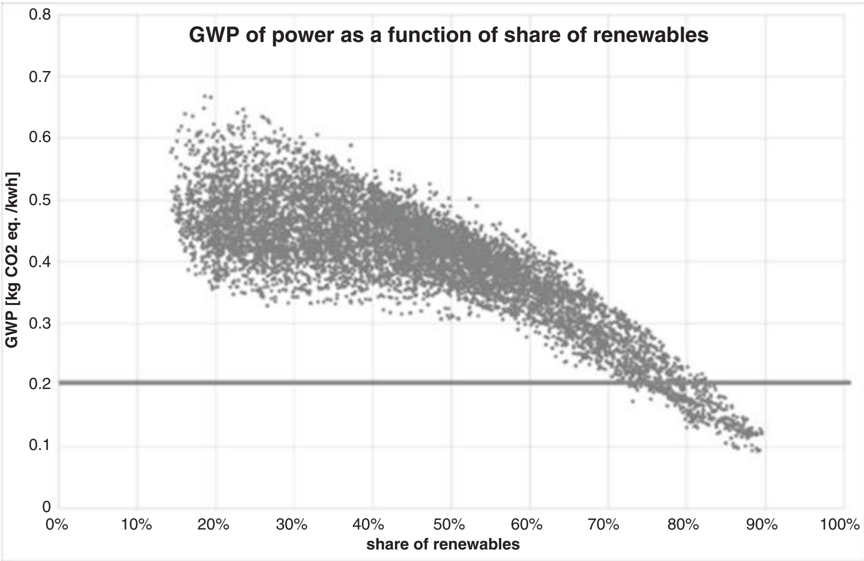

Fig. 4 Share of renewables at 200 g CO_2 eq./kWh

analysis. Hydrogen electrolysis during hours not meeting the low greenhouse gas level would cause a net increase of global warming impact of the CCU concept in comparison with the conventional processes of steel and methanol synthesis. This analysis is very sensitive to the assumed share of renewables and thus curtailment. Political targets for renewables have just been raised after the analysis. The potential of using excess energy for electrolysis will be recalculated under the new framework. The remaining hydrogen demand should be covered by hydrogen directly produced from renewable energy sources.

6 City Air Management

The City Air Management is an online web service which helps cities to manage local air quality at roadside measurement stations for the next 5 days (Fig. 5). It provides three basic functionalities for the air pollutants PM10, PM2.5 and NO_2:

- Monitoring the air quality at public measurement stations on a dashboard.
- Forecasting of air pollutants at these locations for 5 days.
- Intervention simulation and calculating pollution reduction of measures.

Instead of taking year-round measures, cities can take action when and where they have the highest impact.

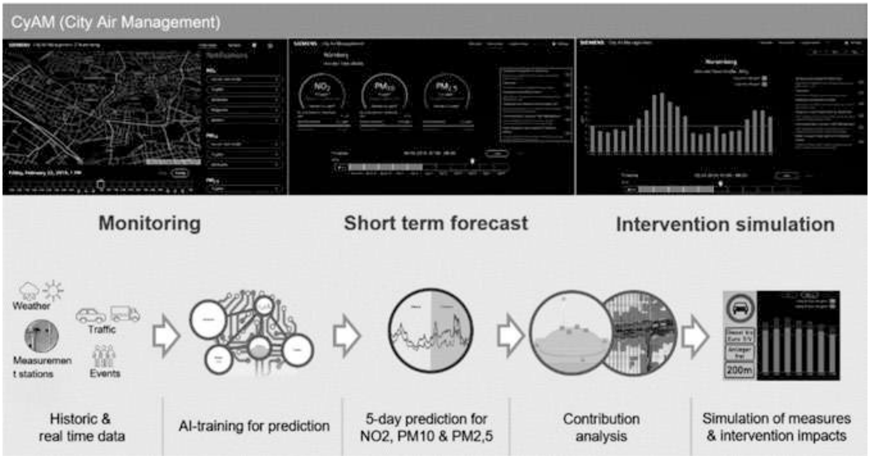

Fig. 5 City air management visualization and process

6.1 Methodology

Monitoring

Cities/counties/states operate their own air pollution sensor networks in order to prove their compliance with national or international regulation. This data is gathered on central servers and publicly available in most parts of the world. The CyAM has an API which allows this data to be pulled from this server or pushed to the CyAM as soon as the data is available. This is commonly every hour. The data for the individual measurement stations is visualized, categorized and benchmarked against the legal thresholds in a dashboard. It provides an immediate evaluation of the current situation and information on whether it is necessary to act. The latest history is also available for review, as well as the gliding annual average.

Forecasting

There are two common options to do forecasting for air pollutants, domain models and artificial intelligence. Domain models in this case are models which understand the physical and chemical processes of emission source behaviour and the atmospheric processes during transmission of pollutants. There are a vast variety of emission sources in and around a city. It involves tremendous efforts to assess all relevant fractions in real time. The modelling of the transmission (distribution plus the physical and chemical processes of the pollutants in the air) is time consuming, requires high computing capacities and is very sensitive to poor weather forecasts.

Thus, CyAM uses artificial intelligence to forecast air pollution concentrations at individual air quality measurement stations. It takes few available parameters which are available as forecasts. With historic data, it builds a temporal algorithm based on standard error backpropagation [2]. CyAM also uses air pollution measurement data, weather data/weather forecast data, calendric data and special events. The AI finds correlations and patterns in this data to predict air pollution for individual measurement stations. It doesn't contain any knowledge about the physical and chemical processes, responsible for these concentrations. Based on real-time data and forecasts of weather – and calendric/event data – a 5-day forecast is provided. The Advantage is a model which has high precision, takes little computing power during operation and requires few data points.

Intervention Impact Calculation
In order to calculate impacts of individual measures, a domain model is inevitable. But it only models the emissions which can actually be impacted by interventions, in this case traffic related. The traffic emissions are calculated for each hour of the following 5 days based on assumptions from historic data, calendric information and temperature forecasts for the baseline. Emissions for scenarios are then calculated for each intervention in SimaPro. Tailpipe emissions are based on HBEFA [3]. Some example interventions for specific street sections are:

- Allocation of eBuses on the lines passing the street section.
- Temporary driving ban of trucks or diesel cars for the street section.
- Low emission zones for the street section.
- Public transport ticket for air pollution season.

The local traffic-related share of the forecasted concentrations at the hotspot measurement station is determined correlating the forecasts of individual measurement stations in different locations. The combination of the traffic emission scenarios, the emission forecast and the traffic-related contribution of the forecasted concentration enables the prediction of the interventions' impact (Fig. 5).

6.2 Results

The accuracy of the forecast is measured by identifying how many of the 30% most polluted days were accurately predicted 5 days ahead of time. For NO_2 at the most polluted measurement station in Nuremberg, which is the lead indicator and location, this is 80%. Since it is an operational web service, the results are visualized on a dashboard as to be seen in the top three screenshots of Fig. 5. To evaluate the efficiency of the traffic interventions, the very same methodology is used as an ex post evaluation during the consulting phase of the project when the city selects which interventions they would like to have on the dashboard. The efficiency increase of temporary vs. all year-round measures is visualized in Fig. 6. The graph shows the results of the flexible truck ban for an individual road section in Nuremberg as a sum curve. The impact of the intervention is calculated for every day, relative to the annual saving. The jagged line is the historical sum curve from January 1 (on the very left, day 1) to December 31 (on the very right, day 365); see x-axis for the number of days per year. The smooth line sums up these savings, starting with the most efficient day of the year (on the very left, day 1), no matter if it is in January

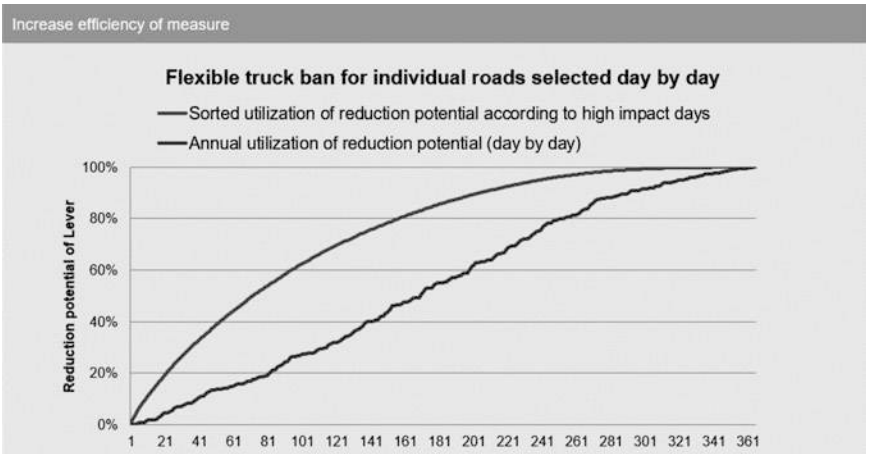

Fig. 6 Example efficiency of temporary vs. all year-round measures

or December, ending with the least efficient day of the year (on the very right, day 365).

6.3 Interpretation

The spread between these two lines shows the potential efficiency increase by implementing an intervention on a temporary basis, compared to an all year-round implementation. If a street section driving ban for trucks was implemented on the 70 most efficient days of the year, the yield in air pollution savings at the measurement station would be 50% of an all year-round implementation. In return, the least efficient 200 days, where there is enough wind to reduce emissions, only yield 20%. The efficiency of interventions measured as local air quality increase over days with traffic restrictions is most significant the fewer days they are triggered. Due to the fact that the forecast is not 100% accurate, the efficiency of the operational system is slightly lower, but cannot be determined at this stage of the project. Despite the efficiency, few cities apply such methods until now [4].

7 Conclusion

The use of environmental target functions in control systems has large potentials, reducing both global and local environmental impacts. Even when compared to economically optimized control strategies, environmental target function-based optimization can deliver significantly better environmental results. This is true even if cost of GHG emissions is priced in to some degree already at the energy markets, for example. The potential depends on the flexibility that is controlled and the volatility of the environmental impact. For some systems, environmental optimization-based control systems become absolutely crucial to create net environmental benefits compared to fossil-based processes. A large-scale hydrogen electrolysis for methanol production from CO_2 requires an optimization based on short-term prognosis for global warming impact of power production in order to meet the target of net reduction of greenhouse gas emissions.

From a methodological point of view, conventional LCA software and tools can deliver the environmental cost or burden of any state of the system for control purposes. The temporal and spatial resolution has to reflect the resolution at which any control system or short-term advisory tool operates.

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Applying the Life Cycle Assessment (LCA) to Estimate the Environmental Impact of Selected Phases of a Production Process of Forming Bottles for Beverages

Patrycja Bałdowska-Witos, Robert Kasner, and Andrzej Tomporowski

Abstract The study concerns the current issues of the impact of packaging on the natural environment. The main goal was to analyse the life cycle (LC) of a beverage bottle made of polyethylene terephthalate. The functional unit comprised a total of 1000 PET bottles with a capacity of 1 l. The limit of the adopted system included steps from the moment of delivery of preforms to the production plant until they were properly shaped in the process of forming beverage bottles. Excluded from the system were the further stages of the production process, such as beverage bottling, labelling or storage/distribution. The processes related to the transport and storage of the raw material were also excluded. The LCA analysis was performed using the program of the Dutch company Pre Consultants called SimaPro 8.4.0. The "ReCiPe 2016" method was selected for the interpretation of lists of emitted chemicals. The results of the tests were presented graphically on bar charts and verified and interpreted.

1 Introduction

Activities of environmental organizations aimed at the development of pro-ecological behaviour of the population effectively communicate about positive and negative environmental impacts [1]. The model of behaviour shaped over the years has led to the development of various methods for identifying the occurrence of environmental threats [2]. An example of a method successfully implemented in industrial practice is the more and more frequently used life cycle assessment (LCA) [3, 4]. The LCA technique represents a new approach to assessing the potential environmental impacts of the beverage bottle manufacturing process. The growing ecological awareness of the society obliges production plants to carry out

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_7

environmental analysis. Such behaviour forces enterprises to strive for continuous improvement of the production process [4]. Change or modernization of technology should limit or minimize negative environmental impacts, take care of the environment and reduce or eliminate the negative effects of the production process [5]. The paper presents the results of the assessment of environmental impacts used in the technological process of bottle production. The goal of the study was to determine the potential levels of impact of individual technological operations on the condition of the natural environment and human health throughout the entire cycle of shaping bottles for beverages.

2 Materials and Methods

2.1 Research Methodology

The assessment of environmental loads was carried out for the production process of shaping bottles for beverages adopted in the study [6]. Collected industrial data from the bottle blow moulding machine made it possible to transform these data into the adopted functional unit. The analysis was performed using the ReCiPe 2016 method. Potential magnitudes of impacts from all environmental impacts were analysed [3, 6].

2.2 Determination of Goal and Scope

LCA is a tool used to assess the overall environmental impact of a product from "cradle to grave" [6]. For this purpose, the technological process of shaping PET bottles in Poland was assessed. The process is broken down into six unit operations, taking into account the demand for media and materials [6, 7]. The scope of the analysis included preform conveyor (CP), heating preforms (HP), stretching and lengthening the preform (SLP), blowing preforms (BP), degassing the bottle (DB) and cooling the finished bottle (CB).

2.3 System Boundary and Functional Unit

Six technological operations were adopted for the analysis (Fig. 1). As a result, the technological operations of the adopted processes were burdened with the same simplifications, which allowed assuming the exclusion level below 0.01% of the share in the entire life cycle. In inventory analysis, the examined systems and their system boundaries are defined, and process flow diagrams are drawn. Data collected

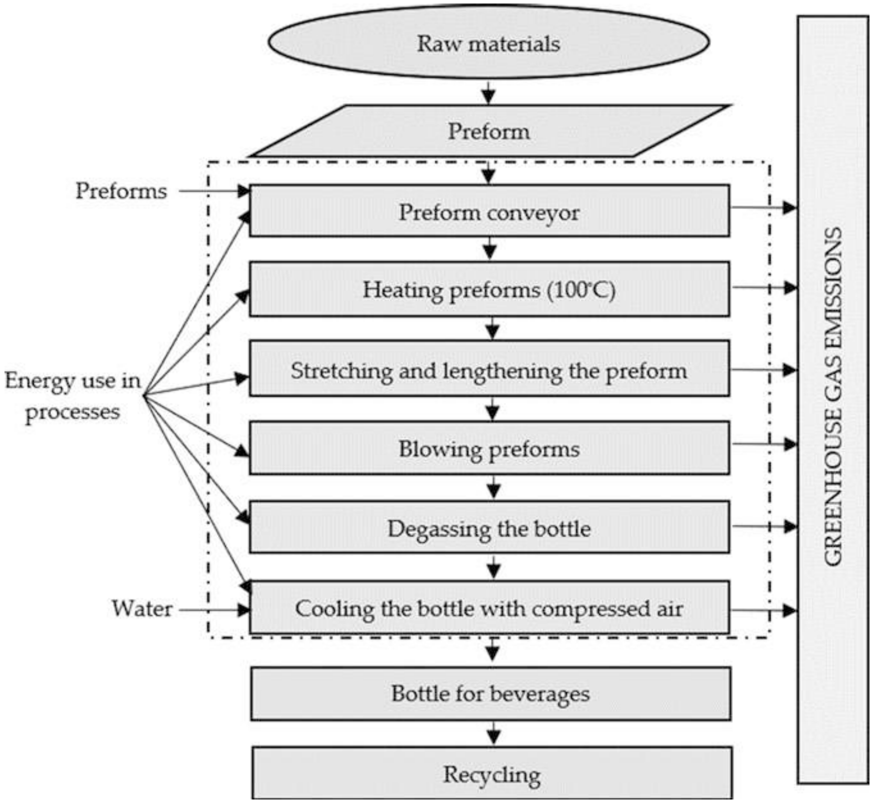


Fig. 1 Block diagram of the PET bottle production process

includes production, resource consumption and energy consumption. The functional unit adopted for the research was determined on the basis of data collected from the production company. It describes the production of 1000 bottles with a capacity of 1 l.

