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Helena Mälkki

IDENTIFYING NEEDS AND WAYS TO INTEGRATE SUSTAINABILITY INTO ENERGY DEGREE PROGRAMMES

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Abstract

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This dissertation focuses on the changes needed in energy education in order to integrate sustainability into the courses of energy degree programmes at technical universities. Education is an important driver of and energy plays a vital role in the development of sustainable solutions locally and globally. As designers, decision-makers and managers, energy engineers must not only possess sustainability knowledge but also the skills necessary to ensure the best sustainable energy solutions for society. In spite of the importance of sustainability in both energy and education, sustainability has been poorly integrated into energy education curricula. This lack of integration motivated the present exploration of sustainability approaches, teaching concepts, and methods to be recommended to guide teachers in the integration of sustainability concepts into energy education as well as to enhance students' understanding of the comprehensive nature of sustainability. This dissertation presents a pedagogical approach to combining sustainability, energy and education by utilising the possibilities of life cycle assessment (LCA) methodology in research-based teaching to promote sustainability knowledge and related skills in students. Qualitative and quantitative research methods have been used to identify the future skills needed in the energy sector, to update the content of energy courses, and to provide guidelines for the use of LCA in research-based teaching for assessing the sustainability of energy systems. In particular, a quantitative method has been demonstrated to measure the sustainability content of learning outcomes with the aim of helping teachers in curriculum planning and discussing the sustainability levels of their energy courses in energy degree programmes. This proven method is capable of revealing the strengths and weaknesses of the present status of sustainability in energy courses. In addition to traditional LCA, there is a growing need for the use of consequential LCA when planning for sustainability of energy systems and related investments at the societal level. To enhance sustainability in energy education, sustainability learning outcomes play a crucial role in integrating sustainability into energy degree programmes. Additional recommendations concern the training of teachers to adopt the sustainability dimensions and the use of LCA methodology to instruct their students about LCA assignments and projects. However, further research is necessary to define the sufficient levels of the sustainability components of energy degree programmes. Moreover, the incentives and barriers should be identified case by case to effectively foster the integration of sustainability into energy education. In conclusion, all energy programme students should be provided with a sufficient understanding of

sustainability during their energy study path in order to be able to communicate and make decisions regarding optimal sustainability solutions in their work places after graduation.

Keywords: sustainability, renewable energy, energy education, energy degree programme, teaching and learning methods, research-based teaching, life cycle assessment, pedagogical choices

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This work was carried out at the LUT School of Energy Systems at Lappeenranta University of Technology in Finland.

This thesis has its roots in environmental research projects and international activities in the development of LCA methodology and LCA standards in the 1990´s at the Technical Research Centre of Finland (VTT). These LCA research projects enabled me to participate in national and international LCA conferences and working groups. Environmental issues also played an important role in my planning and teaching of the master's degree programme in environmental technology as an educational manager at the Helsinki University of Technology (now Aalto University, since 2010).

The academic research project "Pro-Environmental Product Planning in a Dynamic Operational Environment Now and in Future – Methods and Tools (ProDoe)" combined life cycle-based approaches and industrial symbiosis for improving sustainability of the industrial sectors in the Bothnian Arc region. I greatly appreciate the experiences of this project during the years 2007–2010. Particularly, I want to thank Professors Kari Heiskanen and Olli Dahl at Aalto University in Espoo for their expertise and wise leadership and for motivating the research activities. I also thank my co-researchers Nani Pajunen, Jyrki Heino, Maaria Wierink, Gary Watkins, Olli Salmi, Sanni Eloneva, Mikko Mäkelä, and others involved in this project for inspirational and encouraging discussions, close cooperation and fun-filled leisure activities.

My educational studies during the years 2005–2012 at Aalto University, which led to a certified teacher degree, made it possible to understand how important it is to develop and use carefully selected pedagogical choices in teaching subject matter to students. These studies made fertile discussions possible with educational developers and teachers from different disciplines in the development of my own courses. I am very grateful to the educational developers and teachers that I met during my pedagogical studies, particularly Anu Yanar, Laura Hirsto, Maire Syrjäkari, Maija Lampinen, Jukka Paatero, Kari Alanne and many others for sharing their developmental experiences in teaching.

In November 2017, I received an International Life Cycle Academy Award for one of my dissertation articles in Barcelona. The article, "An overview of life cycle assessment (LCA) and research-based teaching in renewable and sustainable energy education", was chosen as the best contribution to LCA communication or teaching, and the award also recognized my long career in the field of LCA. Now, I am grateful that this award pushed me to finalise my dissertation. My warm thanks go to the ILCA jury for this decision and my co-author Kari Alanne for his help in planning and commenting on this article.

The theme of my dissertation was developed together with and supported by my supervisors, mainly between the years 2010 and 2018. I thank my supervisor, Professor Risto Soukka, in the Sustainability Science Unit at Lappeenranta University of Technology for inspiring discussions and for his patience over the long duration of this work. I warmly thank Kari Alanne at Aalto University and Laura Hirsto at the University

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My warmest thanks go to my dear friend Nani Pajunen, who has always wholeheartedly encouraged and motivated me to see “the red thread” and a value of this work. Our excellent lunches together, warm-hearted meetings and multifaceted discussions about the subject led me to believe that this work should be accomplished. There were also many other people involved in my dissertation process. Thank you all very much!

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Helena Mälkki
October 2018
Helsinki, Finland

I dedicate my dissertation to my late parents. I am grateful to my mother Aino and my father Aleksanteri, who enabled my education, and whose wise lifestyle showed a way how to live in a circular economy in the countryside, before the concept was even invented.

Contents

Publications

List of publications

Reprints of the articles are included at the end of this work.

This thesis is based on the following six papers. Rights have been granted by the publishers to include the papers in this dissertation.

I. Mälkki, H., Alanne, K. & Hirsto, L. (2012) 'Energy engineering students on their way to expertise in sustainable energy', *Environmental and Climate Technologies,* vol. 8, 2012, pp. 24-28. ISSN 1691-5208. e-ISSN 2255-8845. DOI:10.2478/v10145-012-0004-z.

II. Mälkki, H. & Alanne, K. (2017) 'An overview of life cycle assessment (LCA) and research-based teaching in renewable and sustainable energy education', *Renewable & Sustainable Energy Reviews 2017,* vol. 69, pp. 218–231, http://dx.doi.org/10.1016/j.rser.2016.11.176.

III. Mälkki, H. & Virtanen, Y. (2003) 'Selected emissions and efficiencies of energy systems based on logging and sawmill residues', *Biomass and Bioenergy*, vol. 24, pp. 321–327, https://doi.org/10.1016/S0961-9534(02)00169-1.

IV. Mälkki, H. & Paatero, J.V. (2015) 'Curriculum planning in energy engineering education', *Journal of Cleaner Production*, Special issue: Bridges for a more sustainable future: Joining Environmental Management for Sustainable Universities (EMSU) and the European Roundtable for Sustainable Consumption and Production (ERSCP) conferences, vol. 106, pp. 292–299, http://dx.doi.org/10.1016/j.jclepro.2014.08.109.

V. Mälkki, H., Alanne, K. & Hirsto, L. (2015) 'A method to quantify the integration of renewable energy and sustainability in energy degree programmes: a Finnish case study', *Journal of Cleaner Production*, Special issue: Bridges for a more sustainable future: Joining Environmental Management for Sustainable Universities (EMSU) and the European Roundtable for Sustainable Consumption and Production (ERSCP) conferences, vol. 106, pp. 239–246, http://dx.doi.org/10.1016/j.jclepro.2014.10.012.

VI. Mälkki, H., Alanne, K., Hirsto, L. & Soukka, R. (2016) 'Life cycle assessment (LCA) as a sustainability and research tool in energy degree programmes', at *the 44th SEFI Annual Conference* "Engineering Education on Top of the World: Industry-University Cooperation", Tampere University of Technology, Tampere (Finland), 12–15 September 2016, European Society for Engineering Education (SEFI), 2016 Tampere - ISBN 978-28735201-44, https://www.sefi.be/.

Author's contribution

I. Helena Mälkki was the corresponding author and responsible for writing the manuscript. Kari Alanne and Laura Hirsto supervised the study and commented on the manuscript.

II. Helena Mälkki was the corresponding author and responsible for writing the manuscript. Kari Alanne supervised the study and commented on the manuscript.

III. Helena Mälkki was the corresponding author and responsible for writing the manuscript. Yrjö Virtanen supervised the calculations of the study results.

IV. Helena Mälkki was the corresponding author and responsible for writing the manuscript. Student feedback data were collected and analysed by Jukka Paatero. The interpretation and writing of the results were done in collaboration with Jukka Paatero, who supervised the study and commented on the manuscript.

V. Helena Mälkki was the corresponding author and responsible for writing the manuscript. Kari Alanne and Laura Hirsto supervised the study and commented on the manuscript.

VI. Helena Mälkki was the corresponding author and responsible for writing the manuscript. Kari Alanne, Risto Soukka and Laura Hirsto supervised the study and commented on the manuscript.

Nomenclature

Abbreviations

ABC	activity-based costing
ASIIN	Accreditation Agency for Degree Programmes
CC	cumulative competence
CDIO	conceive, design, implement, operate
CO_2	carbon dioxide
COP	Paris climate conference
CVM	contingent valuation method
DESD	Decade of Education for Sustainable Development
EC	European Commission
ECTS	European Credit Transfer and Accumulation System
EIT	European Institute of Innovation and Technology
EMS	Environmental Management System
ENAEE	European Network for Accreditation of Engineering Education
EPA	Environmental Protection Agency of the United States
EPD	Environmental Product Declaration
ESD	Education for Sustainable Development
EU	European Union
EUR-ACE	European Accredited Engineer
FINEEC	Finnish Education Evaluation Centre
GAP	Global Action Programme
GHG	greenhouse gas
HEI	Higher Education Institution
IBL	inquiry-based learning
IEO	International Energy Outlook
ILO	International Labour Organization
ILOs	intended learning outcomes
ILCD	International Reference Life Cycle Data System
IPP	Integrated Product Policy
IRENA	International Renewable Energy Agency
ISCN	International Sustainable Campus Network
ISO	International Organisation for Standardisation
JRC	Joint Research Centre of the European Commission
KIC	network of Knowledge and Innovation Communities
LCA	life cycle assessment
LCC	life cycle costing
LCIA	life cycle impact assessment
LCSA	life cycle sustainability assessment
LCSD	life cycle sustainability dashboard
NSCN	Nordic Sustainable Campus Network
OECD	Organisation for Economic Cooperation and Development

PBL	problem-based learning
REN	Renewables Global Futures Report
REPA	resource and environmental profile analysis
RR	relevance ratio
SDG	Sustainable Development Goal
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	social life cycle assessment
SSR	subject-specific criteria
STOPS	Software for Target-Oriented Personal Syllabus
SWOT	strengths, weaknesses, opportunities, and threats
TCO	total cost ownership
TEK	Academic Engineers and Architects in Finland
TEM	Ministry of Economic Affairs and Employment of Finland (MEAE)
TVET	Technical Vocational Education and Training
UESEE	Urban Energy Systems and Energy Economics
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNCED	United Nations Conference on Environment and Development
VTT	Technical Research Centre of Finland
WCED	World Commission on Environment and Development
WTA	willingness to accept
WTP	willingness to pay

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1 Introduction

1.1 Background

Energy plays a vital role in transforming societies towards more sustainable energy solutions locally and globally (UN 2014b). The plethora of agreements and initiatives are evidence of efforts to reach future sustainable energy targets and goals to increase the share of renewable energy and decrease the greenhouse gases in energy production (EU 2009; UN 2015b). Many of these energy goals are fairly ambitious but quite general in nature. A complex of sustainability is part of these ambitious challenges to reach energy goals. As such, the development of sustainable solutions entails the challenge of integrating environmental, economic and social views, all of which should be involved in making choices and decisions regarding the sustainability of energy systems. In addition to the multidisciplinary nature of sustainability, the decisions are also dependent on the attitudes, motivations and life situations of the decision-makers. Therefore, future energy engineers, in addressing sustainability, will be required to act as designers, decision-makers and leaders to improve the welfare of the people and mitigate climate change in an effort to create more sustainable societies. This is also why introducing practical solutions into energy education is important; therefore, this research contributes to the grass roots level of energy education.

As a relevant part of sustainable society, sustainability knowledge and related skills are needed in energy education, particularly concerning the use of renewable energy technologies such as biomass, solar, hydro and wind. The IRENA report confirmed that there is a need to train engineers especially for the field of renewable energy (IRENA 2011). Energy engineers are the key actors in implementing necessary improvements to energy systems to achieve local and global sustainability goals and energy targets. These goals and targets are presented in EU and UN reports (EU 2009; UN 2014b; UN 2015b; UN 2015a). The UN energy goals for affordable, reliable, sustainable and modern energy for all (UN 2015b) generate challenging problems for discussion in the classroom. For example, students could discuss the pros and cons of local and global energy solutions. Moreover, students need topical assignments to practise how to reduce CO_2 emissions, how to increase the share of renewables, and how to improve the energy efficiency of energy solutions. National energy targets vary country by country, but the overall EU energy targets aim at a reduction of CO_2 emissions by 60–80%, an increase of renewables by 60%, and improvement in energy efficiency by 35% by 2050 (EU 2009). It is a challenge to achieve these targets.

Sustainability is a necessary part of energy education. The significant role of education in enhancing sustainability has been indicated, for example, in the UN World Summit on Sustainable Development (WSSD), the UN Decade of Education for Sustainable Development 2005–2014 (DESD), and the goals of the Global Action Plan (GAP). Sustainable energy issues have been emphasised, for example, in the UN Sustainable Development Goals (SDG 7) and in EU policies and national targets. Moreover, the future

demands of sustainability call for new means to minimise the use of natural resources such as water, to recycle wastes such as plastics, and to increase the welfare of people and the planet by mitigating climate change. The concepts of a circular economy, the water-energy-food-nexus, and footprints are based on systemic approaches such as LCA that take into account the whole chain of the production system in order to optimise the use of resources and minimise environmental impacts without shifting the consequences from one part of the production chain to another.

Education has been set as a precondition and a driving force for sustainable development (ILO 2011). Initiatives of the United Nations have urged educational communities to reorient curricula to address sustainability (UNESCO 2012a; UN 2005a; UNESCO 2014). The role of curricula in promoting sustainability in education has been emphasised by many studies (Hancock & Nuttman 2014; Lozano 2014; Wals 2014; UN 2005b). Much of the recent research has highlighted the importance of sustainable development in education in general, but the literature falls short when it comes to integrating sustainability into specific disciplines within education, such as energy engineering. Therefore, this dissertation focuses on the integration of sustainability into energy education. Due to a scarcity of previous research within this discipline, the papers presented in this dissertation provide insight into the subject from different perspectives for the purpose of creating an encompassing impression of the situation of sustainability in energy degree programmes. Overall, this dissertation could be seen as an attempt to find out how educators within the energy disciplines could better integrate sustainability into energy education and to discover the best practices for doing so.

1.2 Scope and objectives

The scope of sustainability in energy education is relevant and necessary because energy solutions are crucial to the future of societies. The objective of this dissertation is to identify educational approaches to teaching sustainability and demonstrate a method to discuss the sustainability content of energy courses with the other teachers of the energy degree programme. Engineers need diverse expertise in designing and making decisions about sustainable energy systems. Therefore, energy education should provide students with diverse basic knowledge and skills so that they can act responsibly with different actors in working life. In particular, a combination of formal, non-formal, and informal learning objectives (Malcolm et al. 2003) is needed to ensure that students understand the complexity of sustainability. The novelty of this dissertation is in how it combines pedagogical and systemic approaches for promoting sustainability in energy education at a university level.

The aim of this dissertation is to create interlinkages between sustainability, energy and education for the purpose of enhancing the sustainability knowledge and skills of energy engineering students during their study path in energy degree programmes. Pedagogical approaches such as curriculum planning, core content analysis, learning outcomes, and

teaching and learning methods are used to explore the sustainability content in energy education (Figure 1). The pedagogical and methodological practices explored herein aim to develop energy curricula that better integrate the comprehensive sustainability assessment of energy systems into energy education. More specifically, sustainability has been examined through the content of learning outcomes across an entire energy degree programme and through the use of life cycle assessment (LCA) as a holistic and systemic sustainability assessment tool in energy research and in energy education.

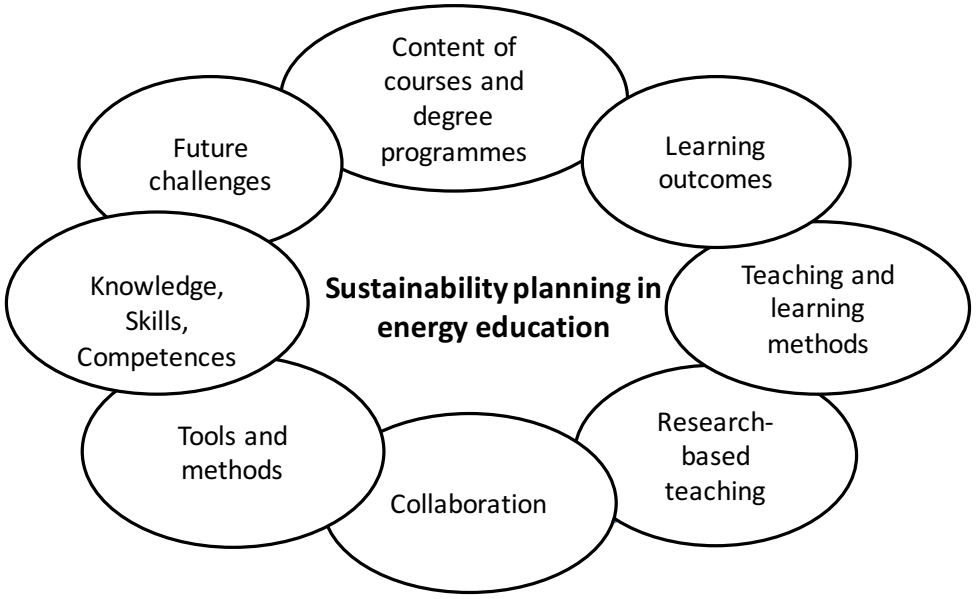


Figure 1. Educational elements for planning sustainability in energy education.

This thesis hypothesises that sustainability skills are in their infancy and are poorly integrated into energy education as yet. The pedagogical choices have not been used in an efficient way to date. For example, teachers are not systematically trained to use appropriate teaching and learning methods that support sustainability and provide practical and real-life learning experiences to students in energy education. The papers of this dissertation explored the roles of the educational elements drawn from different perspectives on curriculum planning (Figure 1).

The main research questions of this dissertation, based on these six (6) papers, are as follows:

- How should learning outcomes be set in order to ensure the integration of sustainability into energy degree programmes?
- How should LCA be applied in energy education in order to exploit all the possibilities the methodology can provide for assessing the sustainability of an energy system?

- What kind of pedagogical choices are the most recommendable to support the needs of the energy sector from the sustainability point of view?

Each paper included theoretical background focusing on sustainability, energy and education to justify its findings. The six (6) papers of this dissertation are presented in Figure 2. The first two papers map out the extent of the pre-existing knowledge within the field. The later papers shift the emphasis to practical applications of the existing knowledge in education. In chronological order, the first paper focused on the future demands of the energy sector and the development of expertise during energy studies at universities. The second paper reviewed the use of life cycle assessment in education and in energy research using a literature search of LCA studies. The third paper was a practical case study implementing a life cycle assessment to assess the environmental impacts of a wood energy system. The fourth paper explored students' and teachers' feedback on the teaching content of an energy major subject. The fifth paper quantified the sustainability content of the learning outcomes in the energy courses of an energy degree programme. Lastly, the sixth paper gathered information on the use of life cycle assessment in the energy degree programmes at technical universities. All of these papers provided valuable insights into the status of sustainability in energy education and proposed solutions for integrating sustainability methods and practices into energy courses to enhance the sustainability knowledge and skills of the students.

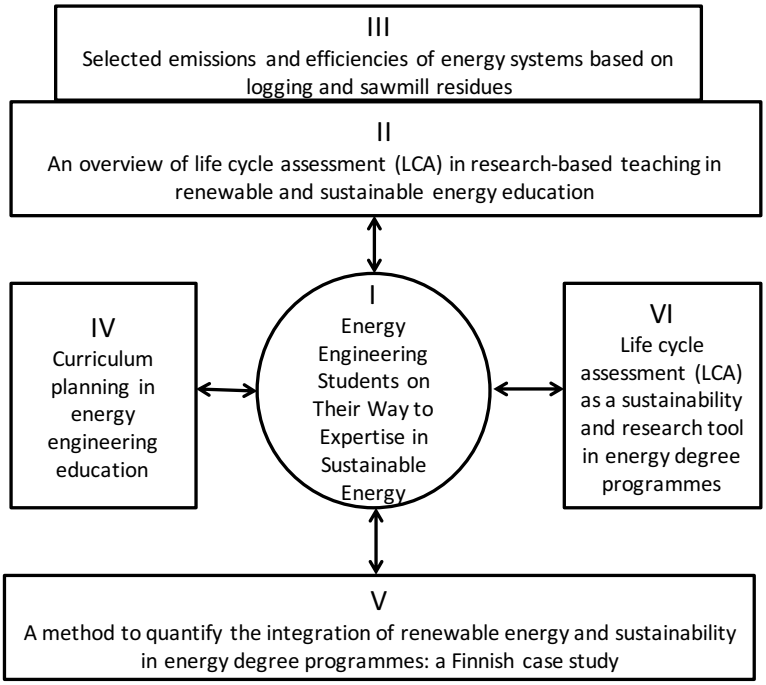


Figure 2: The six (6) papers of the dissertation.