3 Results

The first stage of the research included defining the objectives and scope of the analysis, including checking the completeness and compliance of the adopted measurement data. The second stage of the research included the results of the analysis of the set of inputs and outputs. Developed on the basis of analytical results, it can be concluded that greenhouse gases responsible for the greenhouse effect, ultimately causing global warming, such as carbon dioxide and methane, are often released to the atmosphere from natural causes and anthropogenic origin [4, 8].

Potentially, the greatest negative impact on climate change was recorded for the degassing process of the finished product (DALY 1.16347E-08) (Fig. 2). Lower emission levels were observed for terrestrial ecosystems (3.51106E-11 species.yr) (Fig. 3) and freshwater ecosystems (9.5902E-16 species.yr) (Fig. 4). All of the three impact categories presented show the share of the raw material in the entire process of shaping the PET bottle at the level of approx. 78% of the impact in a given impact category. In the case of the stratospheric ozone depletion category, the highest potential environmental damage was caused by the degassing of the finished bottle (Fig. 5).

The emissions of non-carcinogenic toxicity for human were highest during the degassing step of the shaped PET bottle (8.04032E-11 DALY), while the second value in terms of emission was the bottle pressure forming process and the process of automatic stretching and lengthening of the previously heated preform (Fig. 7).

Fig. 2 Global warming, human health

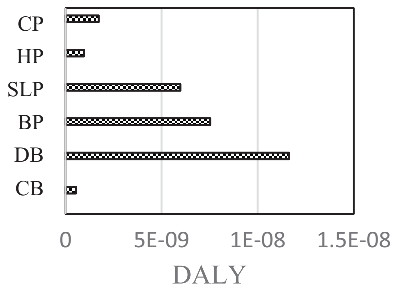


Fig. 3 Global warming, terrestrial ecosystems

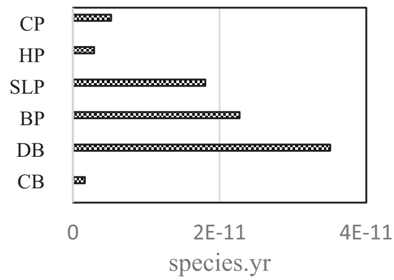
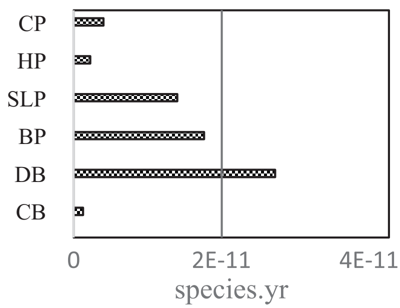


Fig. 4 Global warming, freshwater ecosystems



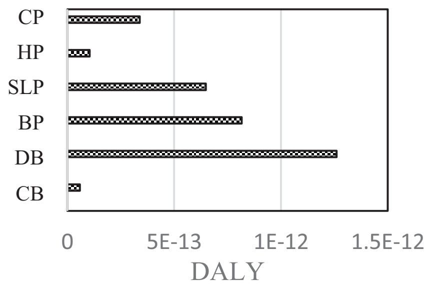


Fig. 5 Stratospheric ozone depletion

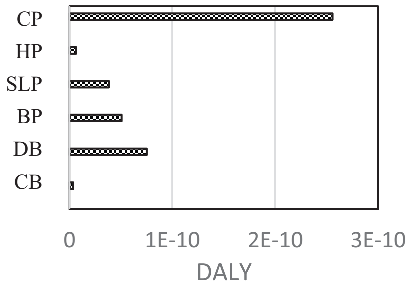


Fig. 6 Human carcinogenic toxicity

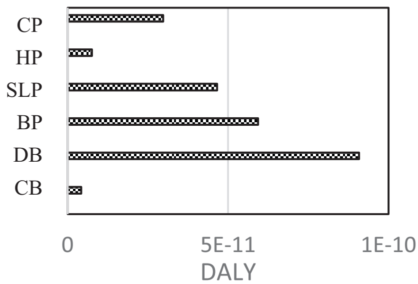


Fig. 7 Human non-carcinogenic toxicity

The total share of PET material in the technological process of shaping a PET bottle was only 1.76E-09 DALY. Significantly lower emission levels were observed for the whole human carcinogenic toxicity category (Fig. 6). The source of electricity is largely responsible for the amount of non-carcinogenic compounds emitted, and the amount of their emissions increases in stages as the production process progresses.

The ozone layer lies in the Earth's atmosphere and plays a key role in protecting living forms of nature [4]. Based on the analysis, it is proved that the process of shaping bottles exhibits greater environmental damage in the case of category zone formation, human health (Fig. 8) than in the case of category ozone formation, terrestrial ecosystems (Fig. 9).

Ecotoxicity of the aquatic and terrestrial environment results from the release of poisonous and toxic substances into the environment. Freshwater ecotoxicity shows the highest potential emission value specified for the degassing process of PET bottles (1.74682E-11 species.yr) (Fig. 11). The greatest potential impact on terrestrial ecotoxicity was exerted by degassing the PET bottle and was 1.79512E-11

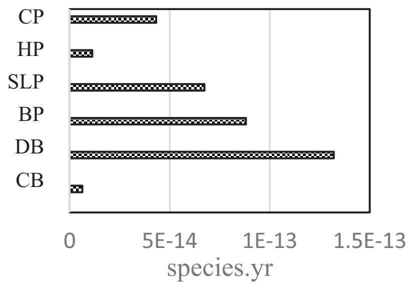


Fig. 8 Ozone formation, human health

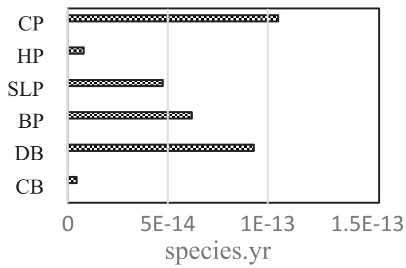


Fig. 9 Ozone formation, terrestrial ecosystems

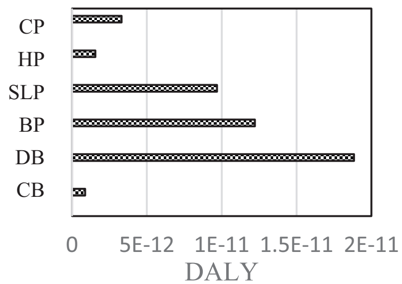


Fig. 10 Terrestrial ecotoxicity

species.yr. (Fig. 10). Among the six analysed unit processes, the lowest negative impact was noted for the cooling process of the shaped bottle.

Acidification of the terrestrial environment is caused by a lowering of the pH value. This phenomenon occurs as a result of disturbance of the ecological balance of the processes of energy and matter exchange between elements of ecosystems [4]. The process of cooling the finished product had the lowest negative impact in the entire shaping process, while the degassing process of the bottle had the greatest negative impact. Lower emission levels were observed for the terrestrial acidification category (Fig. 12). Characterizing the entire process of creating the bottle, the degassing process of the finished product (5.72E-12 species.yr) had the greatest impact on the land use category and slightly less (3.68E-12 species.yr) on the preform pressure shaping process, and nearly 1% of the impact was recorded for the preform-in-mould stretching and elongation process, and less than 1% for the preform processes prior to heating, heating and cooling the finished product (Fig. 13).

Ionizing radiation is a phenomenon that has always been present in the surrounding environment [4]. The greatest potential negative impact was emitted by one of

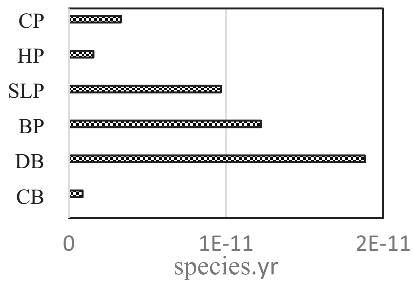


Fig. 11 Freshwater ecotoxicity

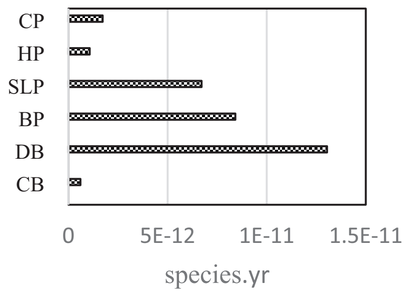


Fig. 12 Terrestrial acidification

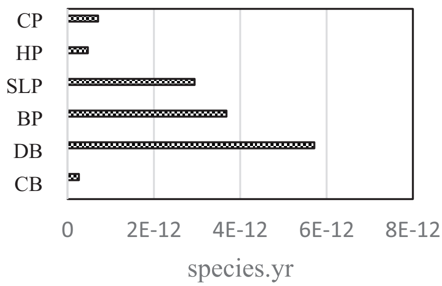


Fig. 13 Land use

the sub-processes related to the amount of finished/semi-finished product used in the process – PET preform. The value of the issue was 2.11051E-13 DALY (Fig. 14). Local values of air pollutants generated by production plants do not provide accurate information on the scale of local emissions. As a result of the conducted analysis, it was determined that the greatest negative impact of the bottle shaping process on human health was recorded for the process of creating a PET bottle (1.18812E-08 DALY) at the stage of degassing the finished product. The lowest value of negative particle emissions affecting human health was determined for the PET bottle cooling process (4.59705E-10 DALY) (Fig. 15).

The PET bottle shaping process showed the higher potential level of adverse effects in the preform collection process for the reheating oven for the mineral resource scarcity category (Fig. 16) than for the fossil resource scarcity (Fig. 17). With the growing global demand for mineral resources, it is important to analyse whether the resources of geologically and technically available minerals in the Earth's crust can meet the future needs of humanity. Increasing recycling, material

Fig. 14 Ionizing radiation

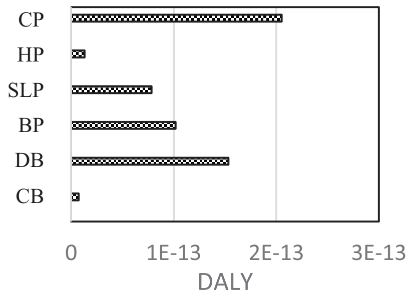


Fig. 15 Fine particulate matter formation

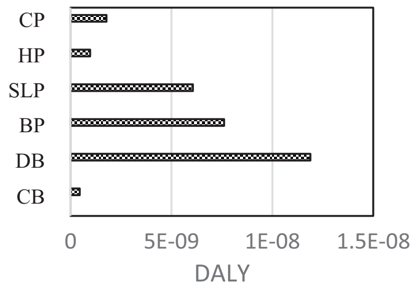


Fig. 16 Mineral resource scarcity

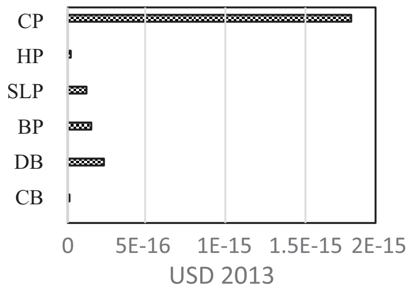
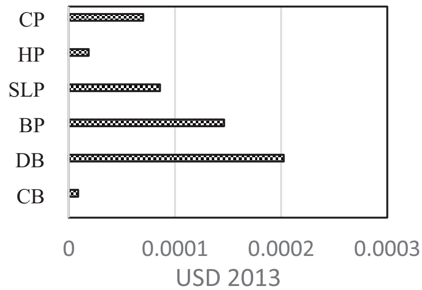


Fig. 17 Fossil resource scarcity



efficiency and demand management will surely play an important role in meeting future generations. A significant high value of potential impacts was recorded for the fossil resource scarcity category. The bottle with the greatest impact on this category was the PET bottle (8.58689E-05 USD2013) in the preform stretching and elongation process; the process of taking the preforms to the heating furnace (7.00854E-05 USD2013) was responsible for a slightly smaller amount of negative effects. This phenomenon is related to the fact that PET requires continuous extraction of fossil fuels, resulting in their depletion. This proceeding confirmed the highest staged impact of bottle production, and therefore the PET bottle probably had the greatest impact in the mineral extraction category. The production of the bottle had a slightly smaller impact in this category, possibly due to the fact that resource extraction is also needed.

Water consumption has an impact on human health and the quality of aquatic and terrestrial ecosystems. Water is critical to industry, the planet and people around the world. The production plant is a tycoon in the production of beverage bottles in the world. It uses a significant amount of the raw material, which is polyethylene terephthalate. However, its production significantly affects the condition of the natural environment. It was shown that for each of the two analysed impact categories, it was

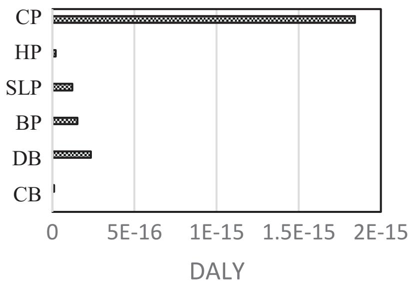


Fig. 18 Water consumption, human health

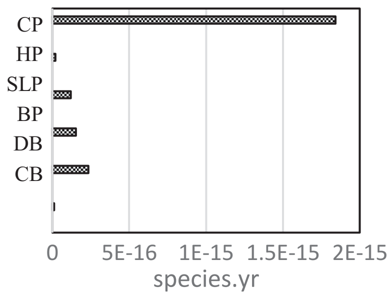


Fig. 19 Water consumption, aquatic ecosystems

the preform conveyor operation that showed the highest potential negative environmental damage (Figs. 18 and 19).

4 Conclusion

The presented analyses of the technological processes of shaping bottles for beverages are characterized by various potential impacts on the condition of the natural environment. The environmental life cycle assessment [9] allowed for the conclusion that at the operational stage, the greenhouse gas emission index depends on the amount of electricity used in the production process [10]. The high level of impact on human health is determined by the raw material used in the production process – polyethylene terephthalate. In order to reduce the emission of negative impacts on the natural environment, producers of the food sector should constantly look for substitutes for raw materials from exhaustible fossil resources. The right direction of development is the popularization of biodegradable raw materials of natural origin. There is an urgent need for further research related to the environmental assessment of the beverage bottle manufacturing processes. In further considerations, the development of a method of waste management in the production process should be considered.

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Part II
Sustainable Technologies

Accounting for the Temporal Fluctuation of Wind Power Production When Assessing Their Environmental Impacts with LCA: *Combining Wind Power with Power-to-Gas in Denmark*

Romain Besseau, Milien Dhorne, Paula Pérez-López, and Isabelle Blanc

Abstract Worldwide wind power capacity is increasing, while the environmental footprint and economic cost of energy produced decrease. However, wind power generation is weather-dependent. At a high penetration rate, storage systems such as power-to-gas may become necessary to adjust electricity production to consumption. This research work presents the environmental life cycle performance of wind power accounting for the energy storage induced by the temporal variability of weather-dependent production and consumption. A case study in which wind power installations are combined with a power-to-gas system in Denmark to provide electricity according to the national load consumption profile was considered. Results highlight an increase, roughly by a factor 2, of the carbon footprint coming from both energy storage infrastructure and induced losses, but remain significantly, at least ten times, lower than fossil counterparts.

1 Introduction

Renewable energy systems (RES), promoted to limit the dependency of the energy mix to fossil fuel, and the environmental impact associated with their use are currently prospering at a global level [1].

Although RES are based on the exploitation of renewable sources, this does not mean that the renewable energy generated is impact-free. Indeed, energy and materials are necessary to build, operate, and dismantle those systems. Life cycle assessment (LCA) is an appropriate tool, often applied to assess the environmental footprint of RES [2]. LCA results published in the literature highlight that RES generally present significantly lower environmental footprint over the life cycle than fossil fuel-based alternatives [3].

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_8

Moreover, it is positive to note that along with the development of RES industries, the efficiency of systems and the underlying manufacturing processes have improved, leading to better environmental performance as well as economic performance with time [4, 5]. These improvements pave the ways to a massive deployment of affordable and low environmental footprint renewable energy.

However, the electricity production of RES can be weather-dependent, as in the case of wind power, and not necessarily in adequacy with consumption. As a consequence, the massive integration of these technologies into the electricity mix requires the use of either dispatchable power plants or storage systems to be able to balance production with the consumption load profile at any time and thus maintain the grid stability [6].