The main focus and research questions of the papers are presented in Table 1. These research questions are formulated to be consistent with the original papers. These papers explored the integration of sustainability into energy education from different perspectives, e.g., curriculum development, research-based teaching, and teaching and learning methods. Moreover, this research process faced questions such as why LCA is important and how LCA could be more useful in energy education.

Table 1. The focus and research questions of the papers.

Papers	Main focus of the papers	Main research questions
Paper I	To characterise the expertise in education and explore the key competencies of an energy engineer for the future demands of industry.	How is expertise defined in terms of higher education? What are the necessary competencies for future energy engineers in working life?
Paper II	To review the use of life cycle assessment (LCA) in energy research and in renewable and sustainable energy education.	To what extent and how is LCA used as a sustainability tool in energy education and in energy research?
Paper III	To assess the environmental performance of an energy system using an LCA tool in a case study.	How should LCA be utilised in an energy case study to discuss the sustainability issues of energy systems in energy education?
Paper IV	To gather student feedback at the course level of the energy degree programme.	How should students' feedback be utilised in planning the content of energy courses?
Paper V	To quantify the sustainability content of the learning outcomes of the energy courses in the energy degree programme.	How should the sustainability content of the energy courses be measured and discussed for planning the sustainability levels of the energy degree programmes overall?
Paper VI	To explore the role of LCA in the energy degree programmes at technical universities.	How is LCA implemented in the sustainable energy education of the energy degree programmes at the surveyed universities?

1.3 Research process

The concept of sustainable development includes different views from various disciplines, such as knowledge of social aspects and people's behaviour in changing

circumstances (Nolan 2012; Wals 2014). These different views should be analysed in the same framework in order to enable decision-making on the comprehensive sustainability of the systems in question. However, this dissertation does not explore the role of behavioural science in assessing the sustainability of energy systems. This work mainly focuses on sustainability from the environmental point of view and explores opportunities where LCA can improve the inclusion of sustainability in energy education.

Teachers play an important role in planning the elements of sustainability pedagogy in their energy courses. They select the content, instruments and materials of their courses. They are also the key individuals who apply appropriate teaching and learning methods to provide students with the knowledge and skills needed to take on real-life sustainability problems. Therefore, the methods of pedagogical education have been used to provide teachers with the pedagogical skills necessary to understand and plan the educational elements of their courses. Pedagogical competencies help teachers to discuss and share their best teaching experiences and further help them to align their choices with the overarching degree programme. Systemic teaching concepts and methods help students to understand the complex issues in their own disciplines (Coyle & Rebow 2009).

This dissertation presents a simplified teaching concept (Figure 3) to guide teachers at the course level to combine energy, sustainability and education, and it points out that sustainability is a multi-phase process in energy education. As a starting point in this concept, teachers are trained to use teaching and learning methods, to understand the principles of sustainable development, and to guide students in the use of sustainability tools. Teachers choose the proper teaching and learning methods, teaching materials and functions to guide students in the sustainability assessment of energy systems. As prerequisite information for this concept, students are expected to have basic knowledge of energy technologies. During the course, students acquire knowledge and skills to understand the principles of sustainable development by using sustainability tools, software and databases through the exercises and projects prepared by the teachers.

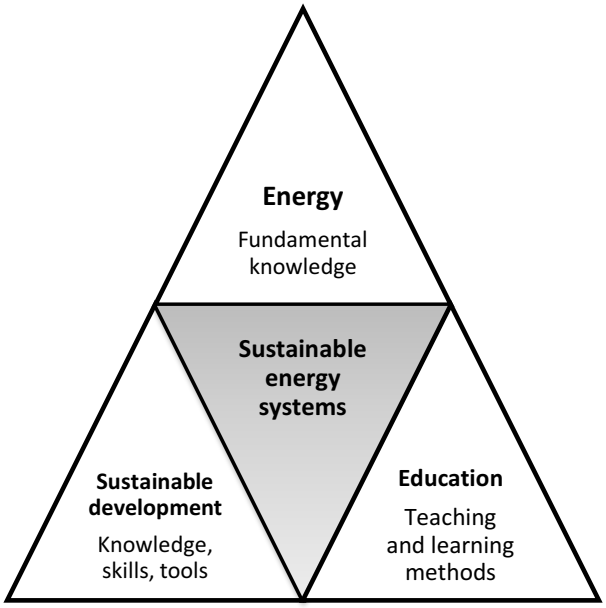


Figure 3. A pedagogical concept for combining sustainability, energy and education.

Sustainability involves a combination of environmental, economic and social issues, and they are recommended to be assessed in the same framework. Therefore, this dissertation guides teachers to focus on life cycle-based approaches, such as by using the life cycle sustainability assessment (LCSA) tool (Klöpffer 2003). It consists of life cycle assessment (LCA) for environmental issues, life cycle costing (LCC) for economic issues, and social life cycle assessment (SLCA) for social issues (Figure 4).

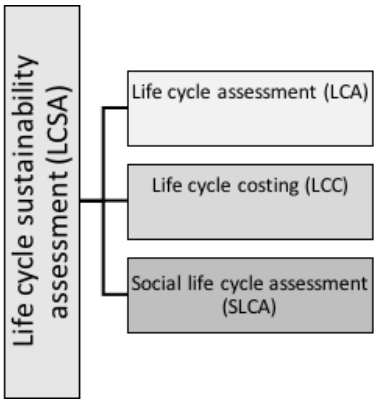


Figure 4. A life cycle sustainability assessment (LCSA) tool for assessing environmental, economic and social dimensions of the studied systems (Klöpffer 2003).

The roles of the papers in promoting sustainability in energy education are presented in Table 2. The research methods included qualitative and quantitative methods to explore teaching and learning methods, research-based teaching, and sustainability content in the learning outcomes. The research materials consisted of literature reviews, student and teacher surveys, and a core content analysis of the energy degree programme. The papers produced findings on sustainability teaching and learning methods, the use of LCA in research and education, and the sustainability content of the learning outcomes of the energy courses. All the results of the papers focused on promoting sustainability planning in the energy degree programmes by analysing sustainability teaching and learning methods, research-based teaching, and the content of the learning outcomes of the energy courses. This dissertation aimed to provide practical guidance to teachers for integrating sustainability into their energy courses in order to provide students with understanding of sustainability and the knowledge and skills needed in making decisions related to sustainable energy systems.

Table 2. The roles of the papers in this dissertation in promoting sustainability in energy education.

GOAL	**Promoting sustainability assessment of the energy systems in the energy courses of the energy degree programmes.**			
RESEARCH METHODS Qualitative and quantitative methods	Literature reviews.	Student and teacher surveys, teacher interviews.	A core content analysis, a sustainability content analysis.	Teaching and learning methods, research-based teaching.
MATERIALS	Background information on sustainability, energy and education (all the papers).	Competencies, knowledge and skills of an energy engineer (Papers I, IV). Curriculum planning (Paper IV). LCA in energy degree programmes (Paper VI).	Sustainability content of the learning outcomes of the energy courses of an energy degree programme (Paper V).	The use of LCA in education and in energy research (Papers II, III).
RESULTS	A pedagogical concept for sustainability, energy and education by using research-based teaching methods.	Current topics in an energy sector. Desired content and teaching and learning methods of the energy courses. Opportunities for the use of LCA in the energy degree programmes.	A method to quantify the sustainability content of the learning outcomes in an entire energy degree programme.	Pros and cons of the use of LCA for assessing sustainability of energy systems. The use of LCSA for assessing comprehensive sustainability with environmental, economic and social dimensions.
OUTCOME	Approaches, methods and best practices to integrate sustainability into energy degree programmes.			
FUTURE	Sustainability energy expertise for decision-makers in choosing the sustainable energy systems needed for the sustainable demands of future societies by local and global organisations, companies, authorities, NGOs, and other stakeholders.			

2 Theoretical foundation

2.1 Sustainability background in energy and education

2.1.1 Sustainability science

The sustainable development definition put forth by the Brundtland Commission in 1987 (WCED 1987) has inspired discussions aimed at understanding the meaning of sustainable development in different circumstances and disciplines.

"Sustainable development meets the needs of the present generation without compromising the ability of future generations to meet their needs" (WCED 1987).

The definition has, however, left room for more detailed and discipline-based interpretations of values and content for establishing initiatives to take direct action towards sustainable development in social, environmental and economic dimensions (Kates et al. 2005). To implement complex sustainable development in practice, sustainability science has begun a new academic discipline aiming to balance environmental protection, economic growth and social equity through integrated research into nature-society interactions (Kates et al. 2000; Peterson 2016).

"Sustainability Science is research and education that result in new knowledge, technology, innovation and holistic understanding which will allow societies to better address global and local sustainability challenges" (UNESCO 2017).

This new approach focuses on the long-term effect of human activity, which causes a variety of climate and ecosystem changes locally and globally (UNESCO 2017). Sustainability science highlights engineering education at all levels, science and research capacity to enhance the interface between academia and practitioners for implementing sustainable solutions in society. Transdisciplinary research and education support wide-ranging expertise in sustainable development and inform sustainability experts. Moreover, governance and educational activities promote cooperation with local actors to take into account local experiences in the integration of social issues, which are a distinct component of economic and environmental issues (Peterson 2016).

Many international natural scientists, social scientists and policy analysts have developed strategies to promote efforts in sustainability science (Kates et al. 2001). They have identified threats such as incomplete knowledge and limitations in the use of scientific research and social relevance that could hinder the achievement of sustainable science (Kates et al. 2001). The United Nations (UN) has been at the forefront in the establishment of initiatives for sustainable development to improve environmental and sustainability awareness around the world. In 2015, UNESCO launched the project, "Broadening the Application of the Sustainability Science Approach", to identify good practices and

develop guidelines to help EU Member States with their sustainable development strategies (UNESCO 2015).

2.1.2 Sustainable energy in society

Society uses energy in homes and commercial buildings, in the transportation sector and in industry to manufacture products. Energy is produced using non-renewable and renewable sources. Renewable energy includes energy modes such as bioenergy, solar power, wind power, hydropower, and geothermal energy (IPCC 2012; WEC 2016). Non-renewable energy uses sources such as coal, natural gas, and nuclear power (WEC 2016).

Sustainable energy has many definitions. Prandecki (2014) pointed out that it is difficult to discern the full definition of sustainable energy and presented the concept of sustainable energy from the viewpoints of both sustainability as well as social and environmental needs for economic development. He also noted that sustainable energy should be understood broadly, taking into account the processing, transportation, distribution, and consumption phases of the entire energy system. Sustainable energy can be understood as meeting the needs of the present without compromising the needs of future generations (Lemaire 2004), reiterating the commonly understood definition of sustainable development (WCED 1987). The sustainable provision of energy can be promoted through technologies that use renewable energy sources and also by technologies that improve energy efficiencies (Coyle & Rebow 2009; EU 2009; Rosentrater & Al-Kalaani 2006; Lemaire 2004; Tan et al. 2015). According to these studies, the key components of sustainable energy are the use of renewable energy sources and the energy efficiency of technologies and systems. Methods of steering energy efficiency include legislation, regulations and guidelines; financial steering methods such as energy taxes and subsidies; energy efficiency agreements and education and communication (Motiva 2006).

All over the world, sustainable and secure energy solutions are needed to overcome environmental problems, mitigate the impacts of global warming and increase the welfare of people (Owusu & Asumadu-Sarkodie 2016). Sustainable energy solutions are at the forefront of national and international research programmes and policy strategies aimed at the mitigation of climate change by reducing the use of fossil fuels (Coyle & Rebow 2009; EU 2009; UNESCO 2016; Ruska & Kiviluoma 2011; UN 2013; UN 2012a). The United Nations (UN) Conference on Sustainable Development, RIO+20, addressed energy as a main and critical driver for sustainable development in concert with global climate change mitigation in the report, "*The future we want*" (UN 2012b).

In addition to policies, laws and standards, energy engineers as decision-makers and professionals need new knowledge and skills to address the sustainability dimensions of energy systems in order to understand the holistic consequences of the energy decisions for human beings and the planet (Seitz & Hite 2012; Turner 2008). Expertise should be based on broad multidisciplinary and interdisciplinary competencies from the

perspectives of working life (Mälkki & Paatero 2012; Mälkki et al. 2012). The FinnSight 2015 report (Academy of Finland 2006) identified important areas of competence, such as "*the operation of ecosystems, the management of environmental issues in Finland and globally, urban environments, water systems and water cleaning technologies, biomass as an energy resource and biomass production technologies, improved energy efficiency or "negawatts", new energy production systems and their integration, smart sensors and new energy conversion and storage technologies, logistics, distribution, mobile and distributed technologies as a platform for energy and environmental services*".

There is a growing need to increase sustainable energy sources and reduce the use of fossil fuels (UNESCO 2016). Global energy consumption has been estimated to grow by 56% between 2010 and 2040, and it means that energy use in non-OECD countries will increase by 90% and by 17% in OECD countries, according to the International Energy Outlook 2013 (IEO 2013). Moreover, the world's population is continuously increasing; it reached nearly 7.6 billion in mid-2017, and it is predicted to reach 8.6 billion in 2030 and to further grow to 9.8 billion in 2050 (UN 2017). Therefore, the growing need for renewable energy sources may cause conflicts over the use of land and competition over raw materials between biofuel and food production systems that may threaten sufficient food supplies and biodiversity at the local and global levels (EC 2006; EC 2010; Uslu et al. 2010).

In the future, the share of renewable energy sources will inevitably grow in energy production systems. The International Renewable Energy Agency (IRENA) has reported that more experts will be needed in the renewable energy sector worldwide, especially in the solar PV and wind categories (IRENA 2017). The *Renewables Global Futures Report* (REN21 2013) identified motivations to develop renewable energy systems such as to increase security of energy supplies, to create new jobs, to obtain financial profits, to avoid the price risks of fossil fuels, to gain access to rural energy, to mitigate climate change, to improve environmental sustainability, and to avoid possible nuclear accidents. Leggett and Carter (2012) pointed out that energy should be available for all people, in spite of the UN's energy goals to increase energy efficiency and the share of renewable energy sources. The *World Economic and Social Survey* (UN 2013) has recognised many sustainable energy pathways to mitigate climate change and increase the welfare of people by using existing energy technology options to deliver sustainable energy solutions. This report highlighted that there is a need to implement relevant energy policies, international collaboration, methods to change behaviour habits and to increase investment (UN 2013).

In the Vision 2050 project, a pathway to sustainability by 2050 was presented (WBCSD 2014). It included nine elements to achieve a sustainable future compared with the present, meaning changes in governance structures, economic frameworks, business and human behaviour (WBCSD 2014). This pathway pointed out that education and economic empowerment have an important role to play in combining behavioural change and social innovation as crucial elements in eco-efficient solutions. The vision emphasised that

sustainability should be embedded into education to improve peoples' mind-sets to understand the sustainability context in social, technological, ecological and political environments (WBCSD 2014). Moreover, the pathway called for an integrated and holistic way of considering the relationships between water, food and energy systems. In the energy sector, the development of secure and sufficient supplies of low-carbon energy has been presented in terms of solar, wind, nuclear and CCS technologies (CCS = carbon capture and sequestration) in order to achieve the reduction goal for carbon emissions by 2050.

In societies, sustainable development can be also promoted by bio-economy strategies aiming at implementing a green economy (EC 2012a; TEM 2014). The EU's bio-economy strategy (EC 2012a) is included in the EU Framework, Programme Horizon 2020 (EC 2012b). These strategies and programmes aim to increase the use of renewable natural resources in the production of food, energy, and other products and services as well as reduce the dependence on natural fossil resources by preventing the loss of biodiversity and creating new jobs through economic growth. However, the transformation towards a green economy will face challenges because the world will need 50% more food, 45% more energy and 30% more water in 2030 (UN 2012a). Moreover, the accomplishment of sustainable development goals through sustainable consumption and production will create synergies contributing to climate change mitigation and supporting the attainment of energy goals (UN 2014a).

2.1.3 United Nations policy on sustainable energy

The United Nations (UN) summits and initiatives focused on sustainable development and the increasing role of energy during the years 1992–2015 (UN 1992; UN 2002; UN 2012b; UN 2014b; UN 2015b; UN 2016). In 1992, Agenda 21 turned more attention to the unsustainability facts related to energy issues (UN 1992). In 2015, Agenda 2030 introduced 17 sustainable development goals (Table 3) and 169 detailed targets to be met by 2030 (UN 2015b). One of the goals (SDG7) was dedicated to the energy targets aiming for affordable, reliable, sustainable and modern energy for all (UN 2015b). In these SDGs, energy plays a central role for jobs, security, climate change, food production and incomes. Moreover, energy is more or less centrally involved in achieving the goals of the other SDGs, which deal with, e.g., health, education, poverty eradication and gender equality. Also, the economic growth and climate actions require low-carbon energy systems, green economies, and development of sustainability solutions locally, nationally and globally. For example, a new global agreement on climate change established by COP21 aims to limit the changes in global temperatures to below 2°C (UN 2015a).

Table 3. Sustainable Development Goals (SDGs) listed according to Agenda 2030 (UN 2015b).

Goal 1. End poverty in all its forms everywhere.
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
Goal 3. Ensure healthy lives and promote well-being for all at all ages.
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
Goal 5. Achieve gender equality and empower all women and girls.
Goal 6. Ensure availability and sustainable management of water and sanitation for all.
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
Goal 10. Reduce inequality within and among countries.
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.
Goal 12. Ensure sustainable consumption and production patterns.
Goal 13. Take urgent action to combat climate change and its impacts.
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
Goal 17. Strengthen the means of implementation and revitalize the global partnership for sustainable development.

2.1.4 **EU policies on renewable energy**

The European Union (EU) energy policies aim to promote the use of renewable energy in Europe (EU 2009). For example, as a result of EU Directive 2009/28/EC (EU 2009) on promoting the use of energy from renewable sources, the Member States published a National Renewable Energy Action Plan (NREAP) in 2010 in which the national targets for the share of renewable energy were set for 2020 (Beurskens & Hekkenberg 2011). These overall EU targets call for reducing CO_2 emissions by 20% and for increasing the share of renewables by 20%, for making a 20% improvement in energy efficiency and for increasing the use of biofuels by 10% compared to the 1990 levels (EU 2009). In Europe, hydropower and biomass are the most abundant renewable electricity sources. Additionally, the capacity of wind power and photovoltaic electricity production has increased, especially in Germany and Spain (Ruska & Kiviluoma 2011). By 2020, the targets vary in the different EU Member States. By 2050, the targets are more challenging.

The CO_2 emissions should be reduced by 60–80%, renewables increased by 60% and energy efficiency improved by 35% (EU 2009).

Finland has set targets of 38% for renewable energy and 20% for biofuel, which are higher than the overall EU targets for 2020 (TEM 2014; TEM 2010). Finland's targets for renewable energy are based mainly on hydropower plants and biomass-fired power stations. Finland is an energy-intensive country, and the energy consumption per capita is among the highest of those countries belonging to the International Energy Agency (IEA 2013). Nuclear and renewable energy form the basis of the Finnish low-carbon electricity production system, according to the vision outlined for Low Carbon Finland 2050 (VTT 2012). In Finland, wood is the most used raw material in renewable energy production systems. Most of the wood-based raw materials stem from forest residues and by-products of wood-based industries. In the future, the by-products of agriculture and the food industry are also possible sources for energy production.

However, these future visions and solutions require concrete actions in terms of sustainability. Above all, employees need training in renewable energy technologies (IRENA 2014) and to understand the principles of sustainable development (Müller-Christ et al. 2014; Littledyke et al. 2013; Lozano 2010). In order to increase expertise in renewable and sustainable energy, universities have a vital role to educate engineers who are able to make decisions about sustainable energy solutions extending far into the future.

2.1.5 Sustainable development in education

Many studies have emphasised that it is important to embed sustainability in curricula at higher education institutions (Adomßent et al. 2014; Hancock & Nuttman 2014; Lozano 2010; Wals 2014; Lozano 2014; UN 2005b; Leal Filho et al. 2017). Sustainability has been indicated as a driving force for new sustainability innovations during the United Nations Decade for Education for Sustainable Development (DESD) 2005–2014 (Nolan 2012; UN 2005a). The *UN Education for Sustainable Development Sourcebook* provides guidance to reorient a curriculum to address sustainability by identifying and integrating the knowledge, issues, perspectives, skills, and values relevant in each of the three dimensions of sustainability, namely environment, economy and society, into the curriculum (UNESCO 2012a). However, embedding all these sustainability dimensions with necessary knowledge, skills and values is a challenge in education (Davidson et al. 2007; Desha & Hargroves 2010; Leal Filho et al. 2015). As an outcome of the DESD, Nolan pointed out in his report that people should be encouraged to change their attitudes, values and lifestyles in order to implement the new challenges of sustainable development (Nolan 2012).

The Delors Report (Delors 1996) highlighted that education sustainability should be based on the knowledge, skills and attitudes of the four pillars consisting of learning to

know, learning to do, learning to live, and learning to be. Additionally, UNESCO addresses the fifth pillar that is necessary in learning to transform oneself and society (UNESCO 2012a). This UNESCO report emphasised that the combination of these five pillars is necessary in order to create a more sustainable future. In spite of this challenge, many formal education systems still require the incorporation of the learning to do activities in addition to the traditional teaching and learning methods. It is essential that education for sustainable development contain elements that activate students to develop their knowledge, skills and attitudes to understand global problems from their own and from other people's perspectives. To help the educators, the UNESCO report *A Multiple-Perspective Approach* supports the development of teaching practices by introducing the eight perspectives (Table 4) to be used in education to help students to understand the complexity of the world (UNESCO 2012b).

Table 4. The eight perspectives in education for understanding the complexity of the world (UNESCO 2012b).

	Perspectives	**Description**
1	Scientific	Science is a systematic and logical way of knowing about the world around us. The scientific perspective is understood internationally.
2	Historical	History records the changes in the world over time; it examines the past to inform actions of today and the future.
3	Geographic	Events, problems and issues take on different complexities when viewed from small to large geographic and temporal scales.
4	Human rights	The Universal Declaration of Human Rights unequivocally states that all humans are to be afforded certain rights including, but not limited to, life, liberty and security of person as well as the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care, and necessary social services.
5	Gender equality	Men and women as well as boys and girls often have different roles in life, which are to be equally valued.
6	Values	The values that individuals, cultures and countries hold influence decisions on a personal level and on a national level.
7	Cultural diversity	Each person brings worldviews and cultural traditions that help bind the individual to a specific cultural group. In a world where mobility is increasingly common and easy, people of different cultures are crossing paths and living closely together.
8	Sustainability	Sustainability balances environmental, social, and economic concerns and focuses on the future to assure the well-being of upcoming generations.

Higher education institutes have been committed to enhancing sustainable development through signing charters and declarations such as Rio+20, the Copernicus Charter and Talloires. The importance of sustainability has motivated surveys and promoted cooperation and sharing of experiences between universities (Fernandez-Sanchez et al. 2014; Leal Filho et al. 2017). The findings of the international survey in 2016 by Leal

Filho et al. revealed obstacles hindering the integration of sustainability in universities, such as lack of support from management, a lack of awareness and concern, a lack of appropriate technology, a lack of environmental committees, a lack of buildings with sustainable performance and governmental barriers (Leal Filho et al. 2017). The greatest obstacles were found in administration and management followed by a lack of interest in or concern with sustainability issues.

The Nordic Sustainable Campus Network (NSCN), established in 2012, cooperates with Nordic universities on sustainability issues. The International Sustainable Campus Network (ISCN) includes world-class universities from all continents that collect and share data on academic and campus activities. The survey on the integration of sustainability into the Nordic Higher Education Institutions (HEIs), which was carried out in 2014–2015, revealed that the representation of sustainability was at a higher level in Swedish HEIs compared to other Nordic HEIs (Karvinen, Löyttyniemi, et al. 2016). The results indicated that the strategies of the HEIs are the key drivers of sustainability, and insufficient and unclear sustainability strategies caused problems in the implementation of sustainability. Moreover, at Nordic HEIs, better sustainability communication and training of staff were proposed to promote the visibility of sustainable development in education. A Sustainability Hub was established in 2017 to address the challenges of sustainable development in teaching, campus development and other operations at Aalto University. One of the goals aims to integrate sustainability with the university curriculum by 2020. In spite of many efforts, sustainability is a continuing challenge in higher education (Karvinen et al. 2017; Karvinen et al. 2016). Moreover, there is a crucial need to integrate sustainability into sustainable and renewable energy education (Acikgoz 2011; Kandpal 1999; Karabulut 2011).

2.1.6 United Nations sustainability initiatives in education

In 1992, the United Nations Conference on Environment and Development (UNCED) recognised in Agenda 21 that education, training and public awareness are crucial elements for achieving the goals of sustainable development by developing educational environments with the sustainability content (UN 1992). Education is also connected to the Rio Conventions of Climate Change (1992), Biological Diversity (1992), and Combat Desertification (1994) as a necessary pathway to promote the actions needed in these conventions. Also, the Millennium Development Goals have pointed out the importance of knowledge and education for achieving sustained, inclusive and equitable economic growth (UN 2000). The United Nations declared the decade 2005–2014 as the UN Decade of Education for Sustainable Development (DESD) to promote actions towards sustainability in education (UN 2005a). The DESD projects produced good practices to raise awareness and influence policies in all the areas of education and learning (UN 2012b). As a result of DESD, many countries have committed to advancing education for sustainable development (ESD) at the national and local levels (Nolan 2012).

ESD includes many types of education that involve the different aspects of sustainability, such as mitigating climate change, minimising risks and ensuring biodiversity (Wals 2012). In spite of good progress, the outcome report of DESD indicated that the social dimensions of sustainability have garnered less attention in education and they should be better integrated into education. In addition to traditional knowledge, sustainability in education requires understanding local content connected with democratic participation. The importance of social aspects in education has been addressed in the Earth Charter, including values such as "*respect and care for the community of life, ecological integrity, universal human rights, respect for diversity, economic justice, democracy, and a culture of peace*" (UNESCO 2000).

The UN DESD has produced a foundation for embedding sustainability in education. Education has been recognised as a catalyst for innovations enabling people to fulfil their individual potential for contributing to social transformation (UNESCO 2012a). However, the complex nature of sustainability in education requires continuous efforts from institutions and educators. Therefore, the decade of the UN DESD has been followed by a Global Action Programme on Education for Sustainable Development (GAP) with the goal "*to generate and scale-up action in all levels and areas of education and learning in order to accelerate progress towards sustainable development*" (UN 2014a). This GAP programme has introduced key action points, such as "*policy support, whole-institution approaches, educators, youth and local communities*", to promote ESD and ensure the commitment of stakeholders in these actions (Wals 2014; UNESCO 2014).

3 Development of energy education and expertise

The development of expertise during education is a multistage, iterative and ongoing process involving different stakeholders inside and outside of the university (Davidson et al. 2007; Barnett & Coate 2005; Klein & Hoffman 1992; Korhonen-Yrjänheikki 2011). Expertise can be promoted by using appropriate formal, informal and non-formal teaching methods for achieving the learning objectives of the students during their study path (Malcolm et al. 2003; MacVaugh & Norton 2011). The educational context of the expertise of an engineer has been presented as a combination of field knowledge, academic skills and practices (Crawley et al. 2007). A skill-building internship must be an integral part of engineering education, enabling students to gain real-life experiences and introducing new inputs and insights into their studies (Tynjalä et al. 2003). Such internships, during the path of study, help the students to build professional identity, facilitate the understanding of the phenomena behind applications, encourage them to seek knowledge and challenge traditional opinions without neglecting well-proven existing practices (Tynjälä 2008). Moreover, cooperation skills and collaborative learning need to be developed as vocational skills of engineers in engineering education (Korhonen-Yrjänheikki 2011).

Engineers graduating from academic energy degree programmes then take on a variety of tasks with a variety of professional titles, such as designers, development engineers, operating engineers, development managers, project managers, production managers, buyers, authorities, consultants, academics and researchers (Backa & Wihersaari 2014). In industry, engineers work on projects, in research and development, and in product development, which are areas frequently mentioned by graduated engineers in the survey of Academic Engineers and Architects in Finland (Hyötynen & Keltikangas 2015; TEK 2016). Moreover, energy engineers are sooner or later promoted to managers and directors who have to make decisions on sustainable energy solutions that have far-reaching effects in society. Energy field knowledge, skills and competencies are necessary to make decisions regarding appropriate renewable energy technologies and improving energy efficiencies. Such a background is also important to being aware of the environmental aspects of energy systems (Mälkki et al. 2012; Aydin 2014; Academy of Finland 2006; SITRA 2015).

Energy engineers who work with renewable energy tasks need to be able to cooperate with a wide range of professionals from the design up to the final dismantling of the plant when working on tasks such as project development, installation, operation and maintenance (IRENA 2011; IRENA 2014). The working paper by IRENA (IRENA 2011) reported not only that these jobs may have differences in required skill levels but also that these skills are dependent on the supply chain of fuel-based and fuel-free technologies. Renewable and sustainable energy issues include the strategically important areas of expertise in ecosystems, environmental management, use of biomass, efficient

use of energy and new energy technologies, according to the report of the Environment and Energy panel (Academy of Finland 2006).

3.1 Energy degree programmes and sustainability

The energy master's degree is normally a two-year programme consisting of 120 ECTS credits at European universities. The programmes typically consist of core and mandatory studies, major and specialisation studies, minor and elective studies, and a master's thesis (30 ECTS). The names, extent and content of energy studies vary depending on the scope of the university. Since 1999, the Bologna Process has harmonised academic degree standards and quality assurance in the European higher education area. The reform has changed education and training systems, enabling the students and job applicants to move more easily within Europe. For example, the Bologna Declaration focused on a reform of the similar credit systems (the European Credit Transfer and Accumulation System ECTS) and an implementation of separate bachelor's (180 ECTS) and master's (120 ECTS) degrees for undergraduate and graduate studies (European Ministers of Education 1999; EC 2011). The reform will take many years before all the changes have been implemented in every institution. After ten years of the reform, the situation of the Bologna Process has been discussed and studied from the students' and teachers' point of view. For example, the findings showed that the new curricula, standardised courses and students' mobility have had impacts on the university system as a whole (Püschel 2012; Cardoso et al. 2008; Alexandre et al. 2008).

Many universities have identified future demand for sustainable and renewable energy education and integrated sustainability into the names and content of their energy programmes and courses. The programmes highlight hands-on experience for solving real-world energy challenges. The renewable energy projects aim to provide students with an understanding of the societal aspects and environmental impacts of energy solutions. All over the world, many programmes and courses in sustainable energy are available, such as the Diploma in Electrical Engineering and Clean Energy at BCA Academy in Singapore, Sustainable Energy at MIT in the USA, and Alternative Energy courses at Universidade Estadual Paulista (UNESP) in Brazil. Moreover, the agenda and commitments of the Paris Climate Change Conference 2015 have increased interest in developing renewable energy education at universities. In the USA, many colleges and universities have attracted attention by teaching about renewable energy, such as the Oregon Institute of Technology, the University of California Berkeley, the University of Texas at Austin, the University of Michigan, Stanford, the Massachusetts Institute of Technology (MIT), North Carolina State University, San Juan College, Ecotech Institute, and the University of Massachusetts Lowell (Baker 2016).

In Europe, many sustainable energy programmes and courses have been supported by the European Institute of Innovation and Technology (EIT) (EU-EIT 2008) and the European Commission Erasmus Programme (EC 2017b; EC 2017a). Cooperation between the

universities has resulted in programmes such as Environomical Pathways for Sustainable Energy Systems SELECT, Innovative Sustainable Energy Engineering, Management and Engineering of Environment and Energy ME3, Nuclear Energy EMINE, and Renewable Energy RENE (KTH 2017). These examples of sustainable energy programmes are the result of increased cooperation among higher education, research organisations and business by establishing a network of Knowledge and Innovation Communities (KICs) (EU-EIT 2008). For example, the KICs for climate change (EIT Climate-KIC) and sustainable energy (EIT InnoEnergy-KIC) aim to promote sustainable energy solutions by addressing societal challenges in Europe and worldwide (EU 2017a; EU 2017b).

Sustainable and renewable energy is a challenge for educational institutions and training providers. Students and workers need continuous training to update their knowledge and skills regarding renewable and sustainable energy to ensure their future employment opportunities (IRENA 2014; Sooriyaarachchi 2015; UNESCO 2012c; ILO 2011; Kandpal 2014; Mälkki et al. 2012). Rosentrater & Al-Kalaani indicated that there is a gap in the renewable energy coverage in engineering curricula (Rosentrater & Al-Kalaani 2006). Therefore, sustainability approaches, tools, concepts and frameworks are needed in the classroom to furnish practical experience in the sustainability assessment of systems and solutions (Wood & Hertwich 2013; Kemmler & Spreng 2007).

3.2 Curriculum planning of the degree programme

Curriculum planning is a continuous process that takes into account the needs of educational institutions and society. *Curriculum* refers to the degree programme, that is, the composition of the modules and courses. The desired outcomes of the degree programme are dependent on the learning outcomes of the courses; therefore, one of the key tasks in curriculum planning is to define the learning outcomes (Biggs & Tang 2007; Wong & Chi-Keung Cheung 2009; Batterman et al. 2011). The curriculum should provide students with ways of knowing, acting and being in order to become an expert (Barnett & Coate 2005; Deem 2005). Therefore, the learning outcomes of the degree programmes and courses play an important role in curriculum planning in order to provide students with the desired competencies.

Many studies have highlighted that curriculum planning starts with being aware of what engineers really do in practice and what kind of skills they need after graduation in different jobs (Eskandari et al. 2007; Blom & Davenport 2012; Miller & Crainn 2011; Carr et al. 2012). Eskandari et al. identified a crucial need to revise curricula due to changes in engineers' roles and responsibilities in industry. The planned curriculum reforms aim to provide the possibility to make desired changes to the content of degree programmes, for example, by taking into account new requirements in working life. Recently, many universities have totally reformed their curricula due to changes in teaching organisations, funding and resources. Since 2005, the Bologna Process has harmonised with European bachelor's and master's degree programmes (Lindblom-

Ylänne & Hämäläinen 2004; Sursock & Smidt 2010). Moreover, the new English-language degree programmes have brought changes to the curriculum, partly due to the internationalisation requirements of the national degree programmes, in accordance with the Bologna model.

A core curriculum analysis is a useful tool to identify and determine the educational content, goals, and learning outcomes of degree programmes and courses (Blom & Davenport 2012; Miller & Crainn 2011; Carr et al. 2012; Levander & Mikkola 2009). There are also other ways to design the whole curriculum, such as the CDIO approach, which presents an integrated curriculum design by using twelve CDIO standards in the context to conceive, design, implement and operate the products, processes and systems (Crawley et al. 2010). The foundation of the integrated curriculum is based on the design of the learning outcomes to take into account the pre-existing conditions and benchmarking of the curriculum. The CDIO initiative aims at a systematic reform of engineering education by providing students with knowledge, skills and attitudes to better meet the needs of working life. Dolence has used the term *strategic planning* in the context of curriculum planning (Dolence 2004). He means that the overall design process considers all the teaching elements and their linkages with the other courses throughout the entire degree programme and other complementary fields.

This strategic curriculum planning helps to implement and adapt to national accreditation standards, university rules and programme traditions (Crawley et al. 2010). At universities, the overall design process of the curriculum increases collaboration between the teaching staff, and the management has a better opportunity to evaluate necessary funding criteria of teaching and research. Curriculum can also be developed from a viewpoint of learning for the future, with reflections from theory and praxis (Barnett & Coate 2005; Helle et al. 2006; Hirsto & Löytönen 2011; Tynjälä 2008). Projects involving real-life problems seem to develop the skills that students require in working life by encouraging them to use problem-solving, team working, and critical and systems thinking.

It is important that academic staff and various stakeholders cooperate with teachers in planning the desired changes in the degree programmes (Barth & Rieckmann 2012; Hirsto & Löytönen 2011; Mälkki & Paatero 2015). The choices made in the learning environment, for example, the appropriate teaching and learning methods, can improve the students' competencies needed in working life (Jennings 2009; TEK 2016; Tynjalä et al. 2003). Appropriate learning activities simultaneously provide students with necessary working-life skills and the discipline-specific fundamentals of their field (Crawley et al. 2007). Community-oriented and constructive learning approaches enhance students' learning outcomes within the systematic curriculum design process and support high-level learning, such as the use of problem-based learning (PBL) (Segalàs et al. 2010; Litzinger et al. 2011; Mälkki & Paatero 2012). In particular, it is relevant that students take part in a sustainability learning process that aims to promote their expertise (Litzinger et al. 2011; Segalàs et al. 2008; Segalàs et al. 2012).

In curriculum planning, teachers need to work together with other teachers to align the courses of the degree programme towards sustainability. The commitment of the whole university staff is needed to motivate teachers to implement changes that integrate sustainability into curricula. In addition to cooperation within their own discipline, an interdisciplinary cooperation is necessary to engage all relevant disciplines inside and outside of the university to refocus sustainability and its complex dimensions in education (Davidson et al. 2007). Moreover, teachers need a global and international context of sustainable development to instruct students in tackling global ecological collapse and to make the necessary changes in the outcomes of their curricula (Mihelcic 2008). Therefore, it is necessary that teachers use sustainability guidelines and practices to change their traditional teaching and learning methods and to update the content of their courses to align with sustainability teaching in curriculum planning.

3.2.1 **Learning outcomes**

Learning outcomes are the key elements in planning teaching and curriculum improvements (Edström et al. 2010). The content of courses should be described in terms of the learning outcomes being attainable, understandable and measurable (Hemminki et al. 2013). Hemminki et al. published a guide to successful teaching by embedding deep-learning approaches and supporting independent, student-centred, critically reflective learning that highlights the active development of pedagogic approaches. There are three dimensions of skills to be developed in higher education, namely knowing, acting and being, all of which should be considered in the learning outcomes of the curriculum (Barnett & Coate 2005).

In designing learning outcomes, the levels of intended learning outcomes have to be specified (Biggs & Tang 2011). There are taxonomies such as Bloom's and SOLO to classify the learning outcomes in terms of the levels of understanding to be incorporated into the learning outcomes (Bloom & Krathwohl 1956; Biggs & Collis 1982). The first version of Bloom's taxonomy was published in 1956. The revised taxonomy of Bloom has six levels for the cognitive processes of learning in which every level has a certain purpose to increase the competencies of the students. These levels are mapped to the tasks of remembering, understanding, applying, analysing, evaluating and creating knowledge and skills (Krathwohl 2002). Knowledge is the basis of the cognitive processes, and it is divided into four types: factual, conceptual, procedural and metacognitive knowledge (Anderson & Krathwohl 2001). The SOLO taxonomy divides the model into five levels, namely pre-structural, uni-structural, multi-structural, relational and extended abstract, in order to increase understanding of the subjects (Biggs & Collis 1982). The SOLO taxonomy is more used in the USA, and Bloom's taxonomy became more familiar to higher education in Europe via the Bologna Process.

In European higher education institutes, the Bologna Process has guided the planning of learning outcomes by using the verbs of Bloom's taxonomy since 1999. In spite of many advantages, Bloom's or other similar taxonomies have been criticised due to their decisions regarding learning outcomes without a deeper understanding of the learning process (Murtonen et al. 2017). Murtonen et al. indicated that "*if the theoretical background of the 'learning outcome' concept is not considered or not known, the use of learning outcomes can lead to unintended consequences*". As an example of the consequences, they mentioned that "*there is a danger in the use of the certain verbs in course descriptions which leads to narrower learning results than was intended"*. As an advantage, they highlighted that well-defined learning outcomes are useful for students and help the responsible teachers to develop their study programmes.

In the revised Bloom's taxonomy, the six levels are introduced using verbs to guide teachers to design learning outcomes and structure appropriate tasks for students at each level. The levels of expertise are listed in order of increasing complexity from Level I to Level VI. The following descriptions of the different levels and their activating verbs are presented by Anderson and Krathwohl (Anderson & Krathwohl 2001):

- **Level I Remember**: students recall the facts and basic concepts according to the tasks using verbs such as *define*, *duplicate*, *list*, *memorise*, *repeat* and *state*.
- **Level II Understand**: students explain the ideas and concepts according to the tasks using verbs such as *classify*, *describe*, *discuss*, *explain*, *identify*, *locate*, *recognise*, *report*, *select* and *translate*.
- **Level III Apply**: students use information in new situations according to the tasks using verbs such as *execute*, *implement*, *solve*, *use*, *demonstrate*, *interpret*, *operate*, *schedule* and *sketch*.
- **Level IV Analyse**: students draw connections among ideas according to the tasks using verbs such as *differentiate*, *organise*, *contrast*, *distinguish*, *examine*, *experiment*, *question* and *test*.
- **Level V Evaluate**: students justify a stand or decision according to the tasks using verbs such as *appraise*, *argue*, *defend*, *judge*, *select*, *support*, *value*, *critique* and *weigh*.
- **Level VI Create**: students produce new or original work according to the tasks using verbs such as *design*, *assemble*, *construct*, *develop*, *formulate*, *author* and *investigate*.