With a wind power production equivalent to 45% of the annual electricity consumption in 2017, Denmark is an example of a country with high penetration of RES [7]. Thus, the balance between production and consumption strongly relies on the interconnection with Baltic countries and local combined heat and power (CHP) plants. Baltic countries are richly endowed with hydropower plants that can adjust their own production and even pump back water to store energy [8]. Denmark is also equipped with particularly flexible CHP plants [9]. Investments have been done to lower their minimum power output, provide overload ability, increase their ramping speed, and reduce the cost and time to stop and start power generation.

Existing hydropower capacities are limited, and the potential for new hydropower installations equipped with large reservoirs remains low in Europe [10]. In addition, the use of CHP plants relying on fossil fuel must be reduced as low as possible to mitigate climate change. As a consequence, new solutions for further integration of weather-dependent RES become necessary.

One of those solutions is the use of power-to-gas (P2G) systems, which consist in turning electric power into synthetic gas. Electricity is used to hydrolyze water molecules and generate dihydrogen (H_2). This gas can be stored and used directly or turned into methane (CH_4) after an additional transformation called methanation. P2G, by coupling electric and gas grids, offers the possibility to store massive amount of energy over long periods of time. Thus, P2G is a storage technology able to provide long-term potentially seasonally or annually contrary to electrochemical batteries that are limited to short-term storage [11]. Once stored, the gas can be used to generate back electricity in a gas power plant or be used for mobility purposes, heat, or industrial uses. For those reasons, IEA [12] and other energy experts [11] see P2G as a determinant technology for electric systems' operation.

As RES themselves, storage technologies require materials and energy to be manufactured, operated, and dismantled and therefore involve environmental burdens. Few LCA studies have been published and most of them focus on mobility applications [13, 14]. For such applications, the P2G system is continuously used to maximize gas production and does not adapt to the fluctuations of RES production. As a consequence, P2G systems considered for mobility applications present ultimate load factors of 91% approximately, corresponding to 8000 h/year at full load [14]. This level is much higher than what would correspond to a P2G system designed to cope with the variability of renewable energy sources. Thus, LCA results calculated for mobility applications cannot be directly extrapolated to assess the environmental performance of P2G systems designed to balance the fluctuation of renewable energy production.

Consequently, we assessed the environmental life cycle performance of renewable energy accounting for the energy storage induced by the temporal variability of weather-dependent production and consumption. A case study in which wind power installations are combined with a power-to-gas system in Denmark to provide electricity according to the Danish load consumption profile was considered. Denmark has been chosen as wind power is highly developed with, in 2017, a production corresponding to 45% of electricity consumption [7], which is expected to increase [7], and P2G technologies already under study with a project of P2G demonstrator [15].

2 Material and Methods

To assess the environmental performance of a system composed of wind turbines combined with P2G storage, the following elements need to be modeled and quantified:

1. The environmental impacts of wind turbines.
2. The environmental impacts of the components of a P2G system.
3. The need and use of storage.

Environmental impacts were calculated using the Python library *Brightway2* [16] dedicated to LCA and using the cutoff version of ecoinvent 3.4 for background life cycle inventories.

2.1 Environmental Impacts of the Wind Turbine

Environmental impacts of wind turbines are assessed making use of the parametric LCA model developed and presented in detail in [5, 17]. This parametric model uses the LCA-specific Python library *Brightway2* and can be accessed online at https://github.com/romainsacchi/LCA_WIND_DK. It enables to create tailor-made life cycle inventories of wind turbines considering their specific technological characteristics and fitting their spatiotemporal context.

Onshore and offshore wind turbines have been selected to have an environmental performance representative of the fleet. Their nominal power is 3.6 MW, and rotor diameter is 120 m corresponding to a power density ratio of 310 W/m^2. The onshore wind turbine has a 95 m hub height, while the offshore turbine has an 85 m hub height. The offshore turbines are considered to be grouped in a farm of 50 wind turbines located 5 km from shore, with a sea depth of 5 m. Onshore and offshore wind turbines are exposed to wind resource leading to load factors of respectively 30% and 50% in coherence with measured production in Denmark [5].

2.2 Environmental Impacts of the P2G Systems

As for assessing wind turbines' environmental impacts, a parametric model has been developed to assess the environmental impacts of the components of a P2G system.

A P2G system is composed of an electrolyzer, a methanation reactor requiring a prior system to capture CO_2 in case of P2M but not for P2H, and a power plant to generate electricity from the produced gas.

The electrolyzer is composed of cell stacks where electrolysis takes place, power electronics to feed the cells with the right current and voltage, and additional equipment such as pipes and reservoirs [18]. The cell stack is modeled by adapting the ecoinvent LCI of solid oxide fuel cell to represent the use of alkaline instead of solid oxide cell stack. To do so, lanthanum oxide is replaced by nickel and zirconium oxide by potassium. The power electronics is modeled using the existing inverter LCI originally created for photovoltaic systems. The additional equipment, which mainly consists of pipes and reservoirs, are modeled by the ecoinvent stainless steel pipe dataset. The methanation reactor is also modeled with stainless steel in accordance with the previous work from Zhang et al. [14]. Carbon dioxide is required for methanation reaction, so its extraction from the flue gas of an industrial chimney is modeled using inventories from Koornneef et al. [19]. Finally, the power plant used to burn the synthesized gas and generate electricity is modeled using the ecoinvent combined cycle gas turbine substituting the fossil gas by the synthesized gas.

The weight, lifetime, and efficiency of all the devices are based on data from industrial reports and scientific literature [18, 20].

2.3 Assessment of the Need and Use of Storage

The need and the use of storage are assessed from the comparison of energy production time series and consumption time series. The approach is represented in Fig. 1.

Firstly, wind power production time series are determined from wind speed time series and the wind turbine power curve. Wind speed data can come from on-site measurements or weather reanalysis data. MERRA-2 wind speeds have been downloaded from the online platform Renewables.ninja (https://www.renewables.ninja/) and are used in this study. Power curve gives the relationship between the wind speed the turbine is exposed to and the corresponding power output. Manufacturer power curves or modeled power curves can be used. A model able to generate a wind turbine power curve based on the nominal power, the rotor dimension and the wind turbulence intensity is used, as well as a wake loss coefficient when wind

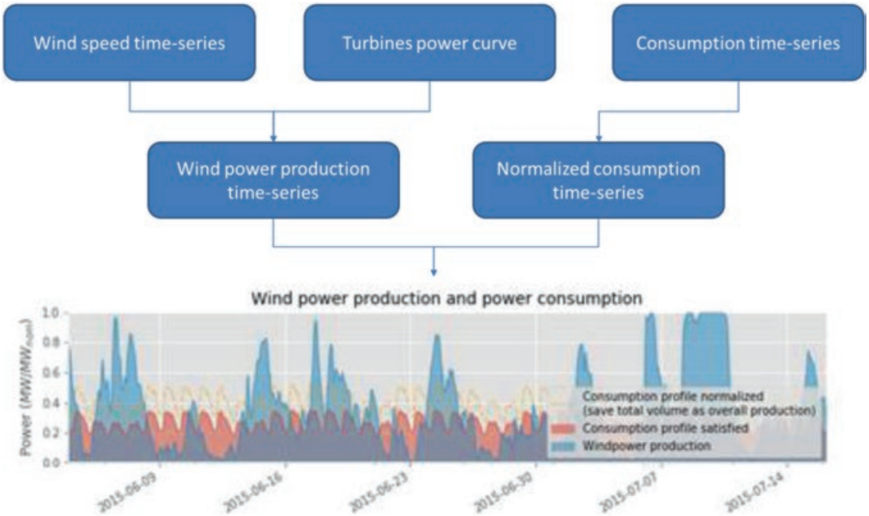

Fig. 1 Graphical representation of the approach used to assess the need and use of storage

turbines are grouped into wind farms [5]. The convolution of wind speed data with the power curve gives wind power production time series.

In a second step, this production time series is compared to the normalized Danish historical load curve. The blue curve (Fig. 1) represents the wind power production per MW installed. The orange dotted curve represents the Danish load curve with an annual consumption equivalent to the wind power production. When the production exceeds the consumption, the excess energy has to be stored, and when the production is lower, the energy difference has to be retrieved from storage. As storage induces energy losses, the amount of energy that can be retrieved from storage is lower than the amount of energy that is stored. As a consequence, a load curve corresponding to a lower annual consumption than the annual production can only be satisfied. The load curve that can be satisfied is calculated by considering the volume of energy that has to be stored and retrieved from storage and the storage efficiency.

Once the load curve is established, it is possible to get, as represented in Fig. 1:

– The wind power production in blue.
– The consumption that can be satisfied in red.
– The intersection of blue and red curves that gives the wind power production directly consumed.
– The difference between wind power production and the intersection of blue and red curves that gives the amount of energy that has to be stored when blue curve exceeds the red one, and retrieved from storage when the consumption exceeds the wind power production.

3 Results and Discussion

One scenario where energy is stored with power-to-methane and one with power-to-hydrogen are studied and discussed below.

3.1 Power-to-Methane Scenario

Figure 2A presents the carbon footprint of the energy provided by the system composed of wind turbines combined with power-to-methane storage. The carbon footprint is respectively 30 g CO_2eq/kWh and 20 g CO_2eq/kWh for onshore and offshore turbines. When neglecting the constraint related to weather dependency of the production, and thus the induced need for storage, the carbon footprint of energy produced is respectively 15 and 10 g CO_2eq/kWh as illustrated by Fig. 2B.

In that case, considering the induced need for storage leads to an increase by a factor 2 of the carbon footprint. Figure 2C presents the impact per power capacity installed and highlights an increase of the carbon footprint of the system wind turbines combined with P2M storage compared to wind turbines alone. However, the difference cannot be explained only by the addition of the storage infrastructure. The second reason leading to that increase of the carbon footprint is the storage energy loss. Figure 2D shows that around half of the wind power production is

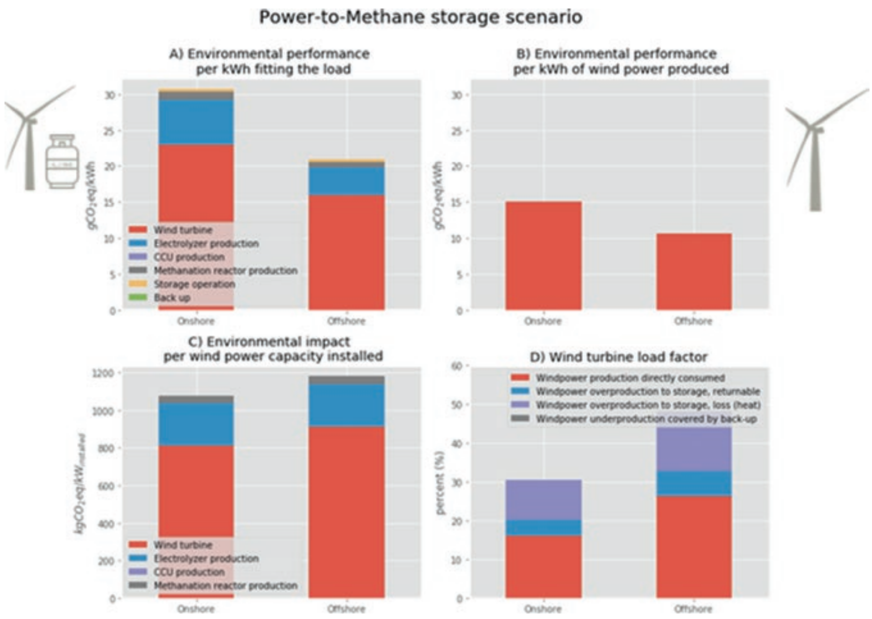

Fig. 2 Carbon footprint of wind power combined with P2M storage

directly consumed and half goes to the storage. Considering the energy going to the storage, 70% is dissipated as heat "loss" and 30% will be restituted as electricity. As a consequence, a significant part of the energy generated will be wasted as heat leading to an increase of the impact per kWh of electricity delivered by the system.

3.2 Power-to-Hydrogen Scenario

If H_2 can be stored over long periods, P2H could be used as an alternative to P2M and provides as well seasonal storage. Figure 3 presents the results considering a power-to-hydrogen scenario instead of power-to-methane. The carbon footprint of wind power combined with P2H is slightly higher than 25 g CO_2eq/kWh for onshore turbines and slightly lower than 20 g CO_2eq/kWh for offshore turbines. These values are lower than those of the power-to-methane scenario due to:

- A reduced storage infrastructure. In the absence of methanation reaction, there is no need for methanation reactors, no need for carbon capture.
- Reduced storage energy losses: the efficiency of the exothermic methanation reaction is limited to 74% [20]. Removing this step limits the decrease of the storage efficiency.

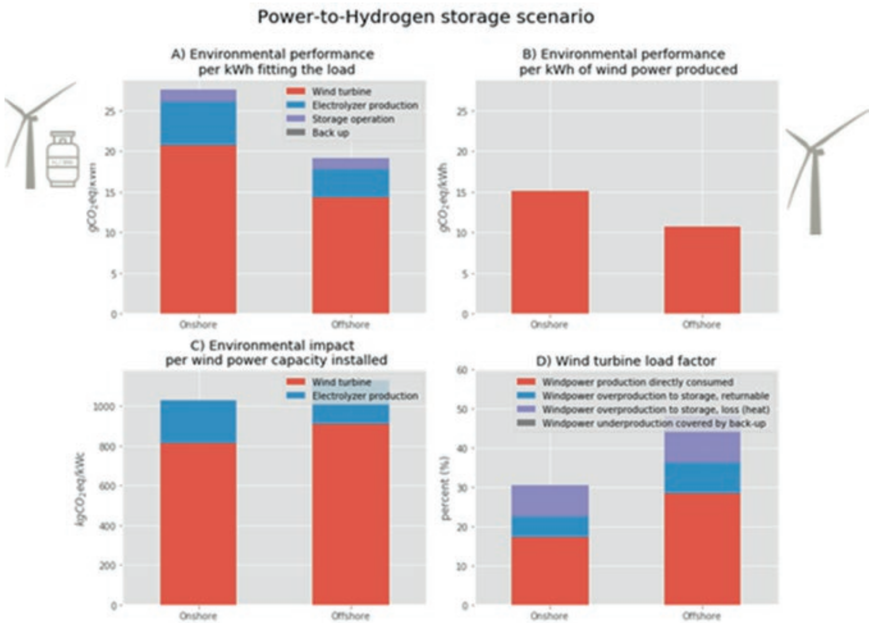

Fig. 3 Carbon footprint of wind power combined with P2H storage

However, the feasibility of this scenario is conditioned to feasibility of storing H_2 over long periods. Storing massive amounts of H_2 over long periods of time may be more complex due to its volatility; H_2 is the smallest molecule on earth. In some countries such as the Netherlands, it is already possible to inject up to 13% of H_2 into the national gas grid [21]. The feasibility of higher levels remains, to our knowledge, to be demonstrated.

Thus, P2H is an option that can be considered in association with wind power to limit the carbon footprint of energy delivered. If hydrogen storage is too complex for long-term storage, a system combining P2H for short-term storage with a higher efficiency and P2M to balance only long-term production variation can be contemplated.

4 Conclusion

An approach to account for the temporal fluctuation of wind power production when assessing their environmental impacts with LCA has been developed. This method has been applied to a case study in Denmark where wind power is combined with power-to-gas to deliver electricity according to the national load curve.

Wind power combined with P2G can deliver electricity as a dispatchable power plant with a low carbon footprint. The carbon footprint of the system "wind power + P2M" is around twice the carbon footprint of wind power system alone. This increase of the carbon footprint comes from additional storage infrastructure but also from energy losses induced by the storage. Despite being doubled, the carbon footprint remains significantly lower than the one associated with the electricity generated from fossil fuels (i.e., by at least a factor of 10). Electricity from fossil fuel typically goes from 400 g CO_2eq/kWh for natural gas to 1000 g CO_2eq/kWh for coal power plant [3].

The environmental footprint can potentially be reduced by limiting the power-to-gas storage to the hydrogen stage. Compared to P2M, P2H requires less equipment for the storage, thanks to the lack of methanation and CO_2 capture. In addition, it reduces the energy losses occurring during storage. However, the feasibility of this scenario is conditioned by the possibility to massively store the volatile H_2 over long periods.