Biggs has noted that the development process of teaching requires all the teaching and learning activities in order to determine the objectives of the whole system (Biggs 1996; Biggs 2003). This 'constructive alignment' approach combines all the components in proper alignment with one another in the teaching environment. Biggs has listed the five elements presented in Figure 5 needed for planning a constructively aligned course. They are 1) intended learning outcomes (ILOs), 2) content selection, 3) teaching and learning activities, 4) assessment methods, and 5) workload and study time allocation (Biggs 1996).

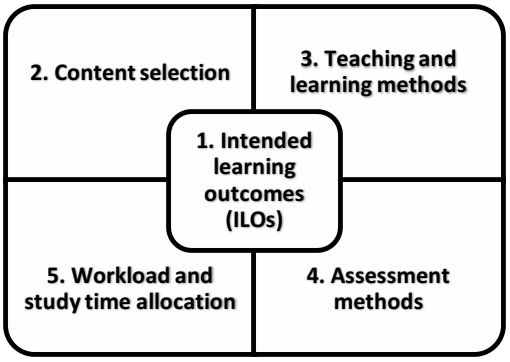


Figure 5. The elements of the constructively aligned course according to Biggs (Biggs 1996).

All these elements are crucial parts of successful curriculum planning at any course level of the degree programmes. Teachers have to determine what is essential knowledge that students must know, what is supplementary knowledge that students should know, and what is specialised knowledge that gives students a deeper insight into their own field. Moreover, the focus in teaching is shifting from teacher-centred to student-centred activities that require the planning of the learning outcomes from the student point of view (Biggs et al. 2007).

3.3 Accreditation of the degree programmes

An accreditation of the degree programmes is normally based on the intended learning outcomes of the programme and its courses (ASIIN 2017; FINEEC 2017). Accreditation is voluntary, but most universities regularly go through the accreditation process to identify their status and receive improvement recommendations. The accreditation reports are publicly available on the Internet. One role of the Finnish Education Evaluation Centre (FINEEC) as an independent government agency is to organise the evaluation of education (FINEEC 2017). FINEEC implements the assessment of learning outcomes in order to support education providers and HEIs in their evaluation and quality assurance and to develop the education evaluation process. The standards and procedures of FINEEC accreditation are based on the European Accredited Engineer (EUR–ACE) framework standards of the European Network for Accreditation of Engineering Education (ENAEE) (ENAEE 2017). ASIIN awards the ASIIN seal, and the specific quality seals for the study programmes (e.g., EUR-ACE, Eurobachelor/Euromaster and Euro-Inf labels) are awarded according to the relevant Subject-Specific Criteria (SSR) of ASIIN (ASIIN 2017).

In an accreditation process, an accredited programme has to fulfil the standards for planning of education, implementation of education, resources and quality management.

For example, the course-level learning outcomes should comply with the programme's learning outcomes describing the knowledge, understanding, skills and abilities. Moreover, the curriculum should provide the accrediting bodies with comprehensive information on all the individual courses of the programme. The general criteria of the ASIIN quality seal highlight that higher education institutions, have to describe the overall intended learning outcomes, how the specific competencies could be acquired through the programme content, and teaching and learning methods in their self-assessment. The FINEEC reference programme describes the knowledge, skills and competencies that master's degree engineering graduates should be able to put into practise in five categories of learning outcomes: 1) Knowledge and understanding, 2) Engineering practice, 3) Investigations and information retrieval, 4) Multidisciplinary competencies, and 5) Communication and team-working. The learning outcomes in which are embedded knowledge and understanding of non-technical aspects such as societal, health and safety, environmental, economic and industrial implications of engineering practice are mentioned in Engineering practice and Multidisciplinary competencies (ASIIN 2017). However, these criteria do not directly demonstrate that the educational bodies should integrate sustainability into the learning outcomes of their degree programmes.

3.4 Research-based teaching

University strategies highlight that the high quality of education calls for a combination of research and teaching. Research and teaching are the main elements in a university education. In particular, the 'teaching-research nexus' is central to higher education, according to many researchers, and this is also reflected in university strategies. Teaching and research can be combined by using research-based assignments and projects inside and outside the classroom (Griffiths 2004; Jenkins et al. 2007; Healey et al. 2010).

The integration of teaching and research requires more changes in the relationship between teachers and students than the use of traditional lecturing methods (Brew 2003; Mayson & Schapper 2010). Brew proposed that students would benefit from their teachers' own research when they have an opportunity to be part of it. Findings by Spronken-Smith affirmed that the role of open-discovery-oriented inquiry-based learning (IBL) develops better inquiry and research skills compared to those developed in traditionally taught courses (Spronken-Smith 2010). Research makes students aware of real-life problems and their possible solutions. Research is also highlighted in the report to the European Commission on improving the quality of teaching and learning, a report that emphasises connections with the latest research (EC 2013). Participative teaching and learning methods and problem-based learning are notable examples in this report.

Active learning and research-based teaching are connected with effective teaching practices. Research by Chickering and Gamson introduced seven effective teaching and learning practices for curriculum planning and improving interactions between teachers

and students (Chickering & Gamson 1987). They proposed that active learning can be encouraged by using structured exercises, challenging discussions, team projects and peer critiques.

Griffiths has explored the four types of knowledge production in the built environment disciplines of higher education (Griffiths 2004). These types focus on empirical science, interpretive inquiry, applied inquiry and integrative scholarship in research-based teaching (Griffiths 2004). Healey has studied how the different concepts could combine teaching and research in the learning environment (Healey 2005). His four-field concept takes into account the perspectives of both students and teachers. This concept includes the four different ways to use research in teaching, namely research-led, research-oriented, research-based and research-tutored teaching methods (Healey 2005). This four-field presentation has inspired continuous development, new applications and deeper interpretations of effective practices that use research in teaching (Elsen et al. 2009; Beckman & Hensel 2009; Jenkins & Healey 2010; Mälkki & Paatero 2012). Singer et al. (2012) noted that in the learning process, discipline-based research using student activities can enhance learning more effectively than traditional lecturing methods. Based on the above findings on activating students' learning, a collection of effective teaching and learning practices that combine research and teaching is presented in Table 5.

Table 5. Good teaching and learning practices combining research and teaching to activate students (Chickering & Gamson 1987; Griffiths 2004; Healey 2005; Singer et al. 2012).

Chickering & Gamson (1987)	**Griffiths (2004)**	**Healey (2005)**	**Singer et al. (2012)**
1. Encourages contact between students and faculty 2. Develops reciprocity and cooperation among students 3. Encourages active learning 4. Gives prompt feedback 5. Emphasizes time on task 6. Communicates high expectations 7. Respects diverse talents and ways of learning	1. Empirical science 2. Interpretive inquiry, 3. Applied inquiry 4. Integrative scholarship	• Research-led: learning about current research in the discipline • Research-oriented: developing research skills and techniques • Research-based: undertaking research and inquiry • Research-tutored: engaging in research discussions	• Learning being stimulated by a question or issue • Teaching in a student-centred approach with the teacher as a facilitator • Learning by doing • A move towards self-directed learning • Constructing new knowledge and understanding by students

4 Life cycle assessment (LCA) and life cycle sustainability assessment (LCSA)

4.1 History of LCA

Life cycle assessment (LCA) has its roots in the 1960s in the United States, when an awareness of the limits of raw materials and energy resources forced society to explore the situation and find new solutions to account for the use of energy and protect the future supplies of resources (Curran 2013; Curran et al. 2005). Concerns about the adequate provision of raw materials and energy resources prompted the publication of *The Limits to Growth* (Meadows et al. 1972) and "A Blueprint for Survival" (Goldsmith & Allen 1972), both of which discussed the resource situation in light of the world's growing population. These publications depicted scenarios based on the speed of depletion of fossil fuels and its consequences in terms of climate change. Thereafter, more detailed calculations were performed on the energy use in industrial processes in order to estimate the costs and environmental implications of the different energy sources.

A study by the Coca-Cola Company in 1969 has been seen as a starting point for the development of the life cycle inventory method in the United States. This study made the first comparisons of different beverage containers and explored which container had the least effect on the environment and had the least impact on natural resources. This study calculated the raw materials and fuels used in the manufacturing processes of the containers. Similar comparative life cycle inventory analyses were compiled in both the United States and Europe in the early 1970s. The results of these studies were based on publicly available data sources, governmental documents, and other technical papers. At that time, specific data on industrial processes were not available.

A resource and environmental profile analysis (REPA) was developed to quantify the use of resources and environmental burdens in the United States. In Europe, this quantification method was called an eco-balance tool. Approximately 15 REPAs were performed between 1970 and 1975. The oil shortage of the period was one reason attention became focused on the accuracy of information in these studies; thus, a preliminary standard for the research methodology for conducting these studies had begun to develop. The EPA and industry developed assumptions and techniques for improving the use of REPAs. From 1975 to the early 1980s, interest in these comprehensive studies on the use of resources decreased because environmental issues of hazardous substances and household waste management eclipsed those of the oil crisis. However, some energy-related studies that continued to be published every year contributed to the development of the life cycle inventory analysis methodology. In Europe, the establishment of an Environment Directorate (DG X1) by the European Commission boosted the environmental practitioners to develop approaches parallel to

those being used in the USA. For example, in 1985, the pollution regulations of the Liquid Food Container Directive in 1985 obliged companies to monitor the energy and raw material consumption and solid waste generation of liquid food containers.

Compliance with environmental laws and regulations has contributed to the development of systematic environmental management concepts and methods such as the ISO certification system and LCA methodology to support, among other things, companies' decision-making, brand marketing and competitiveness. The demands of environmental management have evolved and increased from end-of-pipe treatment and pollution prevention to sustainable development (Figure 6). Due to the broad scope of environmental management strategies, LCA was recognised as an effective tool for assessing resource use, environmental burdens, and human health impacts over the entire life cycle of products, processes, and activities (Curran 2015). Fava (2006) pointed out that the increasing use of life cycle approaches will promote the systematic planning of actions to increase the competitiveness of industry in the global environment.

Figure 6. Development of life cycle approaches during the decades from a place-specific end-of-pipe treatment to a wide scope of sustainable development (Curran 2015).

In the 1990s, the development of the life cycle assessment (LCA) methodology was rapidly resulting in the publication of many guidebooks (Baumann & Tillman 2004; Consoli et al. 1993; Guinée 2001; Lindfors et al. 1995; UNEP 1996; UNEP 2011a) and the first LCA international standards of ISO 14040, 14041, 14042 and 14043 (ISO 1997; ISO 1998; ISO 2000a; ISO 2000b). Thereafter, life cycle approaches and life cycle thinking were also integrated into, among other things, the content of eco-labels, Environmental Product Declarations (EPD), Integrated Product Policies (IPP) and energy policies. LCA was integrated into the international environmental management standards of eco-efficiency, eco-design, material flow accounting, and carbon and water footprints (Guinée et al. 2011). Moreover, concepts such as industrial ecology, design for environment and circular economy are continuously supported by the LCA methodology. The increased use of LCA for various purposes led to a more detailed development of LCA regarding its methods, databases, guidebooks and standards. In 2006, the LCA standards were updated and merged into the two separate standards of 14040 and 14044 (ISO 2006a; ISO 2006b). The UNEP/SETAC Life Cycle Initiative supported the development of LCA to promote decision-making via more sustainable product systems and processes (UNEP 2011b; UNEP 2011a). The European Commission supported the development of the LCA methodology, and the *International Reference Life Cycle Data System (ILCD) Handbook* was published in 2012 (JRC 2012). In the life cycle

management framework (Figure 7), tools such as LCA and other life cycle approaches are needed to describe the environmental sustainability of products (UNEP 2011a).

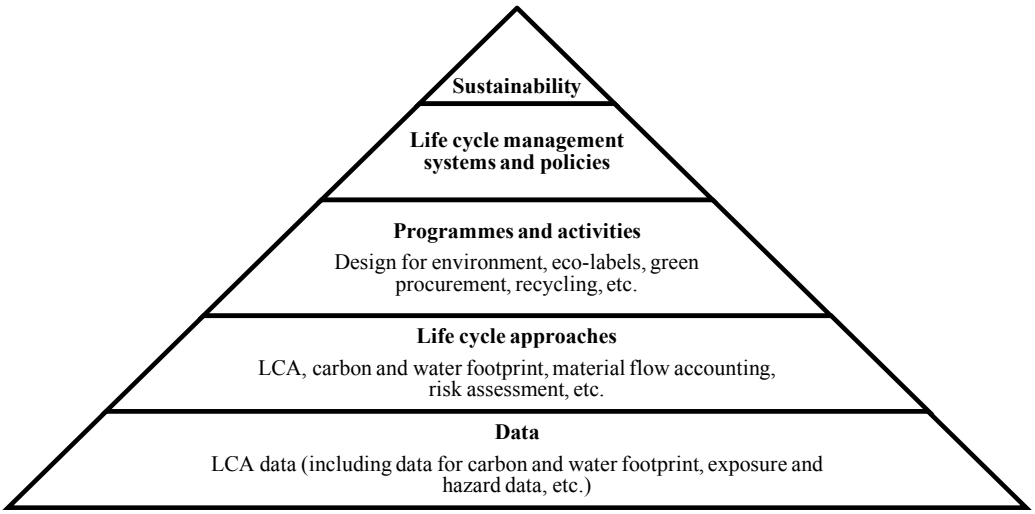


Figure 7. Life cycle management (LCM) framework for the environmental sustainability of products (UNEP 2011a).

Reap et al. (2008) explored problems identified by LCA researchers concerning functional unit definition, boundary selection and allocation in the impact assessment and interpretation phases of LCA. As a result of the review, Reap et al. proposed that the use of dynamic modelling would help to overcome the problems of spatial variation and local environmental characteristics. Moreover, they identified a need for peer-reviewed, standardized LCA inventory and impact databases to improve data availability and quality. Finnveden et al. (2009) stated that the LCA methodology had matured during the previous decades due to the development of databases, quality assurance systems, and harmonisation of methods. They reviewed the development activities of LCA concerning life cycle impact assessment (LCIA), midpoints and endpoints in characterisation modelling, spatial differentiation, resources, impacts of land use, impact from water use, toxicity, indoor air, normalisation, weighting and uncertainties in the interpretation of LCA results. They proposed that it would be useful to further develop tools and methods for assessing consequential LCA and the impacts of ecosystem services.

LCA has been recently been divided into *attributional* LCA and *consequential* LCA to better meet the changing needs of companies for decision-making purposes (Ekvall et al. 2005). On the one hand, attributional or traditional LCA (ALCA) aims at describing the environmental properties of a life cycle and its subsystems by including the full life cycle, using average data, and making allocations in proportion to, e.g., mass or economic values. Consequential LCA (CLCA), on the other hand, aims at describing the effects of

changes within the life cycle, including the affected processes, using marginal data for expected effects of changes and avoiding allocation through system expansion. Consequential LCA aims to assess the potential changes in the use of future resource sources that might have significant impacts for the results of attributional LCA, for example, on the future shifts between renewable and non-renewable energy sources (Stewart & Weidema 2005; Finnveden et al. 2009).

Environmental and sustainable long-term goals and targets include challenges to stakeholders and policy-makers to make changes in national energy infrastructures. It is important to evaluate whole energy systems with future scenarios to achieve an understanding of the potential environmental and sustainability implications caused by changes in different options. Jones et al. stated that a fair comparison of distributed renewables with thermal power stations requires both static and dynamic temporal allocation to account for different impact profiles over time (Jones et al. 2017). Due to the various assumptions in scenarios and models in the CLCA process, wider scopes increase uncertainty in the calculated indicators. Therefore, Jones et al. pointed out that the researchers should clarify the appropriateness of the CLCA method to the aims and questions of the intended research, applied system boundaries, and the use of models to define the causal relationships of the energy systems so that the decision makers could justify and communicate these results. Frischknecht et al. (2017) pointed out that consequential LCA involves causal modelling and that it is more than the marginal mixes and avoided burdens of the product systems. Moreover, consequential LCA is a proper tool to identify social responsibility issues. However, there is a need to further develop LCA databases to meet the needs of consequential modelling (Frischknecht et al. 2017).

4.2 LCA methodology

Life cycle assessments (LCAs) are based on the guidelines of LCA standards 14040 and 14044, published by the International Organisation for Standardisation (ISO 2006a; ISO 2006b). LCA includes four phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation. These four phases form a systematic way to calculate the environmental burdens and impacts in all the life cycle phases of systems. The LCA framework and its four interactive phases are presented in Figure 8 (ISO 2006a).

1. In the goal and scope phase, all general decisions on setting up the LCA system are made and defined, taking into account the purpose, intended application and audience. This phase also includes the decisions on the description of the whole system and its boundaries, the selection of the impact categories and methods, and agreement on data quality requirements and their limitations.
2. In the inventory phase, the collection and compilation of the data are done in an iterative process, taking into account the goal and scope decisions. The inventory phase involves the quantification of inputs and outputs for a given product system throughout its life cycle, as measured by the selected functional unit.

3. In the impact assessment phase, potential environmental impacts are calculated based on the results of the inventory analysis. The impact assessment categories are selected to increase the understanding of the magnitude and significance of the inventory results and the intended goal of LCA.
4. In the interpretation phase, all results are studied against the requirements of the intended application in order to draw conclusions, explain limitations, and provide recommendations.

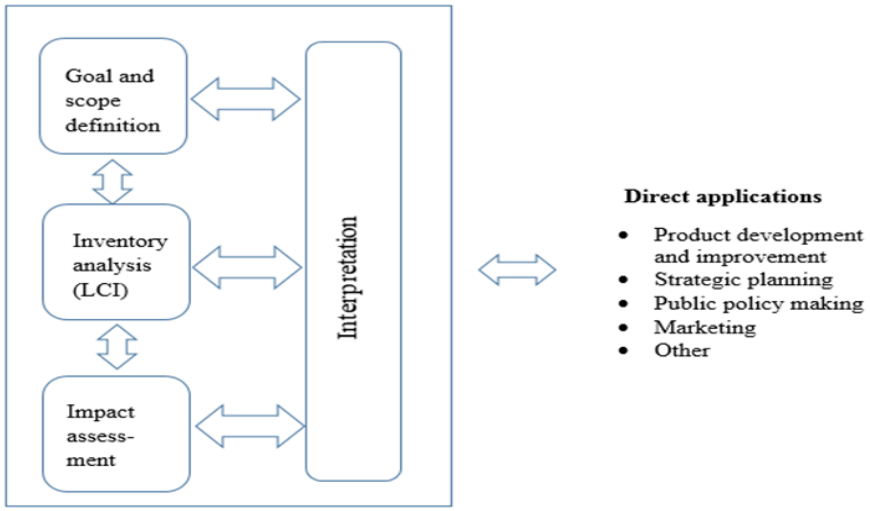


Figure 8. The LCA framework and its four interactive phases with examples of direct LCA applications according to ISO 14040 (ISO 2006a).

The LCA methodology is used to calculate the potential environmental impacts associated with products, systems and services. As a specific feature, LCA considers the entire life cycle of the product system, from the raw material extraction and acquisition through the manufacturing and use phases to the end treatment and final disposal of the product. A systemic application of the LCA methodology aims to address the potential environmental burdens and the use of resources while considering all the life cycle phases of the systems. This systemic approach helps to avoid burden shifting from one life cycle phase to another, and it is useful for optimising whole systems, for example, to improve the environmental performance of existing or new products.

4.3 Life cycle sustainability assessment (LCSA)

Life cycle sustainability assessment (LCSA) aims to combine the environmental, economic and social dimensions of sustainability using the same LCA framework (Finkbeiner et al. 2010; Halog & Manik 2011; Hoogmartens et al. 2014; Jørgensen et al.

2013; Weidema 2006). A variety of different sustainability indicators are useful for policy-making and in public communication for simplifying, quantifying, analysing, and communicating otherwise complex information on sustainability (Singh et al. 2012). It is essential that LCSA employ equal and consistent system boundaries for assessing sustainability as a combination of environmental LCA, life cycle costing (LCC) and social life cycle analysis (SLCA) (Kloepffer 2008). The use of the life cycle approach offers an effective way to reveal the sustainability dependencies of systems and helps to avoid the transfer of problems from one stage of the system to another (Sala et al. 2013). Heijungs et al. (2010) added that these dimensions of LCA, LCC, and SLCA provide three different ways to look at the same system. However, many studies have noted that sustainability is a complex issue and therefore necessitates resolving the existing interlinkages and dynamics between the sustainability dimensions (Ness et al. 2007; Jørgensen et al. 2013; Singh et al. 2012).

The efforts to develop LCSA have increased understanding of the sustainability dimensions in the LCA framework (CALCAS 2009; PROSUITE 2013; Reap et al. 2008; Traverso et al. 2012; Wood & Hertwich 2013; Zamagni 2012). In the project report of PROSUITE, the five impact categories (human health, social well-being, prosperity, natural environment and exhaustible resources) were presented for integration into the sustainability assessment and the scope of LCA (Blok et al. 2013). However, sustainability may cause conflicts between environmental protection, social equity, and economic growth (Jørgensen et al. 2013). This complexity of the social aspects in SLCA has been also pointed out in many studies (UNEP 2009; Jørgensen et al. 2013; Singh et al. 2012; Arcese et al. 2013). Lehmann et al. studied the social aspects for making decisions between two waste management case studies (Lehmann et al. 2011). Their findings showed that assessment of social aspects is also useful in traditional LCA and LCC assessments in spite of the existing methodological differences and practical restrictions.

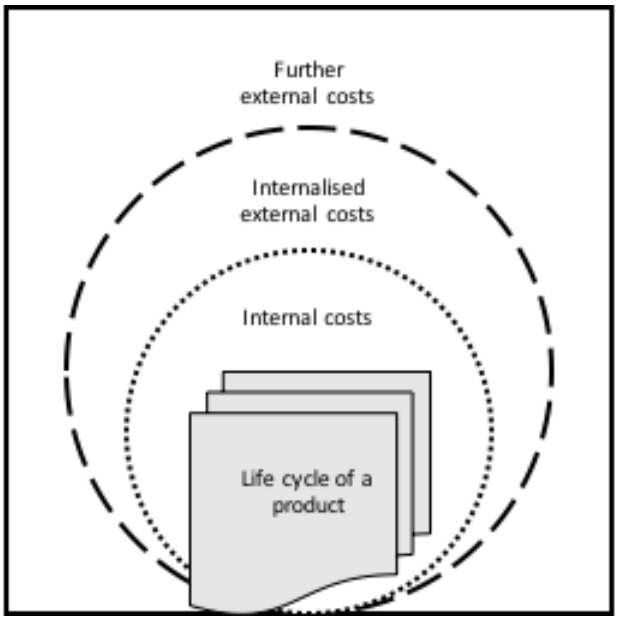
In decision-making processes, the necessity of LCSA for assessing sustainability solutions in society has been recognised. In particular, awareness of social aspects and their importance in assessing sustainability has increased in recent years (Guinée et al. 2011). The level of methodological development, application, and harmonisation of SLCA is still in a preliminary stage compared with the preparedness of LCA. The public statistics and databases with site-specific data are normally used for collecting LCSA data. However, the collection of S-LCA data is more demanding due to the nature of its quantitative, qualitative and semi-quantitative information (UNEP 2011b). In order to help non-LCA experts, a Life Cycle Sustainability Dashboard (LCSD) aims to enhance understanding and communication of LCSA results by means of graphical representations and ranking scores (Traverso et al. 2012; Schau et al. 2012). Examples of three types of sustainability data are presented in Table 6 (Traverso & Finkbeiner 2009).

Table 6. Examples of the data types for LCSA in a case study by Traverso and Finkbeiner (2009).

LCA data, environmental	**LCC data, economic**	**S-LCA data, social**
Energy consumption	Fuel costs	Total employees
Natural resources	Water-disposal costs	Wages
Water use	Electricity costs	Accidents
CO_2	Labour costs	Child labour
NO_x	Revenues	Working hours
SO_2	Raw material costs	Employees, employees gender

4.4 Life cycle costing (LCC)

Environmental LCC is useful in product development and marketing analysis for comparing the LCC of alternatives, detecting direct and indirect costs, estimating and reporting improvements, and identifying win-win situations and trade-offs in the life cycle of a product (Rebitzer & Nakamura 2008). The SETAC Europe Working Group on Life Cycle Costing has defined LCC in three categories, namely conventional LCC, environmental LCC and societal LCC. Conventional LCC focuses on real and internal costs of a single market actor. Environmental LCC is associated with all the costs, including externalities, in the life cycle of a product. The societal LCC quantifies, e.g., the costs of externalities and environmental effects on society in monetary terms and links environmental life cycle approaches to corporate social responsibility (Lichtenvort et al. 2008). These three types of LCC are presented in Figure 9.



…… Conventional LCC: internal costs
_ _ _ Environmental LCC: internalised external costs
____ Societal LCC: further external costs

Figure 9. Conventional, environmental and societal LCC in an LCA framework, according to Lichtenvort et al. (2008).

The traditional costing approaches related to LCC are total cost ownership (TCO) and activity-based costing (ABC). However, the existing traditional LCC approaches are not suitable for assessing the economic implications of the whole chain of a product. Conventional life cycle costing (LCC) is usually based on economic evaluation of the discounted costs in various stages of the life cycle, and it does not always consider the whole life cycle and neglects external costs and costs to be internalised in a consistent sustainability framework (Rebitzer et al. 2008). Many tools are available for the monetisation of externalities such as willingness to pay (WTP), willingness to accept (WTA), hedonic pricing or contingent valuation method (CVM). The estimation of the monetary values of environmental, economic and social impacts differs in discounting and targeting bodies; in particular, numerous social impacts are challenging for the comprehensive assessment of externalities (Steen et al. 2008).

5 Research methods and materials

In accordance with the multidisciplinary nature of this research, which combines sustainability and pedagogical approaches in energy engineering education, a variety of research methods were used to explore appropriate ways of integrating sustainability, energy and education into energy degree programmes. Research methods were used to reveal the current situation and to explore sustainability assessment methods in teaching. The research methods were both qualitative and quantitative and involved literature reviews, questionnaires, interviews, core content analyses and teaching concepts. The research materials consisted of the findings of LCA studies, feedback from students about their energy courses, teacher opinions on curriculum planning, the content of the core curriculum analysis of an energy degree programme, the sustainability content analysis of the learning outcomes, and the survey responses of teachers on the use of LCA in energy degree programmes. These materials provided valuable information and data for proposing sustainability methods, teaching concepts and best practices to enhance sustainability in energy education.

In a literature review of LCA studies, critically selected keywords and their combinations were used to search for educational and energy studies in scholarly databases and specific journals on the Internet. A core content analysis of the energy degree programme included qualitative and quantitative information on the workloads and the learning outcomes of the energy courses, which was used as a context for curriculum planning and developing a method to measure the sustainability content of the energy courses. A method to measure the sustainability was developed by using and analysing the content of the learning outcomes of the energy courses derived from the core curriculum analysis. The student survey, a manually completed questionnaire, collected the students' perceptions of energy education before attending the courses of an energy module of the energy degree programme. Teacher interviews, conducted in a semi-structured form, focused on the themes and practises the teachers used in planning the curriculum of the energy courses. The teacher survey, an electronic questionnaire on the Internet, collected information on the use of LCA in the energy degree programmes at technical universities.

In addition to the research methods presented above, sustainability approaches and best practices are illustrated in the figures and tables of this dissertation. LCSA, a comprehensive sustainability assessment tool (Figure 4), presents a framework that takes into account the environmental, economic and social perspectives of sustainable development in energy education in terms of LCA, LCC and S-LCA. A composition of an engineer's expertise (Figure 12) presents the knowledge and skills needed in working life. A teaching concept (Figures 3 & 14) combines sustainability, education and LCA using research-based teaching to transform education towards sustainable energy systems.

Paper I acted as a starting point that motivated further research to explore the integration of sustainability into energy education. This paper introduced future trends in the energy sector and a theoretical composition of expertise in terms of knowledge and skills seen from the teacher-directed and student-centred points of view. Paper II reviewed LCA case studies and collected experiences on the use of LCA in education and in renewable energy research, e.g., challenges in the sustainability assessment of energy systems. Paper III was a practical study using LCA in assessing the environmental performance indicators of an energy system that was an example of LCA applied to energy research. Paper IV addressed the students' and teachers' preferences regarding teaching methods and course content at a course level and identified the desired knowledge and skills to be taken into account in curriculum planning. Paper V quantified the sustainability content of the learning outcomes for the energy courses of the energy degree programme. This paper introduced a practical method for teachers to measure and discuss the existing amounts of sustainability with other teachers and collaboratively plan the desired sustainability content of the learning outcomes of their energy courses, thereby aligning the entire energy degree programme. Paper VI was a survey exploring the use of LCA in the energy degree programmes at Baltic, Nordic and Finnish technical universities. This paper provided responses to questions regarding the importance of the use of LCA as well as incentives and teaching and learning methods regarding its use in the energy degree programmes. These LCA teaching and learning methods were further analysed in a four-field presentation of research-based teaching.

5.1 A literature review of future skills in the energy sector

In Paper I (Mälkki et al. 2012), a literature review was used to explore the future professional competencies that energy engineers will need in working life in the energy sector (EK 2011; Korhonen-Yrjänheikki 2011; Strietska-Ilina et al. 2011; Academy of Finland 2006). Moreover, pedagogical teaching elements were identified for enhancing the students' skills during their study paths (Batterman et al. 2011; Malcolm et al. 2003; Barnett & Coate 2005; Klein & Hoffman 1992).

The Environment and Energy panel of the FinnSight 2015 project presented ten important areas of expertise where new future competencies in science, technology, society, business and industry will be needed (Academy of Finland 2006):

- ecosystems,
- environmental management in Finland and globally,
- urban environments,
- water systems and water purification systems,
- biomass as an energy resource and related production systems,
- more efficient use of energy (negawatts),
- new energy production systems and their integrations,
- new technologies: production and use,
- logistics and distribution, and

- mobile and distributed technologies as a platform for energy and environmental services.

The Oivallus final report initiated by Finnish working life stakeholders listed teacher-directed and learner-centred practices for better balancing of the different ways of learning, presented in Table 7 (EK 2011).

Table 7. Teacher-directed and learner-centred teaching and learning practices in the Oivallus final report (EK 2011) *(Paper I).*

Teacher-directed	**Learner-centred**
direct instruction	interactive exchange
knowledge	skills
facts and principles	questions and problems
theory	practice
curriculum	projects
one size fits all	personalized
competitive	collaborative
classroom	global community
summative tests	formative evaluations

5.2 Literature reviews of the LCA studies

In Paper II, the literature reviews of the LCA studies searched for LCA studies in renewable energy and education (Mälkki & Alanne 2017). In preparation for this search process, a set of keywords were selected related to education, energy and LCA. Thereafter, an Internet database search (Aalto-library, ProQuest, and ScienceDirect) was carried out in June 2015. Additional search qualifiers were used to direct the search results towards the intended goal of this literature review. In addition to this general database search, a subject-specific journal search was also executed.

The selected educational journals were the *International Journal of Life Cycle Assessment*, the *Journal on Environmental Education Research*, the *European Journal of Engineering Education* and the *Journal of Education for Sustainable Development*. The search did not successfully yield LCA studies in energy education. Finally, an additional Google search resulted a set of LCA articles in education. These articles were investigated and nine (9) different LCA studies in education were manually selected to identify the pros and cons of LCA in educational environments. These selected articles are presented in Paper II (Harding 2004; Vallero & Braiser 2008; Olsen 2010; Crossin et al. 2011; Juntunen & Aksela 2013b; Balan & Manickam 2013; Masanet et al. 2014; Meo et al. 2014; Weber et al. 2014).

In the literature review of LCA studies in energy research, two additional Internet searches of *Renewable and Sustainable Energy Reviews* were carried out in November of

2015 and in August of 2016. The results of these searches did not meet the aim of this research; therefore, the final selection of LCA energy studies was conducted manually from the Internet results. The energy studies were selected with a focus on LCA and the sustainability assessment of renewable energy systems using renewable energy sources such as wind, solar, biomass, geothermal, and hydro and excluding fossil fuels. Finally, 24 studies were selected to explore in more detail the use of LCA in the sustainability assessment of renewable energy systems. Each of them included various LCA case studies in renewable energy, presented in Paper II (Asdrubali et al. 2015; Awan & Khan 2014; Buytaert et al. 2011; Cambero & Sowlati 2014; Cho et al. 2012; Descateaux et al. 2016; Evans et al. 2009; Fthenakis & Kim 2010; Hanff et al. 2011; Hong et al. 2014; Liu 2014; Liu et al. 2016; Lähtinen et al. 2014; Mangoyana et al. 2013; Markevičius et al. 2010; Marvuglia et al. 2013; Milazzo et al. 2013; Ozturk & Yuksel 2016; Pant et al. 2011; Pietrapertosa et al. 2010; Radovanović et al. 2016; Turconi et al. 2013; Varun, Bhat, et al. 2009; Varun, Ravi, et al. 2009). Moreover, the Internet search was used to map the availability of LCA studies with different renewable energy options. An example of the number of LCA studies in renewable energy included:

- 14 LCA studies for bioenergy and biofuels,
- Six (6) LCA studies for wind energy,
- Seven (7) LCA studies for solar photovoltaic (PV) systems,
- One (1) LCA study for geothermal power generation,
- Six (6) LCA renewable energy studies including hydropower systems, and
- Seven (7) LCA studies comparing renewable and fossil fuels.

These manually selected studies were used to identify experiences and recommendations in the use of LCA in research and for guiding the sustainability assessment of renewable energy systems in energy education.

5.3 An LCA case study of a forest energy system

In Paper III, the LCA methodology was used to calculate the emissions, environmental impacts, energy efficiency indicators and produced energy amounts of a forest energy system in Finland (Mälkki & Virtanen 2003). Wood-based logging and sawmill residues were used as primary energy sources in energy production. This LCA case study was done according to the principles of international LCA standards (ISO 1997; ISO 1998; ISO 2000a; ISO 2000b) and used all four phases of the traditional LCA methodology: 1) the goal and scope definition, 2) the inventory analysis, 3) the impact assessment, and 4) the interpretation. The LCA calculations included both the terrain and roadside chipping chains for both fresh (green) and dry (brown) chipping options in energy production. Environmental impacts were calculated for the logging, chipping, transportation and conversion phases of the forest residues. The energy efficiency indicators were calculated as a proportion of the external energy from the total produced energy of the power plant. A process model of the LCA case study including the forest and industry residue chains in energy production is presented in Figure 10.

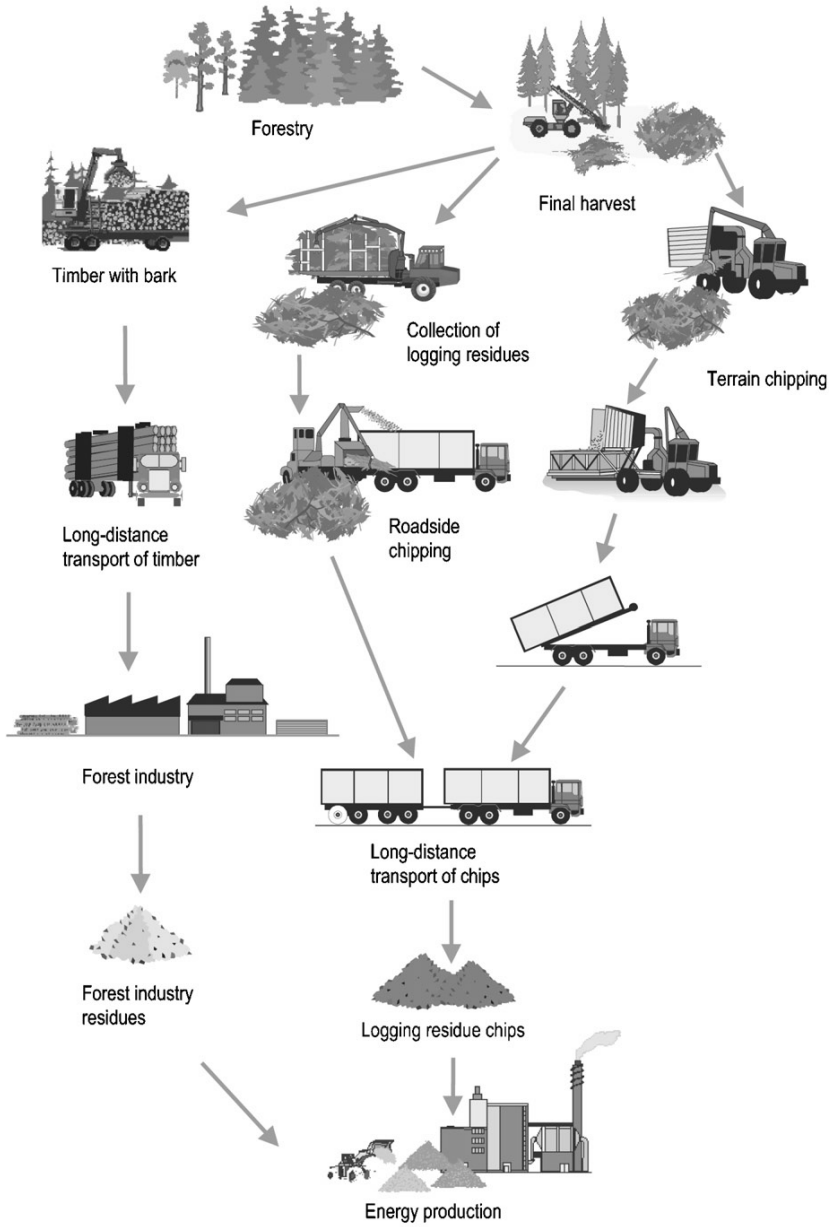


Figure 10. A model of the LCA case study system for the forest and sawmill residue chains in energy production. (Paper III) (Mälkki & Virtanen 2003).

The results were calculated in the relevant functional units for four forest and two sawmill residue systems, where 1 MWh of the energy produced was selected as a main functional unit for presenting the results. Moreover, the produced energy amounts were calculated in three functional units:

- 31,000 kg dry forest residues per hectare,
- 5.6 million m^3 solid brown (dry) forest residues, and
- 8.6 million m^3 solid green (fresh) forest residues.

The two latter values represented the amounts of forest residues estimated as annually recoverable from the logging sites in Finland.

Data for the energy production phase were based on real emission measurements at the plant. The forest residue calculations were based on Norway spruce stands with 200 m^3/h solid stem wood yield, with 390 kg/m^3 stem wood density and with a 155 kg/m^3 logging residues to stem wood ratio (Hakkila et al. 1998). The recovery rate for logging residues was 70% (Alakangas et al. 1999). The emissions of forest machinery and road transport were calculated using transportation models and data developed by VTT Technical Research Centre of Finland.

The LCA study included greenhouse gas emissions (N_2O, CH_4, gross CO_2, net CO_2), acidic emissions (NO_x, SO_2), particulate emissions and oil releases to the ground. The gross carbon dioxide (CO_2) emissions included all the CO_2 emissions from the phases of the forest residue system. The net CO_2 emissions were CO_2 emissions other than those from the combustion phase, such as the CO_2 emissions from the external primary and non-renewable energy sources. The energy efficiency indicators were calculated as a proportion of the external energy from the total produced energy of the power plant. The LCA study excluded the impacts of the compensating nutrients and fertilisers due to the loss of biomass used in energy production. Also, changes in land use, soil emissions and biodiversity of the forests were not estimated in the LCA study. Moreover, the study excluded the manufacturing chains of the forest machinery, the health impacts of particulate and heavy metal emissions, and the physical effects of the working machines on the forest ecosystems.

Although this study is old, its real-world results nevertheless provide sustainability indicators for a bioenergy system, such as global warming potentials and particulate emissions, that can be discussed and used as key indicators in education to plan sustainable energy systems by replacing the use of fossil fuels.

5.4 A teacher survey on the use of LCA

A teacher survey explored the use of LCA in the energy degree programmes at Baltic, Nordic and Finnish technical universities (Paper VI). The responses to the teacher survey were analysed to identify what kind of sustainability issues were connected to the use of

LCA and what kind of LCA teaching and learning methods were used in energy education in the classroom.

An electronic questionnaire was sent to a selected and limited target group of teachers and professors who were responsible actors in their energy degree programmes at their universities. These survey questions and answer options are presented in Table 8. The survey yielded 16 responses from 10 universities. The teacher survey included questions about the importance of LCA, LCA teaching and learning methods, and incentives in the use of LCA at the surveyed universities. For example, the survey included 16 different incentives and 26 teaching and learning methods aimed at identifying the use of LCA in research-based teaching in energy education. The teaching and learning methods of the teacher survey of the use of LCA were selected based on the experiences of the authors and the descriptions of the teaching methods (Hyppönen & Linden 2009), and the results were placed into the four research categories of Healey's model (Healey 2005). These four research categories, research-oriented, research-led, research-tutored and research-based, were used to analyse how LCA corresponded to the use of research-based teaching in the energy degree programmes.

Table 8. LCA questions and answer options of the teacher survey. (Paper VI) (Mälkki et al. 2016).