Whether combined with P2M or P2H, an important share of wind power remains directly consumed. The rest is stored with significant energy losses. To improve the environmental as well as the economic performance of such a system, a key aspect is the heat waste valorization.

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Integrated Life Cycle Sustainability Assessment: Hydrogen Production as a Showcase for an Emerging Methodology

Christina Wulf, Petra Zapp, Andrea Schreiber, and Wilhelm Kuckshinrichs

Abstract Ideally, life cycle sustainability assessment (LCSA) consists of life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA) based on a joint technical model. For an integrated and consistent LCSA, however, this is not enough. Therefore, in this work, a coherent indicator selection based on the Sustainable Development Goals (SDGs) as well as an integration of the impact categories/indicators with the help of multi-criteria decision analysis is conducted. The chosen method PROMETHEE does not allow full compensation of the sustainability indicators, which reflects a possible view on sustainability. The SDG-based approach is compared with a classical approach where the weighting is based on the three sustainability dimensions. Both are tested on comparison case study of a 6 MW pressurized electrolyser located in three European countries, i.e. Spain, Germany and Austria, to illustrate the difference of industrial hydrogen production in industrialized countries with different structures of electricity markets.

1 Introduction

The Sustainable Development Goals (SDGs) published in 2015 by the UN [1] gain more and more importance. This is true not only for countries and for regions, for which they were drafted in the first place, but also for companies and academia. For life cycle sustainability assessment (LCSA), there are several approaches to link those two concepts. For example, the project "Linking the UN SDGs to life cycle impact pathway frameworks" [2] by 2.-0 LCA consultants and PRé consultants under the umbrella of the UN Life Cycle Initiative develops impact pathways for the SDGs, which are cause-effect oriented. These should, for example, serve as impact categories for the social life cycle assessment (S-LCA) [3]. Owsianiak et al. [4]

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_9

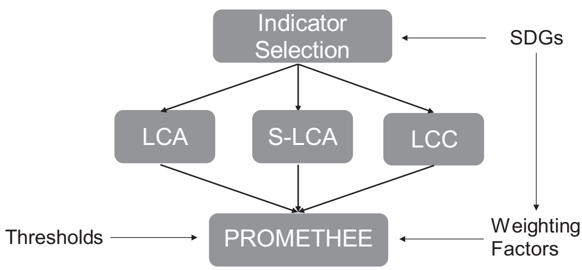
have taken the SDG indicators related to the environment and have tested if they actually help to reach environmental sustainability. For that, they did not only take principles of life cycle assessment (LCA) into account but also the planetary boundaries. A rough match between the SDGs and LCSA indicators has been done by the authors in an earlier study Wulf et al. [5]. They assigned the often used LSCA indicators to the SDGs as well as their indicators.

These approaches concentrate mainly on indicator selection and impact assessment. A further topic of LCSA is the integration of indicators with the help of multi-criteria decision analysis (MCDA) [6, 7]. In this paper, it is presented how the SDGs can guide MCDA for LCSA. The implications of this approach in contrast to the understanding of sustainability based on three dimensions are discussed afterwards. The different effects are analysed on the example of comparing different locations for hydrogen production as an actual LCSA case study.

2 Methodology

In this paper, an LCSA is performed with the guidance from the SDGs (Fig. 1). They are used for the indicator selection as well as for the MCDA. The quantification of the different indicators is done with classical LCA, life cycle costing (LCC) and S-LCA, the latter performing a hot spot analysis. These SDG-guided indicator values describe the performance of the considered systems and form the input for the MCDA method PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations). In many studies, the three assessment methods are regarded as equally important because they are loosely representing the three dimensions of sustainability [6]. This premise is used to derive weighting factors for the different indicators. In this study, however, not the three dimensions of sustainability are considered as equally important, but each sustainability goal has the same importance. This leads to a different set of weighing factors than is the case with the three dimensions of sustainability. In this section, the relation between the SDGs and the LCSA indicators is explained in more detail as well as the choice of method for MCDA and how the weighting factor set is calculated.

Fig. 1 Approach for integrating the SDGs into LCSA



2.1 Sustainable Development Goals and LCSA Indicators

The assignment of LCSA indicators to the SDGs is based on the previous paper [5]. The indicators are selected based on common guidelines. For the LCA, these are the recommendations from the ILCD [8] and guidance documents by theUNEP/SETAC [9]. Indicators on the midpoint level are used as implemented in the GaBi software. The S-LCA indicators are based on the respective UNEP/SETAC guidelines [10] and their interpretation in PSILCA 2 [11] for a hotspot analysis. Indicators in PSILCA 2 tackling issues that are also assessed by LCA are excluded from the selection. The LCC indicators are guided by the European Investment Bank [12]. Particular attention has been paid to avoid double or triple counting of topics. The findings of this matching can be seen in Fig. 2.

It must be mentioned that goals 2, 11 and 17 cannot be described by LCSA indicators.

2.2 Multi-criteria Decision Analysis

When performing a full LCSA, a bundle of very different indicator values with physical, monetary and other units result. In such a case, MCDA can help to structure the decision-making process. Within this MCDA guidance process, fundamental value-based choices have to be made. In particular, it has to be decided to what extent compensation between indicators is allowed. In this work, compensation is not allowed. With respect to a value-based approach, this is a very crucial assumption. However, it helps to clarify the problem. As a specific method representing this, PROMETHEE II [14] is chosen. This method is based on a pairwise comparison of the different options. The most preferable option has the highest result, which is called outranking flow Φnet. A linear preference function with indicator-specific thresholds is applied [15].

2.3 Equal Weighting of SDGs

The premise of the indicator weighting of this paper is that each SDG has the same weight. Furthermore, indicators describing one SDG have the same importance. However, this results in unequal weighting of indicators in case of different numbers of indicators per SDG. Additionally, there are some indicators describing not only one goal but two or more. For example, trade union (density as a % of paid employment total) is describing goal 8 (decent work and economic growth) as well as goal 16 (peace, justice and strong institutions) (see Fig. 1). To avoid an overestimation of such indicators, the number of indicators in one goal m is normalized with the number of assigned goals p. This is mathematically expressed in Eq. 1.

Fig. 2 SDGs and their respective LCSA indicators, icons from [13]; bold LCC indicators (four indicators), italic LCA indicators (13 indicators), normal S-LCA indicators (26)

$$w_i = \frac{1}{n \cdot m_n / p} \tag{1}$$

w_i: weighting factor of indicator i, with $\sum w_i = 1$,
n: number of goals with assigned LCSA indicators, i.e. 14
m_n: number of indicators in one goal
p: number of assigned goals

To calculate the weighting factors based on the sustainability dimensions, the number of goals with assigned LCSA indicators needs to be substituted with the number of sustainability dimensions.

3 Case Study

To test the application of the SDG-guided LCSA indicator set of already existing LCA, S-LCA and LCC are adapted in a case study. The case study comprises a comparison of three locations for hydrogen production with an advanced alkaline water electrolyser. The European countries Germany, Spain and Austria offer different opportunities for industrial hydrogen production. The LCA modelling is based on Koj et al. [16], while the LCC is taken from Kuckshinrichs et al. [17]. The S-LCA [18] is conducted using the PSILCA database [11] integrated in openLCA 1.6. The functional unit for the LCSA is 1 kg of hydrogen (30 bar) produced.

4 Discussion and Results

Here the calculated indicator weights as well as the overall result using PROMETHEE are presented and compared with indicator weights derived from the approach of equal importance of the three sustainability dimensions. The values for each LCSA indicator can be found in Annex, Table 2.

4.1 SDG-Guided Indicator Weights

The derived weighting factors for the different LCSA indicators have a wide range (Table 1). They vary between 0.006 and 0.071. The results are solely based on the numbers of indicators selected for a goal, but not on any subjective assumption on the weight of indicators. Five indicators have the highest weighting factor. These are two LCC and two LCA indicators as well as indigenous rights (human rights issues faced by indigenous people).

Table 1 LCSA indicators and their weights according to SDG equal weighting

Indicator	Goal	Weight	Indicator	Goal	Weight
Child labour, total	8	0.006	Youth illiteracy, total	4	0.024
Frequency of forced labour	8	0.006	Ecotoxicity, freshwater	14	0.024
Goods produced by forced labour	8	0.006	Eutrophication, freshwater	14	0.024
Trafficking in persons	8	0.006	Eutrophication, marine	14	0.024
Net present value	8	0.006	Water depletion	6	0.024
Weekly hours of work per employee	8	0.006	Association and bargaining rights	8,16	0.015
Profitability index	8	0.006	Trade unionism	16, 8	0.015
Photochemical ozone formation	3	0.007	Violations of employment laws and regulations	8, 16	0.015
Health expenditure	3	0.007	Sanitation coverage	3, 6	0.015
Non-fatal accidents	3	0.007	Gender wage gap	5	0.036
Safety measures	3	0.007	Unemployment	1	0.036
Human toxicity, cancer	3	0.007	Women in the sectoral labour force	5	0.036
Ionizing radiation	3	0.007	Acidification, terrestrial	15	0.036
Human toxicity, non-cancer	3	0.007	Eutrophication, ter.	15	0.036
Ozone depletion	3	0.007	Fair salary	1, 8	0.021
Particulate matter	3	0.007	Indigenous rights	10	0.071
Fatal accidents	3	0.007	Levelized cost	7	0.071
Social security expenditures	3, 8	0.007	Marginal cost	9	0.071
Drinking water coverage	6	0.024	Climate change	13	0.071
Education	4	0.024	Resource depletion	12	0.071
Illiteracy, total	4	0.024			

In the approach of equal sustainability dimensions, all LCC indicators have a weight of 0.083, all LCA indicators of 0.024 and all S-LCA indicators of 0.014. With the switch from dimensions to SDGs the indicator indigenous rights shows the highest increase in the weighting factor from 0.014 to 0.071. The largest decrease is recorded for the indicator net present value from 0.083 to 0.006.

4.2 PROMETHEE Results

The PROMETHEE results for the two different weighting sets are presented in Fig. 3. High results indicate the preferable outcome. In both versions, the Spanish option is identified as the least favourable one. Both weighting sets, however, lead to different results for the most preferable option. The set based on SDGs identifies Austria as the most sustainable country for hydrogen production, while an equal weighting of the sustainability dimensions leads to the conclusion that Germany is the most preferable one.

Germany shows the best results with regard to its LCC indicators (Annex, Table 2). As these indicators lose weight (in total 0.155 instead of 0.333), Germany is not considered as the most sustainable option when SDG-guided weighting is considered. The overall weight of the LCA indicators keeps relatively constant (0.352 instead of 0.333), while the social indicators gain influence (0.420 of instead 0.333).

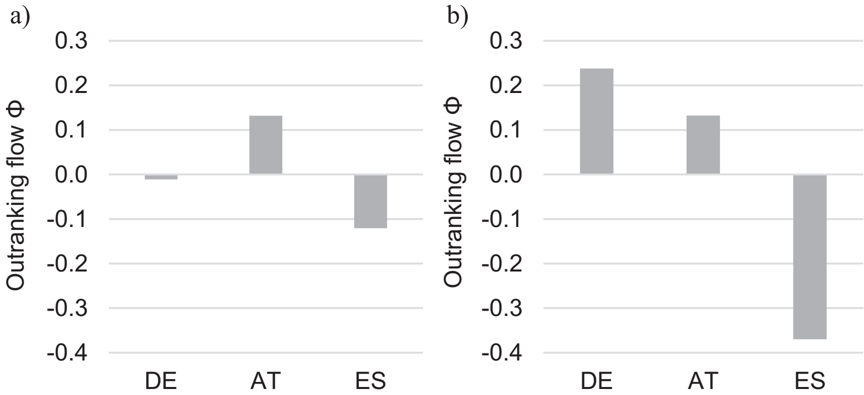


Fig. 3 PROMETHEE results of hydrogen production in three different countries: (**a**) based on SDGs, (**b**) based on sustainability dimensions (DE, Germany; AT, Austria; ES, Spain)

Table 2 LCSA indicator results, based on [5] (med. rh: medium-risk hours)

Indicator	Unit	Germany	Austria	Spain
Child labour, total	Med. rh	0.98	1.08	0.60
Frequency of forced labour	Med. rh	0.46	0.57	0.16
Goods produced by forced labour	Med. rh	0.30	0.29	0.22
Trafficking in persons	Med. rh	2.30	2.81	1.34
Weekly hours of work per employee	Med. rh	0.26	0.48	0.45
Net present value	m€$_{2015}$/kg H_2	−50.1	−58.1	−59.4
Profitability index	Med. rh	−6.38	−7.45	−7.74
Fatal accidents	Med. rh	0.40	0.55	0.26
Health expenditure	Med. rh	6.07	6.24	3.59
Non-fatal accidents	Med. rh	4.03	13.82	27.12
Safety measures	Med. rh	4.89	5.71	5.15
Human toxicity, non-cancer	nCTUh	37.5	14.8	27.1
Human toxicity, cancer	100 nCTUh	9.77	5.07	4.34
Ionizing radiation	100 Bq U235 eq	27.6	0.33	32
Ozone depletion	ng CFC-11 eq	6.32	4.38	5.03
Particulate matter	100 mg $PM_{2.5}$ eq	20	8.7	24.6
Photochemical ozone formation	g NMVOC	30	16.4	33

(continue)

Table 2 (continue)

Indicator	Unit	Germany	Austria	Spain
Social security expenditures	Med. rh	5.79	5.72	2.62
Drinking water coverage	Med. rh	2.60	2.90	1.65
Education	Med. rh	3.01	2.32	4.56
Illiteracy, total	Med. rh	4.45	4.43	2.21
Youth illiteracy, total	Med. rh	0.75	0.81	0.45
Ecotoxicity, freshwater	CTUe	5.59	3.31	3.71
Eutrophication, freshwater	10 mg P eq	12.8	13.3	9.32
Eutrophication, marine	m g N-eq	11.2	7.31	11.6
Water depletion	m^3 world eq.	22	22.3	43.1
Assoc. + barg. Rights	Med. rh	6.54	16.48	1.81
Trade unionism	Med. rh	25.75	18.46	43.89
Violations of employment laws and regulations	Med. rh	1.93	3.22	3.04
Sanitation coverage	Med. rh	13.89	14.17	8.15
Gender wage gap	Med. rh	5.47	31.94	7.96
Unemployment	Med. rh	0.81	0.77	37.43
Women in the sectoral labour force	Med. rh	1.85	1.93	3.93
Acidification	mMole H^+ eq.	44.5	21.6	50.3
Eutrophication, terrestrial	10 mMole N eq.	11.6	6.5	12.1
Fair salary	Med. rh	5.46	7.73	2.30
Indigenous rights	Med. rh	1.44	1.79	0.78
Levelized cost of hydrogen	$€_{2015}$/kg H_2	3.64	4.22	4.31
Marginal cost	$€_{2015}$/kg H_2	3.72	4.52	4.73
Climate change	kg CO_2 eq	29.8	29.8	29.8
Resource depletion	10 mg Sb eq	12.9	3.88	9.38

5 Conclusions

In this work, two different approaches how to cluster sustainability indicators are presented. The results show that the method considered can have a significant influence on the overall preference of options. In the case of hydrogen production in Europe, the classification based on the SDGs prefers a location in Austria, while the other classification based on the dimensions of sustainability results in a preference for a German location.

Using the same indicator set, other classifications are possible. In this paper, the dimensions of sustainability are separated by different methods. The indicators, however, can also be classified by other ways of argumentation. This could mean that human health indicators are assigned to the social dimension [e.g. 19]. In many cases, the three dimensions of sustainability are used [6]. There are other approaches available like the proposed SDGs that have different implications. For example, the SDGs do not cover indicators assessing corruption, and the stakeholder group consumers are not represented. In addition, the focus of the SDGs is less on the economic indicators and more on the social ones. In contrast, regarding the three dimensions of sustainability, some indicators might be assigned to different dimensions, e.g. resource depletion.