Questions	**Options**
Is LCA used in the bachelor's and/or master's energy degree programmes (majors/ minors/ elective studies/ no studies)?	*Yes/No*
What is the importance of LCA in the energy degree programmes and what are the future prospects for LCA and energy?	*Very high/ High/ Medium/ Low/ Not important/ I cannot say*
What are the main incentives used to incorporate LCA into the energy degree programmes?	*Global challenges, Environmental problems, Public pressure, Demand from employers, Demand from students, University strategy, Learning outcomes, Engineering competencies, Interdisciplinary education, Integration of research and teaching, Sustainable development, Economic awareness, Social awareness, Environmental awareness, Environmental politics and laws, Other incentives*
What are the main teaching and learning methods for LCA?	*Assignments, Debate, Drama pedagogy, E-learning, Exams, Exercises, Field trips, Group work, Independent studying, Learning by doing, Learning café, Learning diary, Lectures, Mind map, Panel discussion, Peer teaching, Preliminary test, Personal guidance, Presentations, Problem-based learning (PBL), Project work, Reading circle, Seminar, Supplementary reading, Workplace practice, Other*

5.5 A core curriculum analysis

The core curriculum analysis included the documents available in the summer of 2012. Some of these documents were part of the 2009 re-audit process of Aalto University (Karppanen et al. 2010). Also, part of this curriculum material was available via STOPS, a computer-aided tool developed by Auvinen (Auvinen 2011). In STOPS, the knowledge levels of the educational objectives include five categories, each of which corresponds to a certain level in Bloom's taxonomy (Bloom & Krathwohl 1956; Krathwohl 2002). Aalto University implemented the knowledge categories of Bloom's taxonomy in five levels: 1) remember, 2) understand, 3) apply and analyse, 4) evaluate and 5) create (Mälkki et al. 2015). In this STOPS tool, the role of teachers included the definition of learning outcomes for their courses, estimating working loads and knowledge levels and setting the learning outcome prerequisites from other courses students need before attending their energy courses.

An example of an energy course and its information in STOPS is presented in Table 9 (Paper V) (Mälkki et al. 2015). The credits of the course describe the workload needed by the students to achieve the competences planned for the course. One credit is estimated to be 27 working hours and three credits are 81 working hours, respectively. The course is normally divided into a set of the learning outcomes. Each learning outcome is described in credits (an extent level from the total credits of the course) and in scores (a difficulty level according to the taxonomy). The scoring system helps teachers to determine the difficulty levels of the learning outcomes by using the verbs presented in the used taxonomy. The feedback of the students can be used to update the workloads and difficulty levels of the learning outcomes. The descriptions of the prerequisites are useful for students before attending the courses. The necessary and supporting prerequisites of the courses guide students to attend the energy courses in the right order. All the learning outcomes and prerequisites of the energy degree programme produce a basis of the competences and an expertise of the graduated energy engineer.

Table 9. An example of the core curriculum analysis in STOPS: the course 'Energy Economics' and its learning outcomes, extent per learning outcome, Bloom's scores, and prerequisites as necessary and supporting learning outcomes from the course 'Power Generation from Biomass I'. (Paper V) (Mälkki et al. 2015).

The course: **Energy Economics** **Extent: Three (3) credits (cr)**			**The course:** **Power Generation from Biomass I** **Learning outcomes (LO)**				
			Understands different power plant concepts	Knows the basics of boilers, gas and steam turbines	Can perform process calculations of a power plant	Can use mass and energy balances in calculations	Knows about biomass as a source for energy production
Learning outcomes (LO)	**Extent level of credits per LO (cr)**	**Bloom score (1-5) per LO**	**Prerequisites for the course Energy Economics: N = necessary, S = supporting**				
1) Energy characteristics and basics of energy technology	0.4	1	N	N	N	N	N
2) Descriptions of energy production technologies	0.4	1	N	N	N	N	N
3) Use of energy in Finland	0.5	2	S	S	S	S	S
4) Energy resources in Finland and globally	0.5	2	S	S	S	S	S
5) Environmental impacts and climate change	0.5	2	S	S	S	S	S
6) Costs of energy production	0.2	1	S	S	S	S	S
7) Energy markets	0.5	1	S	S	S	S	S

STOPS was developed to help teachers with curriculum planning, but the principal aim was to help students with planning their target-oriented study paths. For example, students could directly get information on the content of the learning outcomes, working loads and prerequisites for planning their study schedules before attending the courses. Moreover,

the software enabled them to build up their professional competencies from the learning outcomes of the chosen courses. An example of the student's study path is presented in Figure 11. However, this model did not enable the students to choose their energy courses based on the sustainability content of the learning outcomes. Therefore, the existing information of the core curriculum analysis was used to identify the sustainability content of the learning outcomes of the energy courses.

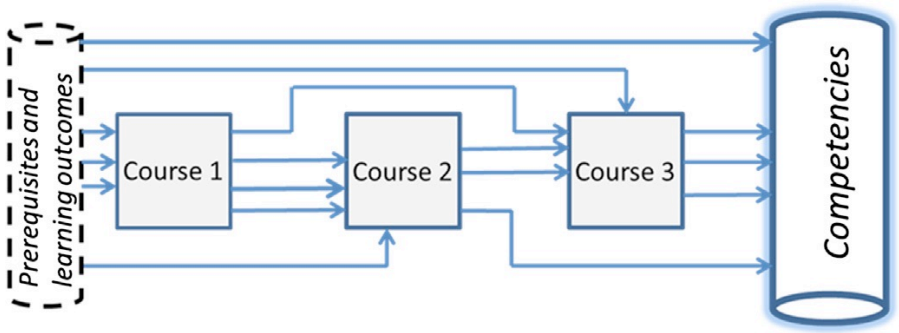


Figure 11. Learning outcomes and prerequisites in the students' study path through the courses in the degree programme facilitating competencies after graduation. (Paper V) (Mälkki et al. 2015).

5.6 A student survey and teacher interviews

In Paper IV, the student-centred and teacher-centred views on curriculum planning were explored via a student survey, teacher interviews and a core content analysis (Mälkki & Paatero 2015). The student survey produced quantitative data, and the teacher interviews produced qualitative information on learning issues before students attended the courses, while the interviews provided qualitative information on the fundamentals of curriculum planning. The information from the core curriculum analysis was used to interpret how the teachers had rated the learning outcomes and workloads for the courses. However, differences in the quality levels of the learning outcomes of the energy courses were evident in the data examined (Mälkki & Paatero 2015).

The student survey and teacher interviews identified student-centred and teacher-centred perceptions of the existing teaching practices and course content in an energy module of the energy degree programme at Aalto University (Paper IV). The content of the core curriculum analysis formed a general context for analysing the findings. The Urban Energy Systems and Energy Economics (UESEE) teaching module consisted of four courses (Table 10). The objectives of the UESEE teaching module focused on the knowledge needed in a planning process involving the different types of energy technologies in an urban infrastructure. Students will become acquainted with urban energy planning, energy investments, energy markets, district heating engineering and energy system models. Each of the UESEE courses had its own areas of energy

engineering. These energy courses were not directly connected to the other courses within the module, except for the course 'Models and Optimization of Energy Systems'. Thus, the direction of the learning path was limited to increasing the knowledge and experiences of the students from one course to another within this module.

Table10. The four courses of the Urban Energy Systems and Energy Economics (UESEE) teaching module. (Paper IV) (Mälkki & Paatero 2015).

Module, Urban Energy Systems and Energy Economics (UESEE) (20 cr)	
Course	**ECTS points (cr)**
Models and optimisation of energy systems	5
Energy markets	5
District heating engineering	5
Energy systems for communities	5

The teacher interviews produced qualitative information on how teachers experienced the curriculum planning practices of their own energy courses. Two of the three teachers of the UESEE module were interviewed in a semi-structured format concerning their experiences in the course planning. Due to the low number of teachers interviewed, these results were analysed by the authors of Paper IV.

The student survey focused on the desired working-life competencies, expectations about improving energy knowledge and skills, preferences in the selection of teaching and learning methods, and expectations about learning information specific to the UESEE energy courses. The survey used the list of competencies and knowledge as presented in Table 11. The student survey was a questionnaire to be manually completed by the students before they attended the energy courses. Altogether, 88 respondents provided quantitative data on the competencies and knowledge by evaluating their current professional skills, expectations for improvement of the skills, preferred teaching methods, and expectations for learning topical knowledge. Students had to rate their knowledge and competence levels using a four-point scale: 1 = 'nothing', 2 = 'basic level', 3 = 'intermediate level' and 4 = 'expert level'. The results of the student survey were analysed using the mean values (Mälkki & Paatero 2015).

Table 11. Competencies and knowledge specific to the UESEE module used in the student questionnaire. (Paper IV) (Mälkki & Paatero 2015).

No	COMPETENCE	KNOWLEDGE
01	Basic natural sciences and mathematics	Conventional energy technologies
02	Analytical skills	Renewable energy technologies
03	Problem-solving skills	Modelling of energy systems
04	Critical thinking	District heating systems
05	Applying theoretical knowledge in practice	Cost accounting and investment analysis Economics
06	Latest research knowledge	Global energy markets (like oil, coal, natural gas)
07	Creativity	Nordic electricity market
08	Basics skills in entrepreneurship	Energy policy
09	Project management	Energy and greenhouse gases
10	Leadership skills	Energy and sustainability
11	Group work	Energy and urban planning
12	Social skills	Innovations in energy technology
13	Dealing with international environments	
14	Information retrieval skills	
15	Presentation, speaking and negotiation skills	
16	Skills with your best foreign language	
17	Writing skills	
18	Lifelong learning skills	
19	Self-knowledge	
20	Ethical awareness	
21	Environmental awareness	
22	Sustainability awareness	
23	Life-cycle assessment skills	

The responses to the student survey identified the students' preferences regarding sustainability competencies such as ethical, environmental and sustainability awareness, and LCA skills. Moreover, the student survey collected their current needs for knowledge in the energy sector. This feedback information was useful to identify needs regarding sustainability in the curriculum planning of the energy courses.

5.7 A method to measure the sustainability content

In Paper V, the demonstration of a method to measure the sustainability content of the learning outcomes included semi-qualitative and quantitative research methods based on the content of the core curriculum analysis of the energy degree programme (Mälkki et al. 2015). The qualitative and quantitative information of the core curriculum analysis were analysed, and a relevance ratio (RR) index was calculated for identifying the percentage shares of sustainability and renewable energy in the energy degree programme. As a case study, the four majors were used to demonstrate a method for

planning the sustainability levels in percentages in the energy degree programme at Aalto University. The four majors consisted of the following:

1. Energy and Environmental Technology (EET),
2. Heat and Ventilation Technology (HVAC),
3. Urban Energy Systems and Energy Economics (UESEE), and
4. Combustion Engine Technology (CET).

The content of the core curriculum analysis included the courses, credits, learning outcomes, and necessary and supporting prerequisites presented in Table 12. The data was available via the STOPS tool (Auvinen 2011), and it was used to analyse the sustainability content of the learning outcomes of the energy courses. An analysis of the renewable energy and sustainability content of the learning outcomes and prerequisites was based on selected keywords relevant to sustainability and renewable energy. Additionally, related terms and verbs were used to precisely identify the content of the learning outcomes and prerequisites in which sustainability and renewable energy were embedded (Table 13).

Table 12. The basic information of the four majors retrieved from STOPS based on the core curriculum analysis document of the energy degree programme. (Paper V) (Mälkki et al. 2015).

Basic information	**Majors of the energy degree programme**				
	EET	**HVAC**	**UESEE**	**CET**	**All majors**
Number					
Courses	**16**	13	13	4	46
Credits	53	49	**67**	20	189
Credits/Course	3.3	3.8	**5.2**	5.0	4.1
Learning outcomes (LO)	**71**	**71**	62	33	237
LO/Course	4.4	5.5	4.8	**8.3**	5.2
LO/Credit	1.3	1.4	0.9	**1.7**	1.3
Necessary prerequisites (NP)	**171**	144	133	92	540
NP/Course	10.7	11.1	10.2	**23.0**	11.7
NP/Credit	3.2	2.9	2.0	**4.6**	2.9
Supporting prerequisites (SP)	**5684**	662	158	495	6999
SP/Course	**355.3**	50.9	12.2	123.8	152.2
SP/Credit	**107.2**	13.5	2.4	24.8	37.0

Table 13. The keywords, terms and verbs used for identifying the sustainability and renewable energy content of the learning outcomes of energy courses. (Paper V) (Mälkki et al. 2015).

Sustainability/Renewable energy			
Keywords for sustainability	**Keywords for renewable energy**	**Related terms**	**Related verbs**
sustainability	renewable energy	energy resources	understand
climate change	biofuels	energy systems	know
emission control	biomass	energy processes	recognise
environment	fuel cells	energy technologies	identify
environmental impacts	geothermal energy	eco-efficiency	search
ecological impacts	hydropower	energy efficiency	compare
economic impacts	solar power	waste treatment	classify
social impacts	wave power		evaluate
global impacts	wind power		estimate
health	wood energy		apply
life cycle assessment			analyse

To demonstrate a method for planning the sustainability levels of learning outcomes, the cumulative competence (CC) and the relevance ratios (RR) were defined and calculated. Cumulative competence (CC) describes the value of the learning outcome. The relevance ratio (RR) describes the percentage share of renewable energy and sustainability in the learning outcomes of the energy courses. CC values were calculated for both the sustainability and renewable energy learning outcomes and prerequisites. These CC values were used to calculate the relevance ratios (RR). An example of the calculations of CC and RR for an energy course is presented in Table 14.

Table 14. An example of the calculation principles for CC and RR based on the content of the core curriculum analysis. (Paper V) (Mälkki et al. 2015).

The energy degree programme				**Major course: Power Generation from Biomass I**					**Cumulative Competence (CC)**				**Relevance Ratio (RR)**			
				Learning outcomes												
Course: Energy Economics (3 cr)				**Understands different power plant concepts**	**Knows the basics of boilers, gas and steam turbines**	**Can perform process calculations of a power plant**	**Can use mass and energy balances in calculations**	**Knows about biomass as a source for energy production**	**Necessary renewable energy**	**Supporting renewable energy**	**Necessary sustainability**	**Supporting sustainability**	**Necessary renewable energy**	**Supporting renewable energy**	**Necessary sustainability**	**Supporting sustainability**
Learning outcomes	**Credit (cr)**	**Bloom score (1 - 5)**	**CC**	**Prerequisites (N = necessary/ S = supporting)**					**CC**	**CC**	**CC**	**CC**	**RR %**	**RR %**	**RR %**	**RR %**
Characteristics of energy and basics in energy technology	0.4	1	**0.4**	N	N	N	N	N	0.4				9			
Concise description of energy production technologies	0.4	1	**0.4**	N	N	N	N	N	0.4				9			
Energy use in Finland	0.5	2	**1.0**	S	S	S	S	S		1.0				22		
Energy resources globally and in Finland	0.5	2	**1.0**	S	S	S	S	S		1.0				22		
Environmental impacts and climate change	0.5	2	1.0	S	S	S	S	S				1.0				22
Costs of energy production	0.2	1	0.2	S	S	S	S	S				0.2				4
Energy markets	0.5	1	0.5	S	S	S	S	S								
Total	**3**	**1 - 2**	**4.5**	**7**	**7**	**7**	**7**	**7**	**0.8**	**2.0**	**0**	**1.2**	**18**	**44**	**0**	**26**

CC was based on the extents of the learning outcomes and related rating scores of Bloom's taxonomy according to Eq. (1) using the definitions, where *CC* is cumulative competence, n is the number of learning outcomes, a_i is the credit points invested in the i-th learning outcome and b_i is the level of Bloom's taxonomy assigned to the i-th learning outcome. The relevance ratio (RR) index has been defined in Eq. (2) as a ratio of the CC for certain subject matter (A) (e.g., renewable energy, sustainability, critical thinking, etc.) and the CC of the total study path (tot) that includes all the subject matter. CC_A is the

cumulative competence (CC) for subject matter *A,* and CC_{tot} is the cumulative competence (CC) of the whole study path.

$$CC = \sum_{i=1}^{n} a_i b_i \quad (1)$$

$$RR = \frac{CC_A}{CC_{tot}} \quad (2)$$

In Paper V, the renewable energy and sustainability learning outcomes were identified, and their CC and RR values were calculated to all the courses of the four majors in the energy degree programme. Moreover, the renewable energy and sustainability prerequisites were identified as necessary and supporting prerequisites, and their numbers were calculated to all the majors of the energy degree programme.

6 Research contribution

6.1 Future sustainability competencies

In the future, energy and sustainability experts will be needed to develop new energy production systems and their integrations, for example, in the use of biomass-based raw materials as an energy source to replace fossil fuels. Sustainability competencies are needed in science, technology, society, business and industry, for example, in planning ecosystems, urban environments, water systems and water purification systems (Academy of Finland 2006). Worldwide, there is a growing interest in focusing on the security of energy supplies and to increase the share of renewable and clean energy technologies in order to combat climate change and reduce the use of natural resources (UN 2014b; UN 2015a; VTT 2012). Policy innovations and voluntary agreements have been identified as means to increase the share of sustainable energy sources and to raise environmental awareness in companies. Moreover, research and innovation activities are needed in the areas of entire production-consumption chains and energy and material efficiencies of systems (Academy of Finland 2006).

The future expertise of an energy engineer will be based on the elements of field knowledge and practical skills. Fundamental knowledge of energy technology is the foundation from which to enhance field knowledge with practical skills. The use of research-based teaching methods enables students to reflect, refine and deepen their communication skills with the other students in dealing with the sustainability problems of energy systems. The students learn to be critical, systemic and creative in solving sustainability problems by using holistic and life cycle-based approaches. Figure 12 presents a procedure comprised of the necessary activities to increase the practical skills of energy students in the classroom (Paper V).

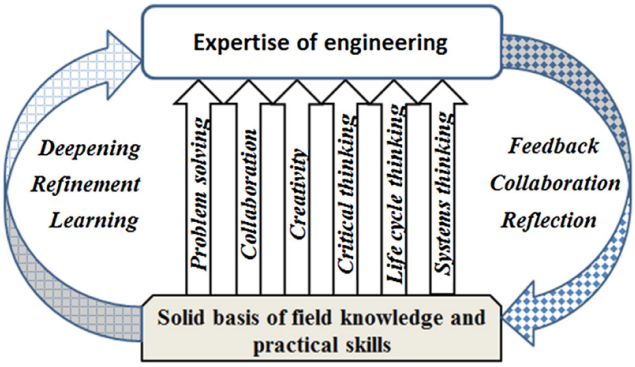


Figure 12. A process of expertise education in the classroom (Paper V) (Mälkki et al. 2015).

Higher education is commonly based on knowledge-driven research, practices and their evaluation. This knowledge-driven education gives the student the fundamental knowledge and basic skills to understand research knowledge and also to produce new knowledge in his own field during the traditional educational procedures of degree programmes. However, in higher education, expertise is defined by all the elements of knowing, acting and being, including the formal, informal and un-formal settings of the teaching and learning methods in curricula (Barnett & Coate 2005; Malcolm et al. 2003). The third element, 'being', is the least understood and most difficult one to embed in curricula. 'Being' means using the teaching and learning methods that help students to develop into responsible experts in working life after their graduation. Therefore, future education should put more effort into the development of career identity and collaboration skills by encouraging students to work in groups instead of alone. New trends in education focus on activating students as participants by minimising the role of the teacher in the learning process. Also, future structures of sustainable education call for collaborative teaching and integration of systemic thinking into energy education. In addition to formal education, the use of more informal learning environments, such as workplace learning and field trips, motivate students to achieve a deeper understanding of sustainability. Practical learning environments, learning by doing, working on multi- and interdisciplinary teams and using problem-solving approaches strengthen the skills needed in actual working life (Crawley et al. 2007; Helle et al. 2006; Mälkki et al. 2012; Mälkki & Paatero 2012; Peltonen et al. 2013; Tynjälä 2008).

6.2 Sustainability views of LCA studies

6.2.1 LCA energy studies

The findings for LCA studies of energy systems were mainly based on 24 review studies, each of which included varying numbers of the LCA case studies in renewable energy presented in Paper II.

LCA was seen as an appropriate methodology for the assessment of greenhouse gas (GHG) emissions, for example, in bioenergy systems. However, the environmental considerations should also include other impacts. GHG emissions cannot be used as a single indicator to represent the environmental performance of an energy system (Milazzo et al. 2013; Turconi et al. 2013). The LCA energy studies included limitations for assessing complex systems, such as acro-systems, due to uncertainties of data and methodologies for assessing the impacts of land use (Marvuglia et al. 2013). For example, Matthews et al. indicated that the GHG emissions of land use varied a lot in their LCA study (Matthews et al. 2014). These LCA studies showed that there are still many difficulties in producing reliable results for energy comparisons. For example, LCA studies lacked transparency when reporting the principles of the data used and local and regional environmental consequences in the calculations (Bayer et al. 2013). An overall

finding for these LCA studies showed that there are many differences between the energy technologies concerning the goals set, scopes and research questions. Moreover, there were deficiencies in knowledge, data, assumptions and considerations of renewable energy sources. Therefore, more LCA studies are necessary to improve the transparency of the calculations and provide comparable information on the sustainability of renewable energy options.

Sustainability of the renewable energy systems has been assessed using the LCA tool, which has produced environmental indicators of renewable energy systems. However, due to the data problems in sustainability considerations, the studies reviewed proposed that it would be useful to apply integrated life cycle-based sustainability approaches to assessing the sustainability indicators of renewable energy systems. The use of consequential life cycle assessment (C-LCA) was especially recommended to integrate socio-economic considerations and economic models and to support decision-making and policy purposes in order to take into account possible changes in future energy solutions (Marvuglia et al. 2013). The inclusion of social impacts was found necessary to identify and quantify the human risks and consequences for improving the acceptance and understanding of renewable energy technologies (Evans et al. 2009). Although, the review results favoured renewable energy technologies, more information was deemed necessary to assess renewable energy technologies as a sustainable source of energy in comparison with the non-renewable energy sources.

6.2.2 **LCA studies in education**

The LCA studies in education dealt with different engineering disciplines, such as chemical, manufacturing, civil, and environmental engineering. There was a scarcity of journal articles focusing on energy engineering education.

LCA was used as a sustainability tool in student assignments, case studies, group work and projects. The LCA teaching concepts were well planned and documented (Balan & Manickam 2013; Juntunen & Aksela 2013b). LCA motivated students to practise their professional knowledge and skills in problem-oriented projects to understand the sustainability dimensions of systems. LCA improved critical and systemic thinking skills and taught students to act as responsible players in society (Harding 2004; Weber et al. 2014; Olsen 2010). LCA combined research and sustainability through a variety of teaching and learning methods in classroom activities. However, more LCA studies in education are needed to increase the scientific use of LCA and to share the best practices for enhancing teaching approaches, methods, and materials in the use of LCA (Juntunen & Aksela 2013b; Masanet et al. 2014). In particular, Juntunen and Aksela proposed that more research is needed to investigate the appropriate learning outcomes to promote students' scientific literacy and advance their moral awareness to act more responsibly in society. Moreover, any education would benefit from the LCA content of learning outcomes (Masanet et al. 2014; Masanet & Chang 2014).

6.2.3 An LCA case study of a forest energy system

The LCA case study of a forest energy system provided an example of how LCA results could be used for decision-making purposes and how the decision calculations affected the results of assessing the potential environmental impacts of the energy system (Paper III). Although this case study is rather old, it presented a simple but accurate example how the findings of an LCA energy study could be utilised in energy education for identifying deficiencies and potential improvements in assessing the sustainability of bioenergy systems.

From the perspective of the overall energy system, the life cycle phase of the energy conversion of the power plant resulted in the greatest quantity of emissions of all the calculated emission categories when considering the whole chain of the forest residue system. The study also showed that the wood-based bioenergy systems are site-specific concerning the data and assumptions used. In particular, the allocation principles seemed to play a crucial role in calculating the final results of the LCA study. Therefore, different LCA bioenergy studies may produce diverse results. Moreover, the results of other similar LCA bioenergy studies are not directly comparable with each other due to the different system boundaries and allocation principles. For example, a Swedish study (Forsberg 1999) yielded higher net CO_2 results (17 kg/MWh) than a Finnish study (Korpilahti 1998) (6–8 kg/MWh) compared with the results of this case study (7–10 kg/MWh). There were also differences in the available energy amounts between the brown and green forest residues. The energy amount was higher for the green forest chips (86 MWh/ha) than for the brown forest chips (58 MWh/ha). The lower energy yield of the brown logging residues was caused by the loss of the needles during the drying period. The results of the potential annual energy amounts were 15 TWh/8.6 million m^3 for solid green residues and 10 TWh/5.6 million m^3 for solid brown residues. These LCA results can be used for estimating the potential energy amounts of forest residues in planning, e.g., national energy strategies and policies for replacing other fuels in energy production.

In energy production, carbon dioxide (CO_2) emissions of wood-based fuels have normally been omitted from the total CO_2 emissions due to the agreed assumptions for the calculation rules. These rules are based on the carbon balance of forest ecosystems. A growing forest is assumed gradually to bind the same amount in CO_2 emissions as is released from the power plant during the conversion phase. In energy production, these free CO_2 emissions of wood-based fuels have been assumed in many research studies (Routa et al. 2011; Röder et al. 2015; Wihersaari 2005) and political discussions on the sustainability criteria of biofuels (EU 2009; Howes 2010; Matthews et al. 2014; Soimakallio & Koponen 2011). However, there are ongoing uncertainties about how to calculate and compensate the wood-based CO_2 emissions in the calculations of the greenhouse gases in energy production (Agostini et al. 2014). The compensation rules are crucial for forest-rich countries that use forest-based fuels to meet their national targets

for fulfilling the demands of EU energy policies in the mitigation of climate change. Moreover, other emissions, such as NO_x and particulates, have gained attention in discussions of the sustainability of wood-based energy production systems. At the moment, bioenergy is one of the promising energy resources for replacing non-renewable energy fuels such as coal and peat; therefore, further discussions and research are needed to assess sustainability that take into account all the emissions and impacts of bioenergy systems.

6.3 Methods to explore sustainability in energy education

6.3.1 Student feedback

The students had clearly distinguishable and consistent opinions about both the methods and the content of the energy education they were receiving. They had a clear opinion on the skills they wanted to improve during the energy courses. However, these skills were not evident in the existing learning outcomes of the energy courses. The existing learning outcomes were based on the core engineering skills, mathematical skills and analytical skills. There was a scarcity of learning goals for informal skills, such as teamwork and presentation skills. The curriculum also overlooked most of the skills needed in the career of a professional engineer, such as leadership, presentation skills and social skills.

Before attending the energy module of the UESEE energy courses, the students had achieved a level of basic knowledge in the natural sciences and mathematics during their earlier studies. Their earlier educational and personal activities had strengthened their social skills, critical thinking and foreign language skills, which are desirable working-life skills for engineers. The students had also achieved competencies in group work, problem-solving skills and writing skills, and they were principally aware of ethical, environmental, and sustainability competencies. However, the students had no competencies in project management, life-cycle assessment skills or leadership skills nor did they possess the latest research knowledge and basic skills of entrepreneurship before attending the UESEE energy courses.

During the UESEE energy courses, the students wanted, in the first place, to achieve competencies in renewable energy technologies, global energy markets, and innovations in energy technology. Moreover, they wanted to acquire or improve their competencies in environmental awareness and sustainability awareness by applying theoretical knowledge in practice, by acquiring life cycle assessment skills, and by training more in critical thinking using the latest research knowledge. All these competencies are crucial in assessing the sustainability of energy systems and solutions. The students had no interest in improving in the areas of self-knowledge, basic natural sciences and mathematics, writing skills, leadership skills, lifelong learning skills and social skills, although they are also skills needed in working life. Also, the students were not interested

in district heating systems, economics, and energy and greenhouse gases. Unexpectedly, the students didn't want to improve their leadership skills even though their current competence level was low. Surprisingly, concerning teaching and learning methods, the students preferred traditional methods, such as lectures and exercises, and had a conservative attitude towards new teaching and evaluation methods, such as reading circles and keeping lecture diaries. They hoped for more field trips, discussions in groups, and a greater variety of assignments. These responses reflected that the students were aware of their need to be prepared for future trends in the energy sector. In curriculum planning, the necessary changes need to be aligned to the courses of the energy module, taking into account the demands of the industry and society.

6.3.2 **Teacher interviews**

The teacher interviews provided information about how the staff in general perceived and implemented the education services they provided. The results dealt with the planning of courses and with applied teaching and evaluation methods. The interviews yielded information on how the teachers had followed the specific teaching demands of the curriculum in planning and implementing the content of their courses. Findings revealed that the choices of the course content were influenced by the interests of the responsible teachers and the existing teaching materials. However, the demands and objectives of the curriculum had not been specified in detail to the teachers. Therefore, teachers had much freedom to design the content of their courses and determine how the courses should be taught. Teachers mainly used traditional university teaching and evaluation methods, such as lecturing, examinations, take-home assignments and exercise sessions in their courses. However, teachers occasionally tested innovative or novel teaching approaches, but not in a systematic manner. Moreover, the individual courses were not systematically planned, and cooperation with the other teachers depended on the interests of the individual teachers. Teachers received systematically collected course feedback through the study software platform, and they also used direct student contacts to collect additional feedback. However, teachers had no systematic manner of processing the collected feedback in order to develop their teaching and curriculum planning. That seems like a missed opportunity as this kind of student feedback provides valuable information to be analysed and discussed together with other teachers in updating the learning outcomes, teaching materials, and teaching and learning methods of the energy courses across the entire energy degree programme.

6.3.3 **A method to measure sustainability**

A method was demonstrated that measures sustainability and renewable energy levels by analysing the sustainability content of the learning outcomes in an energy degree programme. This method included an illustrative representation in the form of the relevance ratio index (RR), which provided a simple way to check to what extent renewable energy and sustainability were embedded in the energy courses of the energy

degree programme. The aim of these relevance ratios, calculated in percentages, is to help teachers to discuss and collaborate with the other teachers of the degree programme to balance the sustainability content of the learning outcomes where it is relevant and necessary.

The calculated sustainability measures for renewable energy and sustainability varied across the energy majors of the energy degree programme at Aalto University. There was only one energy major that required both necessary and supporting prerequisites for renewable energy and sustainability. The other majors had a scarcity of either necessary renewable energy or sustainability prerequisites. These findings showed that there is an urgent need for intensified collaboration between the teachers responsible for planning the sustainability levels of the energy courses in the energy degree programme. For example, the calculation results for the RR indexes, expressed in percentages, for the four majors showed that the Energy and Environmental Technology (EET) major had 49% renewable energy and 16% sustainability compared with the Combustion Engine Technology (CET) major, whose RR results were 0% renewable energy and 4% sustainability (Table 15). In part, these differences may be explained by the engineering nature of the majors and the need to teach fundamental knowledge of energy technologies.

Table 15. Results for renewable energy and sustainability content of the energy majors. (Paper V) (Mälkki et al. 2015).

Renewable energy and sustainability	**Majors of the energy degree programme**				
	EET	**HVAC**	**UESEE**	**CET**	**All majors**
Number of prerequisites					
Necessary renewable energy (NRe)	**64**	0	39	0	103
Supporting renewable energy (SRe)	**1742**	90	56	64	1952
Necessary sustainability (NSu)	0	**26**	2	0	28
Supporting sustainability (SSu)	**945**	116	22	93	1176
Cumulative Competence CC of learning outcomes					
Learning outcomes (total CC)	184	144	182	56	566
Renewable energy (CC-Re)	**90**	2	15	0	107
Sustainability (CC-Su)	**30**	4	18	2	54
Relevance Ratio RR %					
Renewable energy (RR-Re)	**49**	2	8	0	59
Sustainability (RR-Su)	**16**	3	10	4	33

The suggested sustainability content analysis method is currently applicable if the same kind of core content analysis information is available for the learning outcomes, credits and Bloom scores as defined in the STOPS tool. It is also possible to use this method just based on the credits of the learning outcomes without the Bloom or other similar scoring systems. However, the use of these scores produces additional value to calculate the renewable energy and sustainability shares of the courses with more accurate results. This method could also be used to analyse the content and levels of the various informal and non-formal skills presented in the learning outcomes of any degree programme and its

courses. Generally, this kind of relevance ratio (RR) index could help to quantify any desired content within the degree programmes supporting the curriculum development efforts at universities.

Paper V presented a SWOT analysis to study the strengths, weaknesses, opportunities and threats of this method (Mälkki et al. 2015). There are benefits to using the SWOT method. For example, it can reveal the strengths and weaknesses of the present sustainability status of the energy courses. There are also threats that must be taken into consideration. For example, the suggested sustainability content analysis method is not able to quantify the measures of the skills which are not visible in the learning outcomes. Therefore, the actual descriptions of the learning outcomes are crucial, and adequate instructions for teachers are necessary when using this method. In particular, this method can identify potential gaps in the sustainability learning outcomes of the energy courses. Above all, this method aims to improve collaboration between teachers by providing quantified measures for discussion of the desired sustainability levels across the entire energy degree programme.

6.4 A teacher survey to explore the use of LCA

6.4.1 LCA in the energy degree programmes

LCA was more used in the master's level studies than in the bachelor's level studies of the energy degree programmes (Paper VI). The main incentive to use LCA was sustainable development followed by environmental awareness, environmental problems and global challenges. In spite of the three dimensions of sustainable development, the use of LCA was not identified as an important incentive for achieving social and economic awareness. Also, LCA was not identified in the learning outcomes of the energy degree programmes nor in public pressure. Traditional teaching and learning methods such as lectures, assignments and exercises were the most used methods in terms of LCA. Exams, group work, independent studying, learning by doing, personal guidance, presentations, project work and seminars were widely used for LCA by most of the respondents. Drama pedagogy, learning café, learning diary, reading cycle and workplace practice were the least used teaching and learning methods. Moreover, these findings indicated that LCA was not actively used to apply problem-based learning or to map experiences during field trips.

6.4.2 LCA in research-based teaching

The findings regarding LCA teaching and learning methods showed that LCA was used in all the four research categories when applying the research-based teaching model of Healey (Healey 2005). LCA teaching and learning methods were quite equally represented in the student-focused and teacher-focused categories of these four research

categories (Figure 13). In research-oriented teaching, LCA mostly indicated lectures. In research-led teaching, the use of LCA favoured methods such as seminars, exercises, assignments, and exams. In research-tutored teaching, LCA was involved in debate and presentations. In research-based teaching, LCA was best connected to learning by doing, independent studying, project work and group work; less used were workplace practice, problem-based learning and mind map.

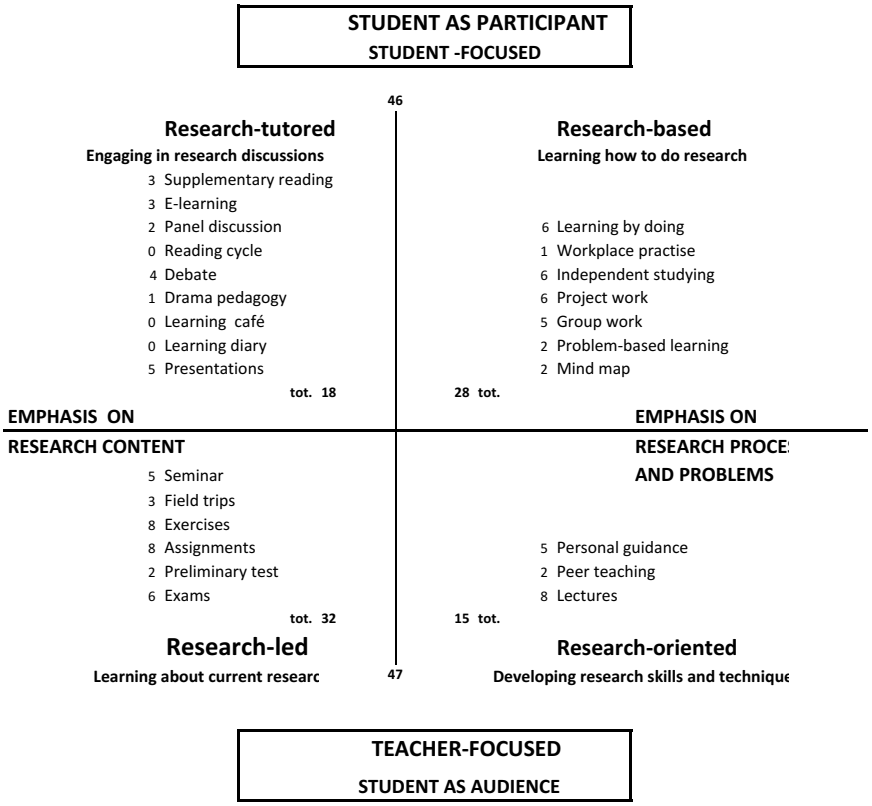


Figure 13. The LCA teaching and learning methods applying the four research categories of the Healey model (Healey 2005) (Paper VI) (Mälkki et al. 2016).

This four-field model revealed that the use of LCA was present in all the elements that enabled the acquisition of the knowing, acting and being skills. LCA seemed to activate the students to act both as audience and as participants by using LCA-based research connected to the research content, research processes and problems. This model showed that knowing is well-integrated into teaching through traditional and popular teacher-focused teaching methods such as lectures and assignments that provide students with new knowledge of their field. This fundamental knowledge in natural sciences,

thermodynamics and energy technology is a prerequisite to learn other informal and non-formal skills. Developing skills of being is identified as a most challenging task in teaching; Barnett and Coate explained that students need experiences of how to grow up to be an expert and interact with different stakeholders (Barnett & Coate 2005). This seems to be possible by using LCA in education combined with methods such as workplace practise, group work, independent studying, learning by doing and problem-based learning. These methods seem to provide students with practise in how to learn to do research and how to learn to be a researcher. The use of LCA supported formal, informal and non-formal skills by using student-focused learning methods such as projects, presentations, discussions, debates, drama pedagogy and learning by doing. However, the use of these activating methods is dependent on the choices of individual teachers; therefore, this model encourages teachers to enhance the use of LCA and the available resources needed to accomplish this. The findings of this model showed that LCA is a relevant tool to be used for sustainability research purposes in energy education.

In order to improve the use of LCA in sustainability assessment, a teaching concept was presented to guide teachers in how to enhance research-based teaching by using a wide range of LCA teaching and learning methods (Figure 14) in energy education. LCA is used as a sustainability tool, e.g., in the development of new or existing products, in comparisons of alternative product systems, and in interpretations of results for identifying potential environmental impacts and improvement possibilities of the systems. The use of sustainability applications combined with teaching activities increases students' awareness that there is more to know, e.g., about the limitations, conditions and boundaries of systems, both locally and globally. They learn to be critical and debate the results of sustainability studies and collaborate with other students.

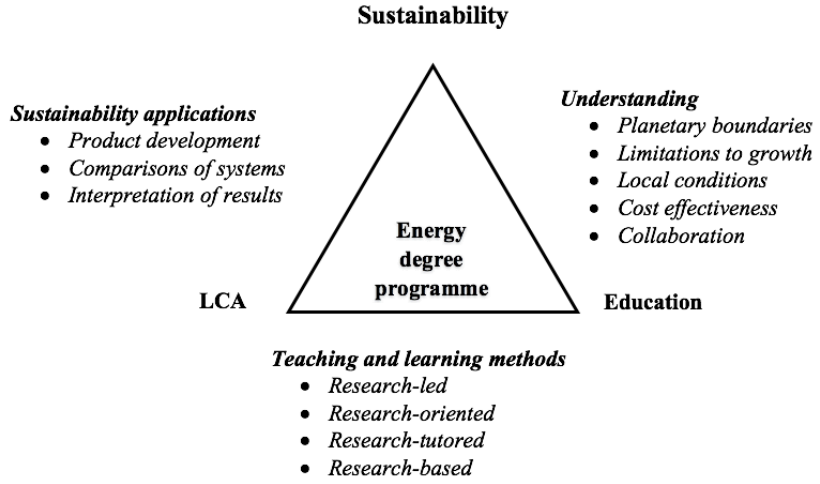


Figure 14. A concept for connecting sustainability, education and LCA in energy education (Paper VI) (Mälkki et al. 2016).

All these activities ensure that students will acquire the knowing, acting and being skills necessary to reach a comprehensive understanding of the sustainability of the energy systems studied. This teaching concept helps teachers to utilise LCA-based research and sustainability applications combined with appropriate teaching and learning methods. Finally, LCA combined with research-based teaching helps students to understand the complex nature of sustainable energy systems and to acquire the experience required to manage future sustainability challenges in real-life problems.

6.5 Reliability and validity of the methods and surveys used

A literature survey was used to identify the characteristics of future expertise in the energy sector and energy education in Paper I. The literature survey included a set of publications describing environmental competencies for future energy technologies and a composition of pedagogical perspectives needed in pedagogy aimed at developing the characteristics of an expert. The findings provided valuable information to guide this dissertation towards an understanding what kind of composition of perspectives is needed for the education of an expert and what the expertise of an energy engineer in the future will be. In particular, expertise with future energy technologies emphasised sustainable energy solutions; therefore, it turned out to be crucial to explore sustainability education and embed it in energy education. However, more information focusing on future energy engineers' working-life skills regarding sustainability would have been useful for benchmarking, supporting and comparing the findings of Paper I.

A broad Internet search was carried out to collect experiences in the use of LCA in energy education (Paper II). Due to a lack of LCA studies in energy education, more general LCA studies in education were used to explore experiences with and views on the use of LCA in energy education. Additionally, an Internet search on the use of LCA in sustainable and renewable energy education at technical universities was undertaken on publicly available university web pages. These findings showed that there were both renewable and non-renewable energy courses, but there was a scarcity of LCA-based sustainability courses in the energy degree programmes. Moreover, it was not possible to compare the content of the learning outcomes of the energy courses due to the limitations of public web pages. Therefore, the comparisons of the technical universities' energy degree programmes, energy courses and learning outcomes in offering sustainability energy education are not included in this thesis. More detailed international comparisons between the technical universities might have revealed what kind of differences existed in the LCA-based sustainability content of the universities' energy degree programmes and their courses. Finally, Baltic, Nordic and Finnish technical universities were selected as a target group for collecting information about how these universities used LCA in their energy degree programmes (Paper VI). The questions of this survey were carefully prepared after exploring the universities' energy education and their teaching staff. The target group consisted of the responsible teachers and professors of the energy degree

programmes; therefore, the responses only consisted of a couple of answers per university. However, in spite of having carefully selected this target group, a survey with a larger number of teachers would have resulted in more relevant and competent findings to further analyse the use of LCA in sustainability in energy degree programmes worldwide.