Another way to establish weighting factors for MCDA is not to derive them from concepts, but to ask stakeholders, e.g. residents and users or LCSA practitioners, about their preferences. It is to be expected that such an approach would probably lead to a different weighting set than the one presented. Here, the social indicator with the highest weighting factor is indigenous rights. Even though this is a very important topic, in the context of hydrogen production in three different European locations, it is probably not the most pressing social issue. Consequently, several questions arise that need to be answered in the future. An important one will be how sustainability is understood in LCSA and which principles should be at the basis?

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Role of Stochastic Approach Applied to Life Cycle Inventory (LCI) of Rare Earth Elements (REEs) from Secondary Sources Case Studies

Dariusz Sala and Bogusław Bieda

Abstract Monte Carlo (MC) simulation using Crystal Ball® (CB) software is applied to life cycle inventory (LCI) modelling under uncertainty. Input data for all cases comes from the ENVIREE (ENVIronmentally friendly and efficient methods for extraction of Rare Earth Elements), i.e. from secondary sources eco-innovative project within the second ERA-NET ERA-MIN Joint Call Sustainable Supply of Raw Materials in Europe 2014. Case studies described the flotation tailings from the New Kankberg (Sweden) old gold mine and Covas (Portugal) old tungsten mine sent to re-processing/beneficiation for rare earth element (REE) recovery. In this study, we conduct the MC analysis using the CB software, which is associated with Microsoft® Excel spreadsheet model, used in order to assess uncertainty concerning cerium (Ce), lanthanum (La), neodymium (Nd) and tungsten (W) taken from Covas flotation tailings, as well as Ce, La and Nd taken from New Kankberg flotation tailings, respectively. For the current study, lognormal distribution has been assigned to La, Ce, Nd and W. In the case of Covas, the weights of each selected Ce, La, Nd and W are 32 ppm, 16 ppm, 15 ppm and 1900 ppm, respectively, whereas in the case of New Kankberg, the weights of each selected Ce, La and Nd are 170 ppm, 90 ppm and 70 ppm, respectively. For the presented case, lognormal distribution has been assigned to Ce, La, Nd and W. The results obtained from the CB, after 10,000 runs, are presented in the form of frequency charts and summary statistics. Thanks to uncertainty analysis, a final result is obtained in the form of value range. The results of this study based on the real data, and obtained using MC simulation, are more reliable than those obtained from the deterministic approach, and they have the advantage that no normality is presumed.

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_10

1 Introduction

This paper presents the utility of uncertainty analysis based on the MC simulation applied to LCI modelling based on research data obtained from 2015 to 2017 as part of the ENVIREE EU-funded from the ERA-MIN programme within the second Joint Call aims at complete recovery process proposal of REEs (rare earth elements) from tailings and mining waste [1, 2].

The REEs are a group of 17 elements with similar chemical properties, including 15 in the lanthanide group, yttrium (Y) and scandium (Sc) due to their similar physical and chemical properties [1, 3]. The lanthanide elements traditionally have been divided into two groups: the light rare earth elements (LREEs), lanthanum (La) through europium (Eu) (Z = 57 through 63), and the heavy rare earth elements (HREEs), gadolinium (Gd) through lutetium (Lu) (Z = 64 through 71) [4]. Although Y is the lightest REE, it is usually grouped with the HREEs to which it is chemically and physically similar [4]. On the other hand, according to [5], REEs can be divided into three groups: LREEs, HREEs and scandium (Sc). LREEs comprise lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd) and samarium (Sm), and the remaining are included in the HREEs. While Koltun and Tharumarajah [6] presented three groups of the REEs classification often used in extraction given in LREEs, lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd) and promethium (Pm); medium rare earth elements (MREEs), samarium (Sm), europium (Eu) and gadolinium (Gd); and HREEs, terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), scandium (Sc) and yttrium (Y) quoted in Australian Industry Commission documents [7]. By the way, definition of REEs found in the same Australian Industry Commission documents [7] is the following: “Group of 17 chemical elements – not rare at all; yttrium, for example is thought to be more abundant than lead. These elements were mislabelled because they were first found in truly rare minerals”.

2 Uncertainty Analysis of LCI

The most popular approach for doing an uncertainty analysis in LCA is the MC approach [8], partly because it has been implemented in many of the major software programs for LCA, typically as the only way for carrying out uncertainty analysis (for instance, in SimaPro, GaBi and Brightway2 and in open LCA).

The MC technique is widely used and recommended for the inclusion of uncertainties for LCA. Typically, 1000 or 10,000 runs are done, but a clear argument for that number is not available, and with the growing size of LCA databases, an excessively high number of runs may be time-consuming [9, 10]. It is an important parameter in simulation modelling. [11] studied stochastic flow shop scheduling metaheuristic model for vessel transits in Panama Canal. It was found that using 200 replications is optimal, because the change in the 95% confidence interval width for makespan was negligible.

According to Good [12], the uncertainty exists when the probability of an event occurring is not 0 or 1. Not only statistic but also uncertainty is a fundamental element in simulation analysis and modelling. Definition of uncertainty given by Huijbregts [13] is the following: "Uncertainty is defined as incomplete or imprecise knowledge, which can arise from uncertainty in the data regarding the system, the choice of models used to calculate emissions and the choice of scenarios with which to define system boundaries, respectively", and uncertainty defined by Walker et al. [14] is as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system". Uncertainty is to be found when a decision-maker cannot mention all possible outcomes and/or cannot attribute probabilities to the various outcomes [15]. According to [16], uncertainty analysis is another important issue in LCA, as average data is usually used without considering the associated variability, and the results can be misleading when comparing systems [16]. Deterministic approaches and the description of processes in the studies of ecological life cycle assessment do not properly reflect the reality [17]. The analysis of uncertainty, a pervasive topic in LCA studies [18, 19], has been a subject for more than 10 years. Many LCA software tools (e.g. SimaPro, GaBi) facilitate uncertainty propagation by means of sampling methods, and most often used MC simulation [16, 20–22]. Detailed description of the combination of sources of uncertainty (parameter, model and scenario uncertainties) and combination of source of uncertainty and methods to address them (deterministic, probabilistic and simple methods) are discussed in [23].

MC simulation has received considerable attention in the literature, especially when MC simulations are used for making decisions that will have a large social and economic impact [24]. As a result, it was the most commonly recommended tool (e.g [25, 26]). Stochastic nature of the MC simulation is based on random numbers, and simulation models are generally easier to understand than many analytical approaches [18]. According to La Grega et al. [27], MC simulation can be considered the most effective quantification method for uncertainties and variability among the environmental system analysis tools available.

3 LCI Data Quality and Collection

Based on the different physical and chemical separations carried out on New Kankberg and Covas tailings [28], the following process treatment scheme is shown in Figs. 1 and 2, respectively.

The possibilities of extraction of Ne, Ce and La using magnetic separation can be reached, thanks to the paramagnetic property of monazite. Inventory data used in the study has been obtained from the following sources: the primary data used in this study is based on the elements determined from the chemical analyses done by instrumental neutron activation analyses site-specific measured or calculated data,

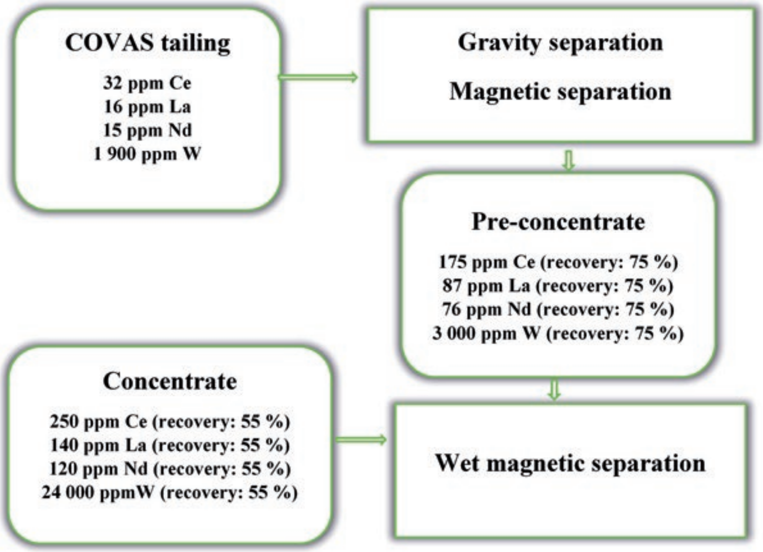

Fig. 1 Proposed process scheme for the beneficiation of Covas tailings. (Adopted from [28])

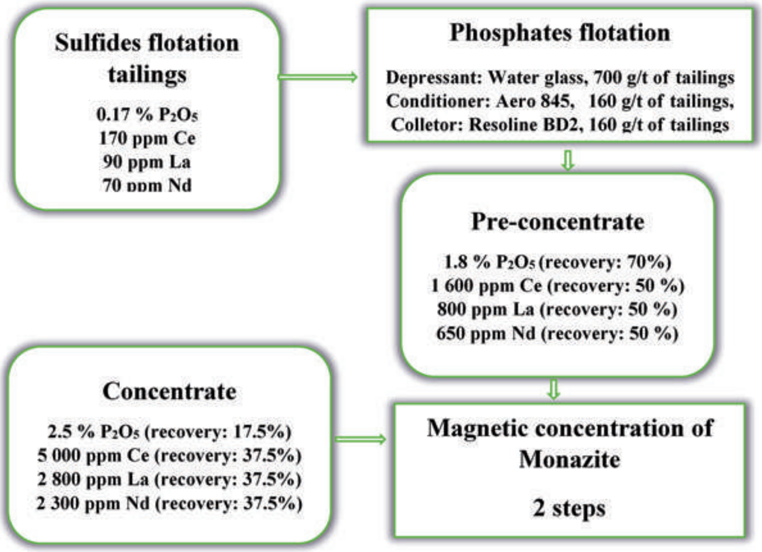

Fig. 2 Proposed process scheme for the beneficiation of REE in the flotation tailings from New Kankberg mine. (Adopted from [28])

and on values found in literature. In the current study, we discuss and model our LCI adopting the proposed process for the beneficiation of REE in the flotation tailings from New Kankberg mine in Sweden and Covas tailings [29].

4 Simulation Model: Model Assumptions

Simulation models are generally easier, when it comes to their interpretation and understanding, than a number of analytical solutions. Moreover, simulation models provide an interesting opportunity to give more reliable and comprehensive data [30]. For input parameters analysed in this study (La, Ce, Ne and W), uncertainty was included in the MC analysis by assigning distributions.

For uncertainty analysis in the LCI study, the lognormal probability distributions have been assigned to each analysed REE. Lognormal distribution is stable and no negative values are possible [21]. In this context, it should be pointed out that the lognormal probability distribution with the GSD equal to 1.13 was applied to rare earth oxides in the ecoinvent background process "Rare earth oxide production from bastnaesite" taken from the "Life Cycle Inventories of Chemicals Data v2.0 Ecoinvent report No. 8" [31].

The decision to choose lognormal distribution is based on the works of [20, 21, 32] and the bibliographies included in the above-mentioned publication because the quality of data was not sufficient to estimate best-fitting distributions.

Several examples of performance of MC simulation by using CB software can be found in [33] as well as in [20, 21, 34]. The MC simulation results for La, Ce, Ne and W are shown in graphical forms (histograms) and descriptive statistics (percentiles summary and statistics summary).

It is important that a sufficient number of replications (runs) should be used in a simulation [35], because the quality of the simulation results depends on the number of replications. In general, the higher the number of replications, the more accurate will be the characterization of the output distribution and estimates of its parameters, such as the mean [34].

5 Results and Discussion

Random values from the probability distribution of each parameter were selected in each run and a forecast distribution for each selected REE. CB's distribution fitting function can analyse a data set and determine not only the best fit but also the quality of the fit [34]. During a single trial, CB randomly selects a value from the defined possibilities (the range and shape of the distribution) for each uncertain variable and then recalculates the spreadsheet [36].

5.1 Covas (Portugal) Old Tungsten Mine Case Study

After activating the simulation with the randomization cycle, set previously to 10,000 trials, the results obtained by MC simulation after 10,000 trials, for the Ce, La and Ne, have been presented in the form of frequency charts (histograms). They are shown in Figs. 3, 4, 5 and 6, respectively; statistics, as well as percentiles, reports are presented in Tables 1 and 2, respectively. The mean values of Ce, La, Ne and W forecast values amounted to the GSD with a 95% confidence interval around the mean values were situated between:

- Ce [26.17 and 38.61] ppm (see Fig. 3)
- La [13.13 and 19.46] ppm (see Fig. 4)
- Nd [12.24 and 18.06] ppm (see Fig. 5)
- W [1556.96 and 2302.73] ppm (see Fig. 6)

The histograms of the outcome variables include all values within 2.6 standard deviations from the mean, which represents approximately 99% of the data, and the number of data points inside 2.6 standard deviations of the mean is shown in the upper right corner of the frequency charts, as presented in Figs. 3, 4, 5 and 6 (see [20, 34] for more details). It is worth noting that if the number of runs increases, the mean standard error decreases [34]. Moreover, the mean standard error can be used to construct confidence intervals as described in Evans and Olson [34].

The confidence interval range expressing 95% presented in the frequency chart (see Figs. 3, 4, 5 and 6) is highlighted with a darker colour marker. In other words, this means that 95% of the results are lying inside this range. Moreover, by setting the certainty values (e.g. 95%), the confidence intervals (minimum and maximum bounds) are set automatically by the grabbers, and the corresponding numerical values are entered in the edit fields at the bottom part of the dialog boxes of the Forecast tab (e.g [20, 34].).

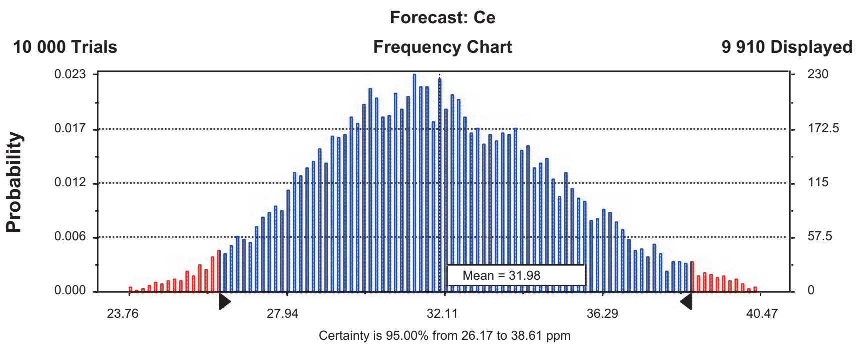

Fig. 3 CB forecast chart: Ce after 10,000 trials (95% confidence interval). Certainty is 95.00% from 26.17 to 38.61 ppm. (Source: own work)

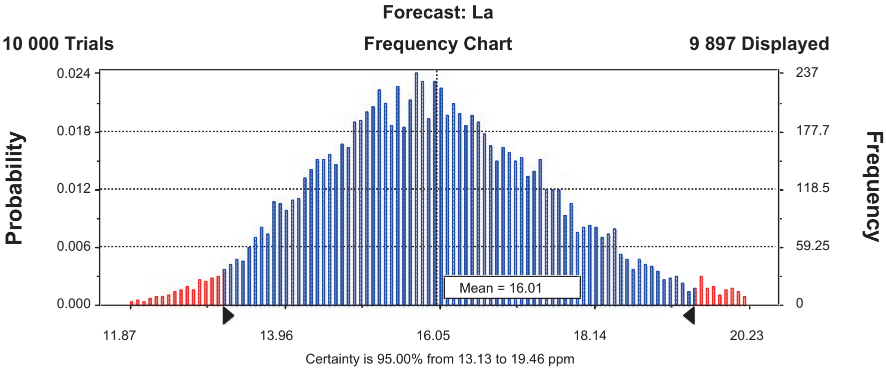

Fig. 4 CB forecast chart: La after 10,000 trials (95% confidence interval). Certainty is 95.00% from 13.13 to 19.46 ppm. (Source: own work)

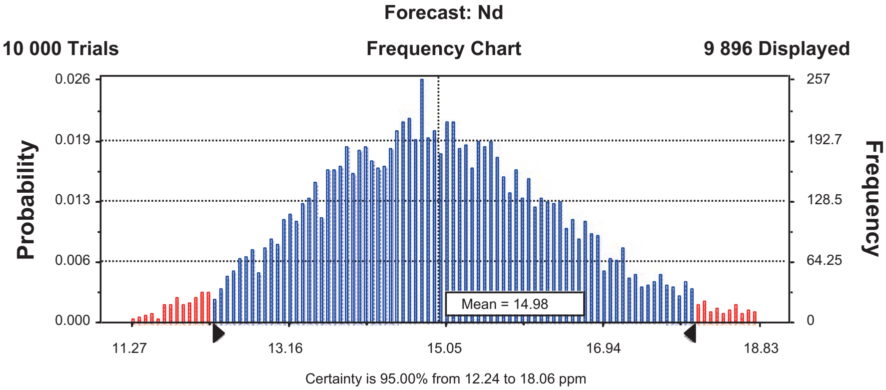

Fig. 5 CB forecast chart: Nd after 10,000 trials (95% confidence interval). Certainty is 95.00% from 12.24 to 18.06 ppm. (Source: own work)

5.2 New Kankberg (Sweden) Old Gold Mine Case Study

The results obtained by MC simulation, after 10,000 runs, for Ce, Ne and La, are shown in Figs. 7, 8 and 9, respectively, as well as in statistics and percentiles reports presented in Tables 3 and 4, respectively. The mean values of Ce, Nd and La with a 95% confidence interval around the mean values were situated between:

- Ce [138.93 and 207.00] ppm (see Fig. 7)
- Nd [57.29 and 84.67] ppm (see Fig. 9)
- La [73.97 and 108.33] ppm (see Fig. 8)

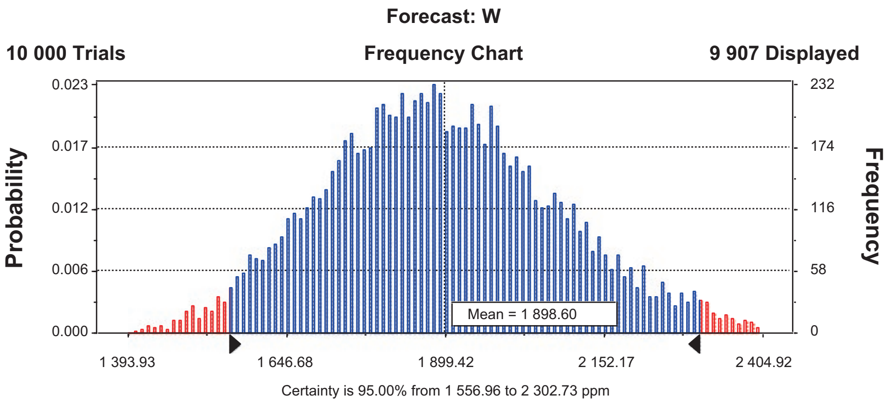

Fig. 6 CB forecast chart: W after 10,000 trials (95% confidence interval). Certainty is 95.00% from 1556.96 to 2302.73 ppm. (Source: own work)

Table 1 Statistics report of outcomes from the simulation

Statistic	Ce (ppm)	La (ppm)	Ne (ppm)	W (ppm)
Trials	10,000	10,000	10,000	10,000
Mean	31.98	16.01	14.98	1898.60
Median	31.80	15.93	14.91	1887.51
Mode	–	–	–	–
Standard deviation	3.19	1.60	1.49	191.02
Variance	10.19	2.56	2.22	36487.08
Skewness	0.27	0.33	0.25	0.31
Kurtosis	3.05	3.23	3.02	3.13
Coeff. Of variability	0.10	0.10	0.10	0.10
Range maximum	36.46	21.10	19.47	1904.42
Range minimum	20.36	10.26	9.66	1284.84
Range width	47.24	23.51	20.81	2692.45
Mean std. error	0.03	0.02	0.01	1.91

Source: own work

6 Conclusions

This study provides new insight into the practical implementation of MC method, based on the stochastic approach, and applied to the uncertainty of the LCI data collection process. To our knowledge, there is a lack of publications and research presentation of stochastic modelling of the data used for the LCI, for beneficiation of REEs, in the flotation tailings processes. Probabilistic techniques using MC simulations must consider the strategy based on the specification of the optimal distribution. The MC simulation in this study provides justification for the lognormal distributions assumed for the analysed parameters. Thanks to uncertainty analysis, a final result is obtained in the form of value range. As a result, the results of this

Table 2 Percentiles report of outcomes from the simulation

Percentile	Ce (ppm)	La (ppm)	Ne (ppm)	W (ppm)
0%	20.36	10.26	9.66	1284.84
10%	28.04	14.03	13.13	1659.92
20%	29.26	14.65	13.71	1736.95
30%	30.17	15.13	14.14	1793.51
40%	31.01	15.53	14.56	1841.49
50%	31.80	15.93	14.91	1887.51
60%	32.62	16.33	15.29	1938.46
70%	33.61	16.78	15.71	1900.61
80%	32.94	16.95	15.90	1989.04
90%	36.19	18.11	16.92	2147.66
100%	47.24	23.51	20.81	2692.45

Source: own work

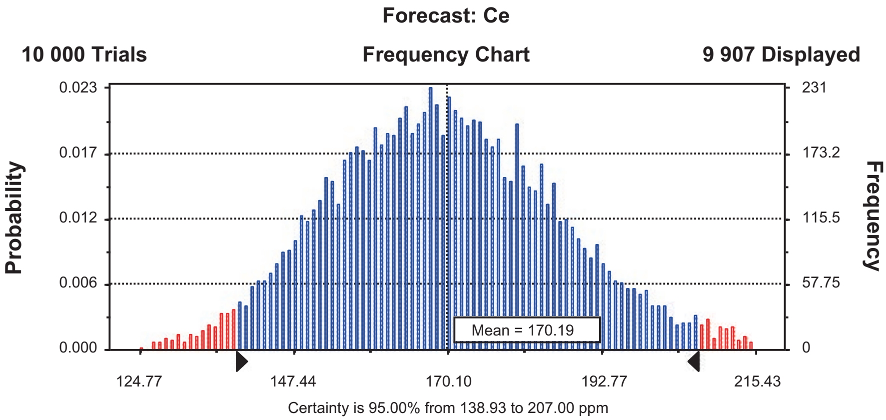

Fig. 7 CB forecast chart: Ce after 10,000 trials (95% confidence interval). Certainty is 95.00% from 138.93 to 207.00 ppm. (Source: own work)

study, based on the real data and obtained using MC simulation, are more reliable than those based on the deterministic approach. An additional advantage is associated with the fact that no normality is presumed.

Finally, it is concluded that uncertainty analysis offers a well-defined procedure for LCI studies, early phase of LCA, and provides the basis for defining the data needs for full LCA of the beneficiation of REE process. It must be pointed out that MC simulation needs to know the probability distribution for the purpose of an uncertainty analysis in contrast to bootstrap sampling, which creates an uncertainty analysis without knowing the probability distribution of the analysed data.

Stochastic approach used to LCI supports decision-makers in the interpretation of final LCA results and leads to better understanding of many analytical approaches. The results of this study will encourage other researchers to consider this approach in their projects. Results can improve current procedures, and they can help the

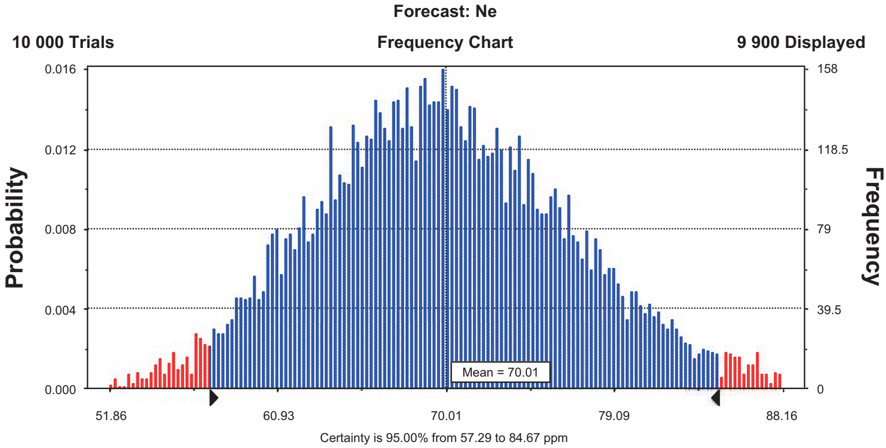

Fig. 8 CB forecast chart: Ne after 10,000 trials (95% confidence interval). Certainty is 95.00% from 57.29 to 84.67 ppm. (Source: own work)

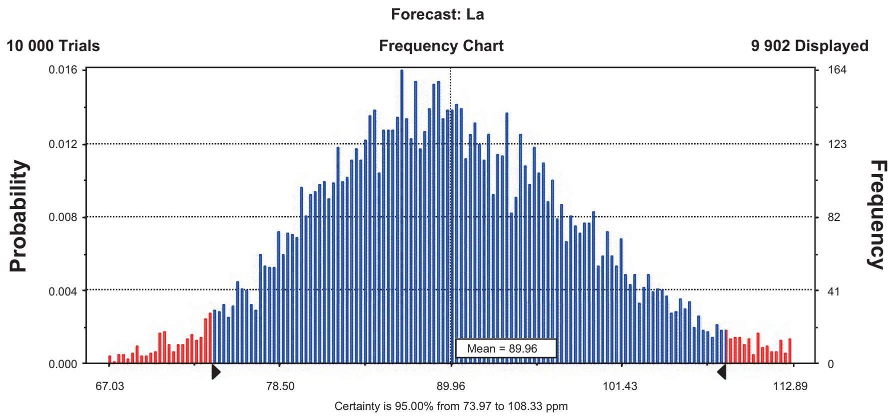

Fig. 9 CB forecast chart: La after 10,000 trials (95% confidence interval). Certainty is 95.00% from 73.97 to 108.33 ppm. (Source: own work)

LCA practitioners and decision-makers in the REEs beneficiation processes modelling and management. They can also contribute to better understanding of many analytical procedures and bring closer to industrial application – industrially relevant focus – and may also stimulate innovation in the stochastic studies.

Summarizing, consideration of uncertainty in LCA will make the LCA field more robust and credible in supporting the practitioner decisions, as discussed in the work of Igos et al. [10].

Table 3 Statistics report of outcomes from the simulation

Statistic	Ce (ppm)	La (ppm)	Ne (ppm)
Trials	10,000	10,000	10,000
Mean	170.19	89.96	70.01
Median	169.42	89.44	69.67
Mode	…….	…….	…….
Standard deviation	17.23	8.82	6.98
Variance	296.77	77.77	48.75
Skewness	0.30	0.28	0.29
Kurtosis	3.18	3.10	3.16
Coeff. of variability	0.10	0.10	0.10
Range maximum	245.86	131.45	103.56
Range minimum	113.19	62.87	43.33
Range width	132.67	68.58	60.23
Mean std. error	0.17	0.09	0.07

Source: own work

Table 4 Percentiles report of outcomes from the simulation

Percentile	Ce (ppm)	La (ppm)	Ne (ppm)
0%	113.19	62.87	43.33
10%	148.78	79.10	61.20
20%	155.45	82.45	64.07
30%	160.49	85.00	66.17
40%	165.08	87.28	67.95
50%	169.42	89.44	69.67
60%	173.82	91.70	71.40
70%	178.62	94.38	73.44
80%	184.30	97.25	75.81
90%	192.43	101.51	79.09
100%	245.86	131.45	103.56

Source: own work

Acknowledgements The authors are grateful for the input data provided, as part of the environmentally friendly and efficient methods, for extraction of rare earth elements from secondary sources (ENVIREE) project funded by NCBR within the second ERA-NET ERA-MIN Joint Call Sustainable Supply of Raw Materials in Europe 2014.

Funding This work was supported by the Management Department of the AGH University of Science and Technology, Kraków, Poland.

Compliance with ethical standards. *Conflict of interest*: The authors declare that they have no conflict of interest. Research is not involving human participants and/or animals.

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Extending LCA Methodology for Assessing Liquid Biofuels by Phosphate Resource Depletion and Attributional Land Use/ Land Use Change

Heiko Keller, Horst Fehrenbach, Nils Rettenmaier, and Marie Hemmen

Abstract Many pathways towards reaching defossilization goals build on a substantially increased production of bio-based products and energy carriers including liquid biofuels. This is, amongst others, limited by land and phosphorous availability. However, it is challenging to adequately capture these limitations in LCA using state-of-the-art LCI and LCIA methods. We propose two new methods to overcome these challenges: (1) attributional land use and land use change (aLULUC) evenly attributes LU-/LUC-related burdens (emissions) occurring in a country to each hectare of cropland used in that country and (2) phosphate rock demand as a stand-alone resource indicator for a finite resource that cannot be replaced. Approach, calculations and used factors are described for both methods, and exemplary results for biofuels are presented. We conclude that both methods can yield additional insight and can support finding solutions for current challenges in agriculture.

1 Introduction

As for most bio-based products, replacing fossil fuels by biofuels mostly creates environmental advantages and disadvantages at the same time. Advantages typically relate to climate change mitigation and savings of fossil energy resources, and disadvantages of various kinds are usually caused by the required biomass production. This well-known pattern is reflected in standard LCA results in the field.

Public and scientific discussions more and more focus on environmental burdens and limitations of agriculture that are becoming important bottlenecks of agriculture on a global scale. These aspects include land use/biodiversity, water and increasingly also limited phosphate resources. These could also become limiting for currently discussed pathways for defossilization of the society, which often builds on using more bio-based products in general and biofuels of various kinds in particular.

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_11

Results of state-of-the-art LCAs however often do not effectively support finding new solutions in these areas for various reasons. This paper focusses on the aspects land use/land use change (LUC) and phosphate resources. In the following chapters, limitations of current state-of-the-art LCA methods are discussed, and two new methods are proposed as solutions: (1) attributional land use and land use (aLU-LUC) change as new alternative to dLUC/iLUC and (2) phosphate rock demand as new stand-alone resource indicator.

2 Attributional Land Use and Land Use Change

2.1 Background

Land use change (LUC) describes the relative change in the use or management of an area compared to a previous use of the same area and the associated emissions (or emission avoidance). Which methodology is suitable for the quantification LUC-related burdens depends on the goal and scope of a study. This can include the overall greenhouse gas balance of a country, the traceable direct consequences of a specific product in its supply chain (dLUC, direct land use change) or the indirect consequences of a change in the market, e.g. triggered by the support of a specific product such as biofuels (iLUC, indirect land use change).

In theory, dLUC could accurately determine the actual LUC emissions from a product such as rapeseed diesel. However, this is not applicable in practice for several reasons: Firstly, existing data is not available and subject to data protection. Secondly, more biomass not associated with land use change is available than interested customers or regulated markets are demanding. Thus, dLUC is not useful to mitigate or stop continuing land use change.

iLUC factors are calculated by combining land use models with an economic equilibrium or partial system and are intended to estimate the overall impact of a targeted or shock-like increase in production on global land use. Fehrenbach [18], amongst others, analysed and described the wide range of results depending on the choice of model. The iLUC approach is therefore only of limited use for developing solutions based on life cycle assessments due to the disagreement amongst experts about the suitability and reliability of the various iLUC models. Moreover, iLUC always describes results of changes or measures, which is incompatible with attributional LCAs describing the status quo. Finkbeiner [19] also discussed these aspects in detail.

We propose a life cycle inventory approach termed attributional land use/land use change (aLULUC) to attribute existing and documented burdens caused by land use change and continuous burdens/emissions from using converted land to products [1]. Here we focus on climate impacts although further impact categories such as biodiversity [2, 3] can also be assessed using the life cycle inventory method aLULUC.

2.2 Approach

A decisive premise for aLULUC is that land use changes to arable land take place in reality. These land use changes are usually recorded and associated emissions are backed up with data. This includes one-time emissions from actual LUC and continuous emissions mainly from organic soils caused by LUC but occurring for many decades of land use (LU) that can only be stopped if land use is given up and appropriate protection measures are taken.

The aLULUC concept is independent of models of future land use change as it is the case for iLUC. In the same systematic way as real emissions are attributed to the processes of a life cycle, real LUC processes can be attributed to the associated processes, as it is also done applying the dLUC concept. However, even if actual land use changes can be clearly assigned to certain agricultural products, all agricultural products of a production area compete for limited availabilities on the local market for cropland. The reaction of the markets on, e.g. the EU biofuels policy, has shown that crops on and products from recently logged land (or from "LUC-free" land) can be flexibly allocated to customers according to their preferences. For that reason, a land-market-based attribution of aLULUC to products produced on that land following the aLULUC concept is a more consistent representation of the underlying processes than a direct attribution following the dLUC concept. For the majority of agricultural products, country borders are the most appropriate geographical reference areas for the aLULUC concept. Firstly, there are no internal trade barriers within national markets. More importantly, however, decisions and policies regarding the conservation of areas such as rainforests, wetlands and grasslands are made or influenced at the country level. A more specific attribution of LUC to individual crops within these markets would require economic assumptions and models that seek to establish causalities. These do not necessarily reflect the complex socio-economic and political processes that can cause, promote or prevent LUC.

Following the proposed aLULUC approach, the real land use changes that have been caused by agriculture (of a defined region) are allocated to all agricultural products in proportion to the land requirements. It is therefore an allocation according to the attribute land demand. aLULUC can be calculated for arable land as well as for other types of land such as grassland. The country- and year-specific aLULUC factor for arable land is determined as follows: All carbon stock changes in biomass and soils caused by net conversion from other types of land use to arable land in a country in a certain year are summed up and divided by the area of arable land used in that year. One-time changes in biomass and soil carbon stocks (LUC) are attributed to the year in which the LUC occurs although actual CO_2 emissions may be partially delayed by a few years. Continuous emissions of CO_2, CH_4 and N_2O from the cultivation of organic soils (LU) are counted in the year in which they occur. Averages of aLULUC factors over the last ten available years result in stable values that do not disregard medium- to long-term developments. Detailed calculation procedures and data sources are discussed in [1]. Current emission factors for the climate impact of land use and land use change according to the aLULUC concept for selected countries can be found in Table 1.

2.3 Application Example: GHG Emissions Including aLULUC of European Rapeseed Biodiesel

Biodiesel can achieve certain climate change mitigation if it replaces conventional diesel. This is however only the case if land use does not cause high additional greenhouse gas emissions. Usually, this problem is discussed for palm oil biodiesel and deforestation. However, depending on the used land and the methodological approach used to attribute emissions from LU and LUC to the fuel, also European rapeseed biodiesel can cause in total more greenhouse gas emissions than it saves (Fig. 1). Greenhouse gas emissions from LU and LUC in Europe mainly stem from conversion of grassland and from cultivation on organic soils, i.e. drained wetlands/ peatland.

The cultivation of rapeseed on former grassland can lead to overall additional contributions to climate change following the dLUC approach if common time horizons of up to about 25 years are used. If organic soils/peatlands are used, an analogous direct attribution of LU to the product (termed dLU in the figure) could even lead to very high additional greenhouse gas emissions. Where such emissions have

Table 1 Exemplary country-specific aLULUC emission factors for annual crops cultivated on arable land selected from [1]

Country	Total aLULUC t CO_2eq/(ha year)	aLU t CO_2eq/(ha year)	aLUC t CO_2/(ha year)
France	0.90	0.41	0.50
Germany	1.44	1.22	0.21
Italy	0.26	0.14	0.12
Netherlands	4.50	4.08	0.41
Poland	1.60	1.59	0.01
Romania	0.17	0.14	0.03
Spain	0.04	0.04	0.01
United Kingdom	0.55	0.55	0.00
EU 28	1.05	0.85	0.20
Argentina	3.36	0.03	3.33
Colombia	52.3	0.00	52.3
Brazil	9.32	0.00	9.32
Malaysia	55.4	42.9	12.5
Indonesia	30.4	13.7	16.7
India	0.06	0.06	0.00
Russia	0.80	0.30	0.50
USA	0.52	0.52	0.00

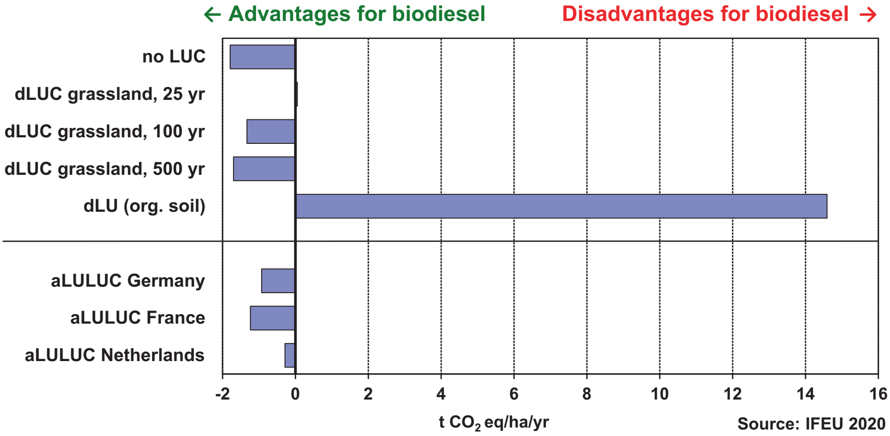

Fig. 1 Life cycle greenhouse gas emissions of European rapeseed biodiesel compared to conventional diesel. All results are based on the same life cycle comparison with differences only in the used land and the methodological approach to land use (LU) and land use change (LUC). The time horizons, over which one-time emissions are distributed, are specified where applicable

to be attributed to a fuel according to the European renewable energy directive [4], no farmer would of course cultivate crops for biofuels. Nevertheless, biofuel crops occupy land and increase the pressure to use former grassland and peatland for cultivation of crops in general. Following the aLULUC approach, LU- and LUC-related emissions are evenly distributed over all cropland of the respective country. This leads to somewhat reduced climate change mitigation for French rapeseed biodiesel. Especially emissions from cultivated organic soils in Germany and even more so in the Netherlands lead to a substantial reduction of greenhouse gas emission savings.

This application example shows that LU and LUC can make significant contributions to carbon footprints also in European countries. The aLULUC approach helps that these emissions are not neglected because direct attribution of these emissions to products does not take place in practice – neither in Europe nor overseas. Hardly anybody would, for example, consider that, e.g. his/her meat could stem from animals raised on corn grown on drained Northern European peatland.

3 Phosphate Rock Demand

3.1 Background

Phosphate rock is the basic raw material for the production of phosphoric acid, which is essential for the production of phosphate products such as fertilizers, animal feed, food and other industrial products. Ninety per cent of the global supply of phosphate is used as fertilizer in agriculture [5]. Eighty-five per cent of phosphate ore is extracted from marine sedimentary deposits and 15% from magmatic deposits, with phosphate ore chemically including iron and aluminium salts as hydrate complexes with very different phosphorous and phosphate contents. Deposits based on guano deposits are largely exhausted [6]. The main producing countries are currently China (52%), the USA (10%) and Morocco (12%) [7]. Marketable rock phosphate contains between 27% and 40% phosphate ([8] cited in [6]). Besides, recycled phosphate can be recovered from sewage sludge by several processes [9, 10].

As a mineral raw material, phosphate is a non-renewable resource. Depending on the source, the static lifetime of global phosphate reserves is only several decades to a few centuries [11–14] (see Fig. 2).

This shortage is further worsened by a growing world population and simultaneously changing consumption patterns [15], resulting in an increasing demand for phosphate.

Due to this growing importance, the impossibility of substitution by other raw materials in central applications and simultaneous limitation, we recommend integrating the resource "phosphate" in life cycle assessments using a separate indicator. We suggest using the indicator phosphate rock demand as proposed in [16] and presented below.

3.2 Approach

Various indicators can be used in LCA to address resource use. One indicator is the cumulative raw material demand (CRD), which is defined as the sum of all raw materials entering a system – except water and air – expressed in mass units. Other indicators also include weighting of the individual raw materials by, e.g. scarcity. These established indicators have in common that the mineral resource consumption of phosphate is not reported separately. This is not sufficient especially for LCAs with a strong focus on agriculture such as LCAs on biofuels because phosphate/phosphorus is a raw material that cannot be replaced by any other element in

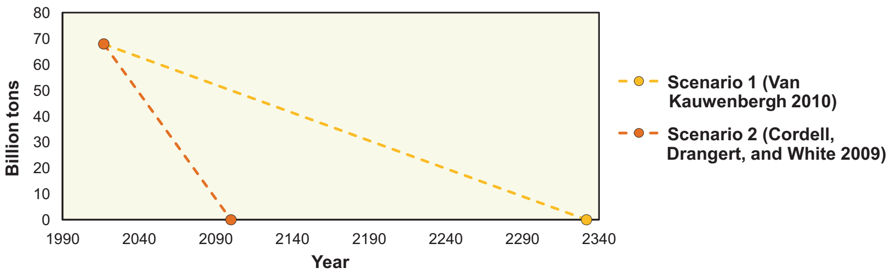

Fig. 2 Range of scenarios on the static lifetime of global phosphate reserves

its main application as a fertilizer. Therefore, the consumption of non-renewable phosphate rock needs to be addressed independently from other raw materials.

We propose a new indicator phosphate rock demand (informally also "phosphate rock footprint") following the concept of the CRD but only including phosphate rock. Phosphate rock demand is determined by the initial rock mass. The recommended unit for the life cycle inventory is "phosphate rock standard" [16]. The definition of a standard is necessary because phosphate rock can have significantly different phosphate contents. Based on [17], an average content of 25% of P_2O_5 is set for phosphate rock standard. P_2O_5 is the reference substance/unit commonly used in agriculture. This corresponds to 32% raw phosphate. This means that 1 kg of mineral P_2O_5 fertilizer corresponds to 4.0 kg of phosphate rock (std.) or 3.125 kg of raw phosphate (std.). This specification explicitly refers to mineral fertilizers. For organic fertilizers, a specific procedure must be derived depending on the goal and scope of the study. If consequential modelling is applied, for example, additional phosphate sources are taken into account, which can replace mineral phosphate without restrictions and which are available in limited quantities during the reference period of the study.

Results can be normalized to inhabitant equivalents by dividing them by the average annual resource consumption per inhabitant. The following normalization factors were derived for this purpose ([16] for details):

- For the reference area Germany: 16.1 kg phosphate rock (std.)/(inhabitant • year).
- For the reference area Europe: 23.1 kg phosphate rock (std.)/(inhabitant • year).

These factors refer to the 5-year average and thus remove short-term fluctuations in the statistics. Normalization factors for other regions can be derived accordingly.

3.3 Application Example: Phosphate Rock Demand of Different Biofuels

With the approach described in Chap. 3.2 outlining the definition and calculation of the indicator "phosphate rock demand", the resource phosphate can be integrated into life cycle assessments. In the following, the application of this approach is explained using an illustrative example. Several bio-based fuels were analysed: bioethanol, biomethane, biodiesel, fuel from vegetable oil and Fischer-Tropsch diesel. Figure 3 shows the ranges between minimum and maximum phosphate rock demand per biofuel.

The phosphate rock demand of different biofuels differs significantly. First-generation biofuels tend to perform much better than second-generation bioethanols with respect to phosphate rock depletion. Results also depend heavily on the biofuels' production schemes, co-product uses and their local conditions. This striking difference between first- and second-generation bioethanols mainly results from phosphate inputs into fermentation processes without subsequent productive

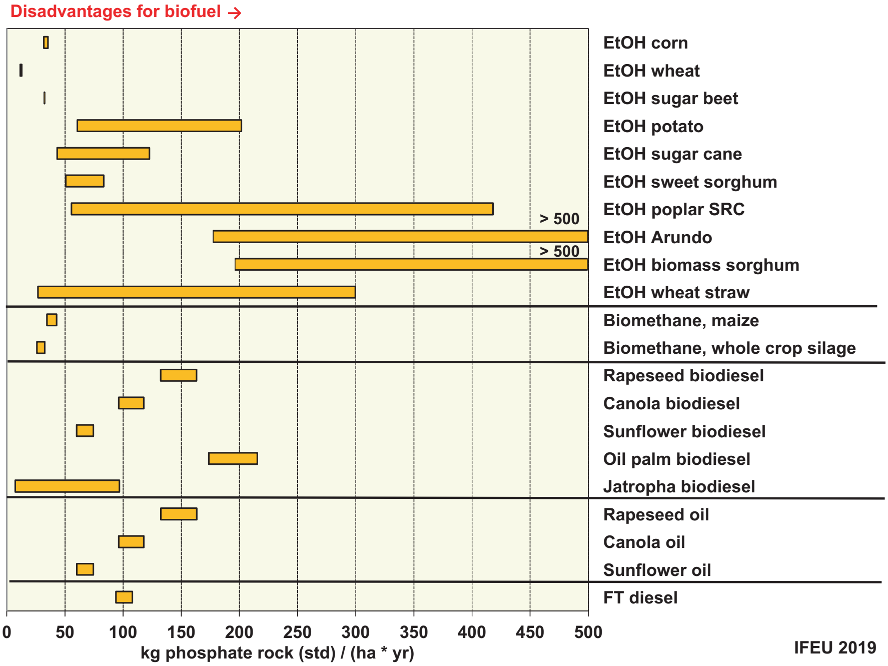

Fig. 3 Phosphate rock demand of different biofuels compared to the respective conventional fossil fuel. The ranges encompass conservatively and optimistically estimated phosphate rock demands for each fuel. EtOH stands for bioethanol, SRC for short rotation coppice and FT for Fischer-Tropsch

recovery. Based on the large range of results, it seems plausible that this aspect has not been optimized or not even been recognized as potential problem in the current state of process development and maturation. This underlines the importance of the indicator phosphate rock demand to support finding solutions to the problem of declining non-renewable phosphate resources.

4 Conclusions

In this paper, we presented two LCA extensions that intend to better address limitations of current agriculture in decision-making processes.

The life cycle inventory method attributional land use and land use change (aLULUC) evenly attributes impacts of deforestation, grassland conversion (both LUC) and organic soil use (LU) actually taking place in a country to each hectare of cropland used in that country. This has several advantages over commonly used dLUC or iLUC:

- Firstly, aLULUC is based on available data and does not require complex economic models or value-based choices of crucial parameters such as time horizons. This makes results more robust.
- Secondly, a comprehensive and regularly updated database is available based on the respective national inventory reports and FAOSTAT for LUC and LU.
- Thirdly, in contrast to iLUC, aLULUC is compatible to attributional LCA, because it attributes burdens/emissions to products and not to change processes. Finally, aLULUC factors on a country level can help to derive meaningful messages to politicians in charge for protection measures or to consumers.

The LCIA indicator phosphate rock demand was introduced as a stand-alone resource indicator because phosphate is a finite resource that cannot be replaced in its vital major application as fertilizer. Thus, phosphate consumption without recycling needs to be reduced which requires measures that are independent of other finite resources. The phosphate rock footprint was shown to be a valuable tool to identify such measures. For biofuels, for example, hot spots of phosphate use were found in various life cycle stages. This information can easily be lost in common evaluations of common aggregate resource indicators.

In summary, the LCI/LCIA methods aLULUC and phosphate rock demand are suitable to derive additional insights and recommendations for LCAs with a wide range of goals and scopes. In particular, both methods are designed to yield recommendations how to overcome crucial bottlenecks of agriculture that are solution-oriented and useful in practice. Therefore, these methods should be considered as an extension of or, if already addressed, alternative to methods nowadays routinely applied in LCA.

Acknowledgements A joint effort in several projects led to this work. The projects have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nos. 727698 ("Magic"), 763911 ("eForFuel") and 727463 ("BioMates") as well as from the Bio-Based Industries Joint Undertaking (JU) under grant agreement No. 792004 ("UNRAVEL"). The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Bio-Based Industries Consortium. Furthermore, the authors would like to thank all colleagues at ifeu, in particular Guido Reinhardt, Regine Vogt and Nabil Abdalla, for their contributions, discussions and recommendations in developing the LCA methods discussed in this paper.

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The Environmental Assessment of Biomass Waste Conversion to Sustainable Energy in the Agricultural Biogas Plant

Magdalena Muradin

Abstract Operating an agricultural biogas plants offers the potential of stable, clean, renewable and diversified energy source. It is also a good opportunity to reduce the amount of organic waste. The objective of this study is to evaluate the main environmental hot spots of operating agricultural biogas plants using LCA methodology. This article presents the environmental impact assessment of two agricultural biogas plants with different type of feedstock provision. The environmental life cycle assessment was carried out from "cradle to gate" using the SimaPro software and the ILCD 2011 Midpoint+ methodology. The boundaries of the system included cultivation of maize, delivery of feedstock to the plant, energy production, storage and transport of digestate. The results show that transport of liquid manure induces the highest environmental impact.

1 Introduction

In 2019, the European Parliament assigned the resolution on the climate and environment emergency. Based on that, it is an urgent need to implement and develop many new technologies especially in energy sector, to prevent the further intensification of the crisis and reduce the global temperature growth.

It was expected that carbon dioxide produced by human activity would be absorbed by the oceans. Meanwhile, by warming the atmosphere, CO_2 is additionally released from the oceans and melting ice, so that its concentration may increase exponentially and cause more and more negative climatic phenomena. Food production and consumption account for as much as 35% of all greenhouse gases in the atmosphere, of which agriculture alone accounts for 10%.

Developed countries are struggling with ever-increasing amounts of waste, including the agri-food industry waste, due to overproduction and consumption of food. The issue of the generation of biodegradable waste is often marginalized, while animal production and the generated livestock manure contribute to 30% of

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Z. S. Klos et al. (eds.), *Towards a Sustainable Future - Life Cycle Management*,
https://doi.org/10.1007/978-3-030-77127-0_12

the total emission of anthropogenic methane to the atmosphere. The global warming potential for methane is from 23, which means that the same amount of methane in the atmosphere as CO_2 will have a 23 more significant impact on climate warming. Technologies based on anaerobic digestion are very useful in reducing the amount of waste from agri-food industry and at the same time enable controlled methane capture and energy production in cogeneration systems.

Manure is a livestock residue that has little commercial value [1]. The slurry digestate which is a result of the anaerobic fermentation can be used as more bio-available fertilizer form [2] and helps to reduce the number of pathogens entering the soil with direct application. Furthermore, storing animal manure in the open air results in methane and carbon dioxide emissions through the process of self-remediation [3]. Anaerobic digestion of animal manure reduces the environmental impacts caused by carbon dioxide, methane and nitrous oxide emissions from storage and reduces waste and odours [4]. For example, in Finland case, anaerobic fermentation on cattle farms contributes to the reduction at approximately 9% of the national agricultural GHG emission reduction goal during the 2005–2020 period [5].

However, animal manure has low biogas yield (9–36 m^3/Mg) compared with different feedstock especially maize silage. In this case, the co-digestion of different biodegradable substrates is often used at farms. The most effective in producing biogas is digesting liquid manure with maize silage, what is however economically unfavourable, and what even worse, maize cultivation for the energy production purpose stays against cultivation for feeding. The solution could be co-digestion with different waste from agri-food production. Such products have often relatively higher methane yield than manure, e.g. potato pulp or fruit pomace. Very favourable to use as a feedstock is also distillery waste. The methane yield for that waste is lower and similar to liquid manure but to manage with this waste is also very problematic and biogas plant can be a solution.

Anaerobic digestion seems to be a very efficient way to close the material and nutrient loop according to EU circular economy paradigm. The field application of digestate is also a part of nutrients' circularity. Digestated materials have advantages for their use as soil amendments which are microbial stability, hygiene and high amount of N present as ammonium. It improves also the total organic C concentration in soil [6, 7].

Biogas is a promising substitute for natural gas of fossil origin [8]. Published articles about environmental impact of biogas production analysed heat and energy production [9], biomethane purification [10] and domestic use [11]. Reviews also describe biogas LCA from manure in a global perspective, technological studies of biogas production and specific studies for specific countries or region. Studies also concern a transport of feedstock and indicate that it can play an important role in the environmental performance of biogas production [12]. The maximum transportation distance should not extend 10 km to make biogas environmentally viable for small-scale plants [9, 13], and for large-scale plants, it should be within 64 km [14]. However, mostly studies focus on electricity generation from biogas than on the possibility of biomass waste treatment.

The aim of this paper is to present the results of selected two biogas plants, which mostly differ with the type of feedstock, the way it is transported and the transportation distance, in order to highlight the most critical factors (hot spots) from the environmental point of view of operating those installations whose main purpose is the waste treatment.

2 Materials and Methods

The life cycle assessment (LCA) methodology was chosen for this study based on ISO 14040 and ISO 14044 as the most comprehensive evaluation of environmental impact. LCA analysis includes four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation of results [15, 16]. In this work, the ILCD 2011 Midpoint+ v.1.10 method was considered. The ILCD was developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in cooperation with the Environment DG which is widely used in Europe. In this method, 16 very detailed impact assessment categories are distinguished [17]. The inventory data for this study were taken directly from tested agricultural biogas plants located in Poland and from the ecoinvent database v. 3.3 and processed using the SimaPro calculation program.

Selected biogas plants were assessed in details from gate-to-gate perspective. Input data were collected for separate unit processes implemented under the modern mesophilic fermentation technology: maize cultivation, feedstock delivery, energy production and digestate storage and transport. All results were analysed relative to the reference unit, which is named as a functional unit (FU) and defined as "a delivery of 1000 Mg of feedstock designed to biogas conversion". The values of the eco-indicator were presented in impact categories, expressing the value of impact at environmental ecopoints (marked with the Pt symbol).

The allocation cut-off by classification model was used in this study, and the primary production of input of raw materials and pig slurry was allocated to the primary user/producer. It was also considered that the main product is electricity with 100% allocation, but the main purpose of those plants is the biomass waste management. Only the maize cultivation was taken into consideration as a dedicated tillage.

Two agricultural biogas plants A and B were taken into consideration with installed power 1.0 MW and 0.526 MW, respectively. In both cases, slurry digestate is not separated and used as a natural fertilizer on arable fields. The most important parameters of the tested plants are collected in Table 1. The construction and demolition of the biogas plant as well as the production of biomass waste feedstock and digestate application on fields were excluded from the scope of the study. The environmental impacts of the electricity production from biogas based on anaerobic co-digestion of pig slurry, silage maize and different feedstock from agri-food industry were determined (Table 2).

Table 1 The most important parameters of the tested biogas plants

Parameter	Biogas plant A	Biogas plant B
The amount of biogas [m^3/year]	4,169,760	1,725,155
The amount of electricity produced [MWh/ year]	786.1	300.7
The amount of heat produced [MWh/ year]	776.9	319.3
The amount of heat used [MWh/ year]	147.0	222.1
The amount of digestate [m^3/year]	35,515	19,744
Total efficiency [%]	51	69

Table 2 The feedstock input in relation to annual operations

Biogas plant	Type of feedstock	The amount of feedstock [Mg/year]	Biogas yield [m^3/Mg]	Maximum transport distance [km]
A	Pig slurry	14,824.0	232.0	5.0
	Maize silage	21,693.0	36.0	1.0
B	Maize silage	2,025.0	230.0	45.0
	Distillery residues	11,489.7	31.0	Gravity pipeline
	Carrot pomace	1,595.9	76.0	11.3
	Potato pomace	5,919.6	94.0	22.5
	Pig slurry	590.0	9.0	3.8
	Protein sediments	402.6	700.0	172.5

Liquid animal manure was transported by a farm tractor with a barrel. Maize harvested from the fields was transported to a biogas plant using heavy wheeled transport. The remaining raw materials from the agri-food industry were transported with a trailer or with different types of lorries. Only distillery residues in biogas plant B were delivered by a gravity pipeline.

3 Results and Discussion

The results were estimated by using the ILCD 2011+ method and the 16 midpoint categories. The results were described on two different levels of LCA methodology: characterization and weighting for four-unit processes – maize cultivation, feedstock delivery, energy production and digestate storage and transport. The feedstock delivery includes transport of agri-food residues, maize ensilaging on-site and delivery to the digester. In analysed biogas plants, we can distinguish six types of transport: (1) road transport of pig slurry to the plant, (2) road transport of raw materials to the plant, (3) pipeline transport to the plant, (4) internal transport on-site, (5) maize transport from the field and (6) digestate transport for final use as fertilizer.

The cumulative environmental impact of biogas plant B (1.48 kPt) is significantly lower than that of biogas plant A (42.66 kPt). The liquid feedstock with low organic mass content and biogas yield in plant B are provided by gravity pipeline. In an installation A, a feedstock is delivered by a tractor with a barrel (Table 3). The highest environmental burdens of biogas plant A stem from the delivery of a feedstock, whereas of plant B, it is related to the storage and transport of the digestate.

The highest value of eco-indicator for plant B concerns the digestate storage and transport. In this case, the transport of liquid digestate takes place using a tractor with a barrel. The storage of the digestate itself does not involve any energy consumption or emissions to the atmosphere. The digestate is stored in a sealed container, so transport in this process is the main contributor. Moreover, the fields for the application of the digestate are located in the vicinity of biogas plant B and the distance is 0.9616 km maximum. The transportation distance of a digestate to biogas plant A is almost twice longer (1,606 km), which can significantly affect the higher environmental impact. The area required for the spreading of the digestate and the maximum transportation distance were calculated as follows [18].

Biogas plant A exhibits a significant impact on almost all categories; however, the contribution of all categories for both biogas plants is almost equal (Table 4).

Only for the water resource depletion category for both biogas plants, the value is below zero. It means that in this category, the environmental impact can be positive. The lower is the value, the more positive is the impact. The reason for obtaining such results for this impact category is the temporary storage of the liquid digestate. It may provide a reservoir of water for field irrigation just next to the fertilization purpose.

Based on the results, three leading groups of factors with the highest environmental impact were separated: transport, electricity consumption and others. The factors were classified in terms of the value of environmental burdens and significance for the impact on climate change. In both biogas plants, transport is the main contributor and represents 99.9% and 98.1% of the total cumulative impact value, respectively (Fig. 1). Even electricity consumption, which in both cases comes from the grid, represents a negligible part of the total impact, 0.03% and 1.56%, respectively (Fig. 1).

Comparing all different types of transport as it was mentioned earlier in this article, for biogas plant A, the highest environmental impact is related to the transport of pig slurry (91%), while for biogas plant B, the impact mainly stems from the transport of the digestate (87%) (Fig. 2). The transport of raw materials to biogas plant B is characterized by a relatively low environmental impact, even though the distance from the production site to the biogas plant is up to 100 km. Raw materials from agri-food industry such as fruits and vegetable pomace have a higher organic mass content and a higher biogas yield per unit weight (Table 2). Then the

Table 3 The cumulative eco-indicator values for individual stages of operation

Biogas plant	Maize cultivation [kPt]	Feedstock delivery [kPt]	Energy production [kPt]	Digestate storage and transport [kPt]
A	0.58	38.68	0.01	3.39
B	0.01	0.18	0.02	1.27

Table 4 LCIA results of each biogas plant on the characterization level

Impact category	Unit	Plant A	Plant B
Climate change	kg CO_2 eq	1.93E+07	957E+05
Ozone depletion	kg CFC − 11 eq	2.30E+00	134E-01
Human toxicity, non-cancer effects	CTUh	5.82E+01	1.85E+00
Human toxicity, cancer effects	CTUh	2.12E+00	7.84E-02
Particulate matter	kg PM2.5 eq	1.82E+04	7.31E+02
Ionizing radiation HH	kBq U235 eq	1.26E+06	6.50E+04
Ionizing radiation E (interim)	CTUe	6.65E+00	3.67E-01
Photochemical ozone formation	kg NMVOC eq	1.59E+05	6.70E+03
Acidification	molc H+ eq	1.61E+05	6.86E+03
Terrestrial eutrophication	molc N eq	5.56E+05	2.36E+04
Freshwater eutrophication	kg P eq	5.93E+03	2.47E+02
Marine eutrophication	kg N eq	5.11E+04	2.17E+03
Freshwater ecotoxicity	CTUe	3.02E+08	1.14E+07
Land use	kg C deficit	1.35E+08	5.37E+06
Water resource depletion	m^3 water eq	−1.94E+06	−5.85E+04
Mineral, fossil and ren resource depletion	kg Sb eq	3.27E+03	1.27E+02

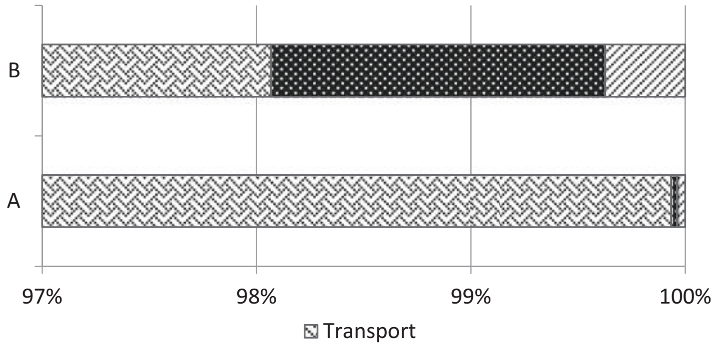

Fig. 1 The contribution of main critical factors in total environmental impact

transportation can be significantly extended obtaining the same results compared with the distance for pig slurry. In plant B, the distillery residues were transported by gravity pipeline what leads to negligible environmental impact at the exploitation stage. The impact can be visible at the construction or demolition stage when the input of metal used for pipelines is taken into account. However, in this study, these two stages were omitted.

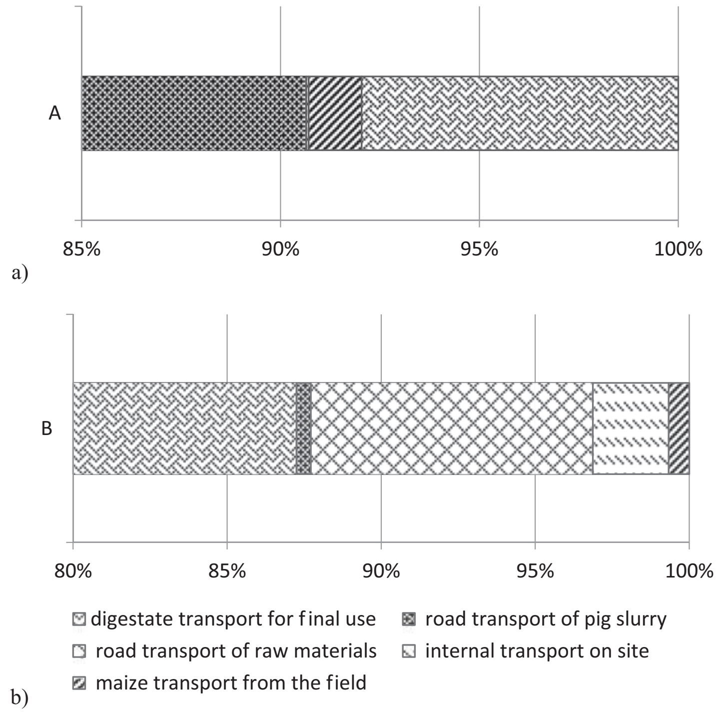

Fig. 2 The share of different types of transport in feedstock delivery process: (**a**) biogas plant A, (**b**) biogas plant B

4 Conclusions

The production of renewable energy from biogas is an unquestionably effective way to replace energy from conventional sources and reduce negative environmental impact and climate change. Biogas plants can also provide a solution to the problem of managing many agricultural and agri-food industry waste. However, taking into account many previous studies and this work, we can conclude that transport is the main contributor of the cumulative environmental impact of operating an agricultural biogas plant. Liquid raw materials with a low biogas yield should be transported by pipelines, and biogas plants using this type of raw materials should be located in the vicinity of feedstock sources. This is also confirmed by Cherubini et al. who claimed that keeping animals close to biogas plant provide the reduction of the environmental impact [19].

In the case of the ferment, the distance over which it is to be extracted should be limited or other solutions should be used to limit the quantity of the ferment that is needed to be used, e.g. by drying. The environmental impact of drying processes and the possible pelletization of the resulting biomass should be studied.

Undoubtedly, biomass waste is a key source of renewable energy (not only a biogas), but we have to be aware of the possible environmental impact.

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