As a systemic and standardised method, LCA was chosen to be used as a recommended sustainability assessment tool of the energy systems in this dissertation. LCA is demonstrably one of the most used tools for improving product development and for making comparisons of systems, according to the findings of the LCA studies (Paper II). Experience has shown life cycle-based approaches to be mandatory in assessing the sustainability of systems. LCA is an internationally accepted measure of environmental performance that represents an essential part of life cycle management (LCM) (Finkbeiner 2011). As Finkbeiner put it, "*In order to achieve reliable and robust sustainability assessment results, it is inevitable that the principles of comprehensiveness and life cycle perspective are applied. By considering all attributes and aspects within one assessment in a cross-media and multidimensional perspective, potential trade-offs can be identified and assessed*". However, as a single indicator, environmental LCA is not enough to evaluate the comprehensive sustainability of the systems studied. Therefore, a comprehensive sustainability assessment tool concept was introduced in a form of life cycle sustainability assessment (LCSA) to combine the environmental LCA, economic LCC and social SLCA dimensions of sustainability (Klöpffer 2003; Kloepffer 2008). However, in spite of the development efforts of LCSA, sustainability assessment continues to challenge academics and stakeholders in working life, especially in the integrating of social aspects into the scope of product systems and services. Moreover, the differences between traditional and consequential LCA require more attention in assessing the sustainability of energy systems in energy education.

As a sustainability planning tool, Paper V presented a method applicable to quantifying the sustainability content of courses whenever the learning outcomes, credits and Bloom scores are defined in a similar manner as in the STOPS tool (Auvinen 2011). However, this method is demonstrated in a case study using general but carefully selected keywords, terms and verbs to identify the sustainability and renewable energy content of the learning outcomes of energy courses. Therefore, the sustainability content of the learning outcomes should be analysed case by case and according to the same principles in every energy degree programme. Moreover, in order to use this method as a curriculum planning tool, a core curriculum analysis and Bloom's taxonomy should be available for identifying the content of the courses in terms of learning outcomes, prerequisites, study loads and Bloom's scores. The method presented and its RR index are applicable to any energy degree programme when this kind of information is available for the teachers to calculate the percentages of sustainability content of the energy courses. A SWOT analysis of this method is presented in Paper V to identify the strengths, weaknesses, opportunities and threats of this method. The most important weaknesses of this method are that it does not support discussions on how to learn sustainability skills and it lacks

repetition of the learning outcomes when progressing along the study path. These main threats concerned a variety of weaknesses highlighted by inconsistent learning outcomes, a lack of adequate instructions, misuse of the method, and that not all the teachers use the STOPS tool. The STOPS tool should be further developed to integrate the characteristics of this method. In this way, it could better reveal the sustainability skills of students across the entire energy degree programme. This method and its RR index are useful for quantifying any desired content of the learning outcomes within any degree programme by applying the calculation principles presented in Paper V. Thus, this flexible method supports efforts to develop any teaching content in curriculum planning at any university.

7 Discussion and recommendations

Here, theoretical and practical implications are discussed based on the findings of the papers of this dissertation. The discussion highlights the need for sustainability in energy education, mainly based on external and internal driving forces (Figure 16). The recommendations offered below point out ways to integrate sustainability into energy degree programmes. The recommended changes for planning sustainability are mainly discussed at the energy degree programme and energy course levels. They include how teachers could take advantage of pedagogical choices, the planning of sustainability learning outcomes, the use of LCA in research-based teaching, and training to implement these changes, for example, how to improve the sustainability skills of students in the classroom before they enter working life. An enhancement of sustainability in the energy degree programme is also discussed through the decisions made at the top management level of the university (Figure 15).

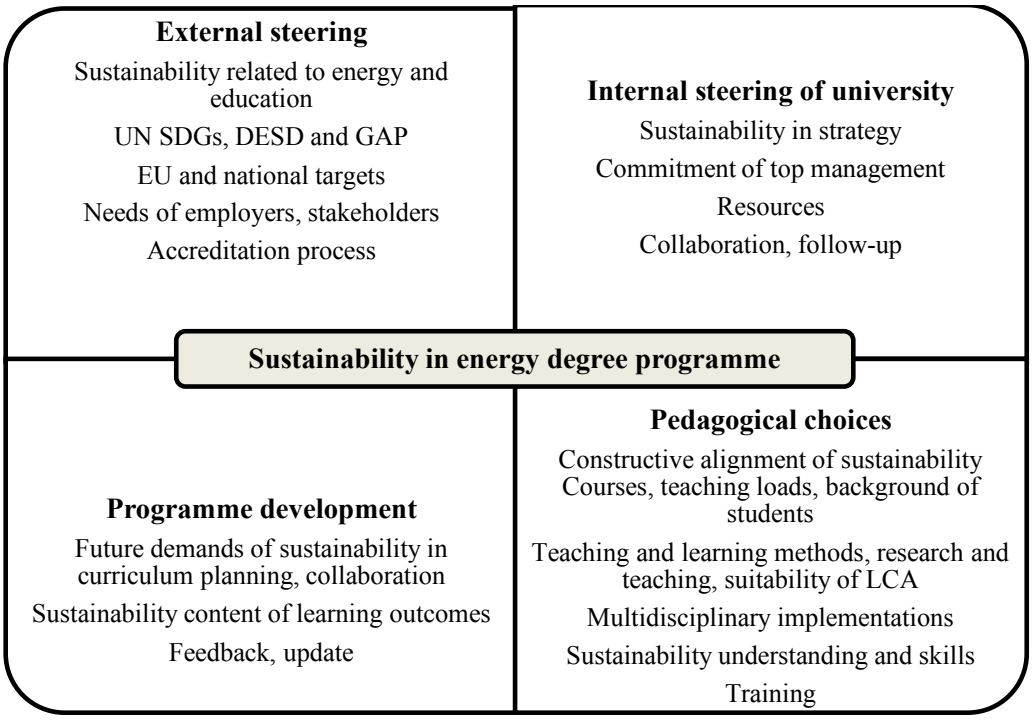


Figure 15. Driving forces to enhance sustainability planning in the energy degree programme.

7.1 Enhancing sustainability in energy education

At the top management level, universities should take into account the external demands of sustainability presented in global and national goals and embed necessary demands in their strategy with the clear targets to improve sustainability in education and other internal activities. Universities should also be committed to supporting sustainability teaching by allocating the necessary resources. The visibility of sustainability seems to play an important role in the strategy, the accreditation process of the degree programmes, and the environmental management systems (EMS) of the universities in order to ensure the implementation of sustainability elements within the degree programmes. For example, in Sweden, since sustainable development was included in the accreditation process of degree programmes and in the EMS of the universities, sustainability was better embedded in education than in the other Nordic universities (Karvinen et al. 2017). At the moment, there are no similar indicators to measure sustainability content of the energy degree programmes in order to produce comparable data to interpret and benchmark the evaluation results of the accreditation process at the desired level. However, the feedback of the relevant stakeholders should be analysed and used for checking and updating the necessary level of sustainability to be taken into account in a continuous planning process of the energy degree programme and its courses.

There are enthusiastic teachers and researchers carrying out individual sustainability solutions in education. However, more effort is needed to enhance the visibility and uniform appearance of sustainability in order to ensure permanent routines in higher education institutions, as many studies have indicated (Karvinen, Löyttyniemi et al. 2016; Karvinen, Mälkki et al. 2016; Karvinen et al. 2017; Takala & Korhonen-Yrjänheikki 2016). Ways of sustainability planning need to be developed case by case because the necessary efforts may vary from one university to another (Karvinen, Mälkki et al. 2016). Therefore, it may be necessary for energy degree programmes to be able to identify their own incentives and barriers in order to enhance the integration of sustainability into energy education. Barriers may vary, for example, from lack of resources, support and competencies to fear of change. The means to overcome these barriers in sustainability planning may include improvements in communication, awareness-raising, resources, and cross-disciplinary, internal and external collaboration, such as those indicated in the survey of the Nordic HEIs (Karvinen, Mälkki et al. 2016). In order to improve awareness and understanding of sustainability, it would be necessary to organise sustainability training of teachers. Such training should include basic and expert levels, depending on the role of the teachers and the courses in the energy degree programme. The importance of training has also been pointed out in the UN Global Action Programme (UN 2014a). Therefore, energy teachers need incentives, support and resources to be motivated to integrate sustainability into their courses across the entire energy degree programme. The programme leader plays an important role in motivating teachers to work together to discuss the appropriate sustainability content of the energy degree programme and its courses.

To enhance sustainability in energy education, sustainability learning outcomes should be discussed and planned at the course and degree programme levels. Therefore, it is necessary to check that the content of the learning outcomes is consistent with the desired sustainability targets indicated by the external and internal needs of different stakeholders. It is also necessary to motivate the teachers so they are committed to the implementation of sustainability learning outcomes by supporting their efforts and providing necessary resources. Moreover, pedagogical competencies could help the teachers to choose appropriate sustainability teaching and learning methods when applying multidisciplinary solutions throughout the entire energy degree programme. The manager of the energy degree programme is a relevant actor who can support these sustainability efforts of the teachers.

7.2 Planning sustainability learning outcomes

Learning outcomes play a crucial role in sustainability planning. The content of learning outcomes should ensure that sustainability is a relevant part of the energy degree programme and its energy courses. In order to improve the students' learning process, the sustainability learning outcomes could be replenished with the suitable pedagogical choices to support sustainability teaching and learning methods and sustainability tools. The learning outcomes should be carefully planned, built and implemented to support the sustainability continuum from one course to another through the whole energy degree programme. In this way, the constructive alignment of the courses, proposed by Biggs (1996), could deepen the sustainability knowledge and skills of the students as they move from one course to another through their complete energy study path.

The bachelor's degree programme could be a good starting point to provide students with basic sustainability knowledge and skills to remember and an understanding of the principles of sustainable development from different perspectives. These basic sustainability skills would ensure that the students are enabled to complement and develop their skills at a deeper level during the master's degree programme. In the master's level studies, the students should learn to analyse sustainability problems and create new solutions, for example, how to mitigate climate change. At the programme level, the learning outcomes should be much broader in scope than at the course level and point out the higher-level thinking skills. The selected energy courses that include sustainability learning outcomes should include specific and discrete skills and knowledge necessary to learn how to use sustainability tools for comparing and making decisions about the best solutions aimed at sustainability. For example, the verbs of Bloom's taxonomy (Anderson & Krathwohl 2001) guide teachers in designing the learning levels and the content of learning outcomes. The selected verbs help to increase the complexity of the tasks and improve the students' sustainability expertise step by step in the classroom. The use of the taxonomy also helps in moving from the lower levels, such as remember and understand, to the higher levels, such as apply, analyse, evaluate and create, by using activating tasks, for example, for comparing and drawing connections

between the alternatives and producing new information and solutions. Therefore, sustainability should be constructively aligned with the learning outcomes of the selected courses in order to ensure the continuity of sustainability from one course to another across the energy degree programme. This alignment approach was also recommended by Biggs (1996).

In order to integrate sustainability into the learning outcomes of energy courses, the present content of the learning outcomes should be analysed and the amount of sustainability content should be measured. For example, a core curriculum analysis, descriptions of the learning outcomes, credits and related scores should be defined to plan the necessary sustainability content of energy courses. The sustainability content may vary depending on the purposes of the different courses throughout the entire energy degree programme. Therefore, teachers should discuss these sustainability measures with the other teachers in the energy degree programme to make decisions on the sufficient levels and content of sustainability in each energy course. Moreover, there are critical views on how to plan learning outcomes based on the verbs of the taxonomies. However, it is useful to have different ways to develop teaching and build a foundation to facilitate discussions about sustainability learning outcomes. According to Murtonen et al., the learning outcomes should be used as a starting point that leads to a wider understanding of the subject (Murtonen et al. 2017). Therefore, the students' learning of sustainability should not be merely based on predetermined learning outcomes because sustainability has a complex nature, and future energy engineers will probably meet new and unknown sustainability challenges in their working life.

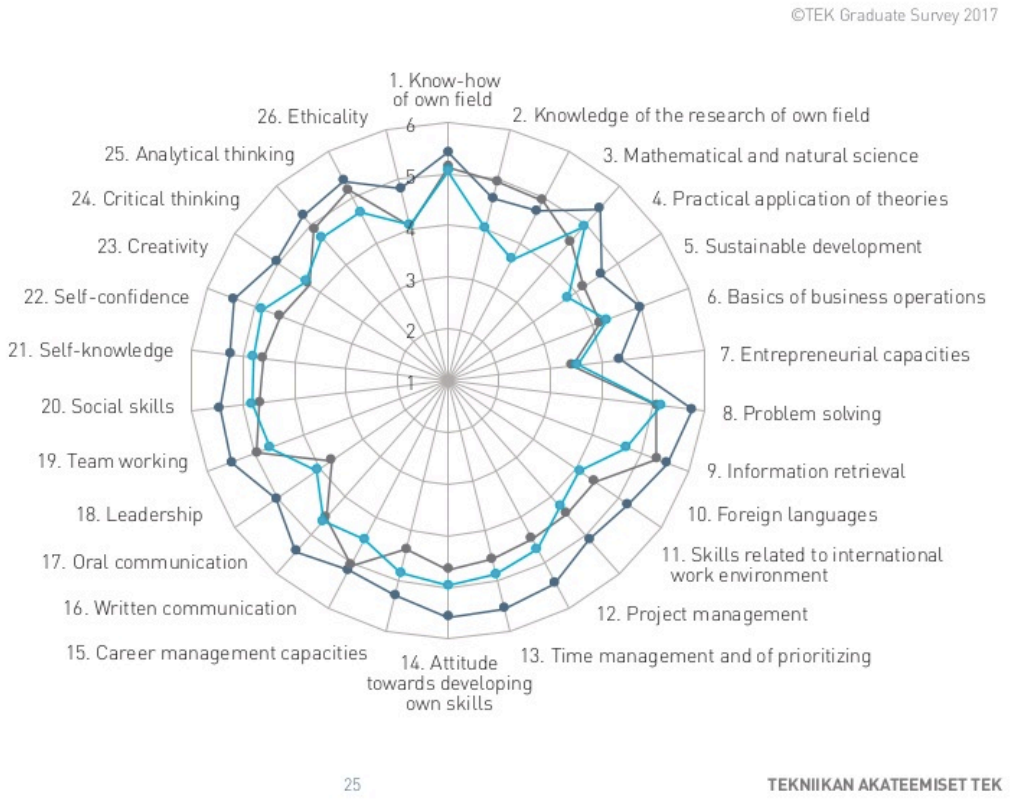
7.3 Fostering the use of LCA in sustainability teaching

The use of LCA should be strengthened in energy education to fulfil a growing need for future experts in LCA and sustainability. In energy education, the practical use of LCA should enable students to learn by doing, create new knowledge, think critically and solve sustainability problems. In spite of the availability of the LCA standards and guidebooks, teachers need skills and practical experience providing instruction in the use of LCA in students' assignments and project work, as indicated in many studies (Juntunen & Aksela 2013a; Masanet et al. 2014; Masanet & Chang 2014). Therefore, the training of teachers in sustainability and in the use of LCA software, databases and materials is needed to improve the practical use of LCA in the classroom. For example, a sustainability teaching concept (Papers II, VI) guides teachers to use LCA applications in research-based teaching and generates discussions on the local and global characteristics and limitations of assessing the sustainability of energy systems. The LCA framework should be used for all these dimensions of sustainability in order to render the results comparable between energy systems. In addition to attributional LCA skills, consequential LCA skills are necessary when planning the sustainability of energy systems and solving the physical and monetary causalities of the related investments at the society level.

In particular, the use of LCA could be improved by combining LCA activities with research and teaching and by using the four research categories presented by Healey (Healey 2005). These four research categories are divided into teacher-focused and student-focused activities. Lectures are aimed to provide students with the basic knowledge and skills regarding LCA methodology. However, teachers should ensure that students have understood the basics of LCA by using exercises based on simple LCA examples. After an orientation phase, the students should start carrying out their own LCA activities, working on projects alone or in groups. The teachers are available to provide guidance in the use of LCA software and databases when it is necessary. Research-based teaching helps students to practise problem-based learning by doing their own LCA studies and arguing for and against other LCA studies. It is important that the students learn how to do LCA research and how to communicate the results of their LCA studies in the classroom. LCA studies and projects generate valuable discussion about the data used, assumptions and system boundaries. Furthermore, these LCA tasks should motivate and enable the students to innovate new sustainable solutions with their classmates.

7.4 Applying pedagogical choices to improve the sustainability skills of energy students

Pedagogical choices play an important role in planning the sustainability skills of energy students. These choices concern the planning of the entire energy degree programme, and all the teachers should take part in discussions about which courses are relevant in terms of sustainability. Thereafter, the sustainability materials used and teaching and learning methods should be discussed so that each course gradually complements the next by increasing the sustainability skills of the students. Energy students need a variety of skills for making decisions, cooperating and communicating with different stakeholders in working towards sustainable energy solutions after their graduation. For example, in Finland, TEK (Academic Engineers and Architects) and Finnish universities of technology together conduct a yearly feedback survey for graduated academic engineers and architects for the purpose of developing university education and to influence educational policy-making (TEK 2017). In the TEK Survey 2017, the importance of sustainable development was almost at the lowest level compared with the other categories of expertise and skills (Figure 16). Therefore, the development of sustainability skills requires more attention at the university level in order to graduate sustainability experts who can enhance the understanding of sustainability in their future places of work. However, the results showed that many of the other skills were highly valued among the respondents, which are also necessary skills for the implementation of sustainable development.



All, n = 1985

1 = Not at all (important), 2 = Very little, 3 = Little, 4 = Somewhat, 5 = Much, 6 = Very much, (7 = Cannot answer)

Importance (black line)
Development in work (grey line)
Development in studies (green line)

Figure 16. The results of the expertise and skills of Finnish graduated academic engineers and architects in the TEK Graduate Survey 2017 (TEK 2017).

The sustainability skills necessary for working life should be discussed when planning the content of the selected energy courses in the energy degree programme. Sustainability learning outcomes are an important part of curriculum planning to ensure that the students achieve at least the basic skills before entering working life. Moreover, the students need

theoretical and practical examples of how to understand and possibly change their values and mind-sets to be more firmly committed to sustainability efforts in society. These changes are fundamental, according to the report, *Educating for a Sustainable Future*, by UNESCO (Delors 1996). Therefore, it is necessary that all the energy students be provided with sustainability knowledge and skills to be aware of the impacts of the different energy sources and understand their consequences in society.

Energy students should also cooperate with multi-disciplinary student groups and practise how to combine their sustainable energy skills with other product systems, for example, those based in the concepts of industrial ecology and circular economy. These concepts call for qualified workers with specific skills as well as for social dialogue, for example, to minimise waste, prevent the use of scarce materials, reduce green-house gas emissions, and improve the material and energy recovery of systems (EU 2015). Moreover, specific skills are needed to reduce the dependence on natural fossil fuel resources and to prevent the loss of biodiversity in order to implement the EU's bio-economy strategy (EC 2012a). In the future, sustainable solutions will become more crucial for energy, food and water systems to maintain a viable and healthy planet. According to future scenarios, people will need 50% more food, 45% more energy and 30% more water in 2030 (UN 2012a). All these sustainable solutions and concepts are also connected with life cycle-based knowledge and skills. Therefore, energy students should be trained to use LCA in different concepts to solve multi-disciplinary sustainability problems.

An overcrowded energy curriculum may hinder energy teachers and professors from doing extra work to integrate sustainability into their energy courses. Moreover, the complex content of sustainability may require a lot of time and effort in planning appropriate teaching content and finding ideas for the sustainability assessment of energy systems. Therefore, many teachers may need training to understand the sustainability issues of energy systems in order to implement necessary changes in the content of the learning outcomes and choose appropriate teaching and learning methods aimed at integrating sustainability. Furthermore, the lack of teaching resources may hinder the integration of sustainability into the energy degree programme.

However, at the moment, it is not possible to educate all the energy students to be experts in sustainability and related tools such as LCA due to limited study time, overcrowded curricula and the traditional content of the energy degree programme. In spite of these obstacles, sustainability-oriented energy students should be encouraged to choose cross-disciplinary sustainability courses available at their own or other universities to deepen their traditional knowledge of energy technology with sustainable energy know-how. However, stand-alone sustainability courses may pose a danger that they isolate and dislodge students from their own mainstream studies when environmental and sustainable development issues are taught outside their own energy degree programme. Therefore, it is necessary to integrate a sufficient number of sustainability learning outcomes in the context of LCA and sustainable development into selected energy courses of the energy degree programme.

8 Conclusions

Energy is used in all sectors of society, and the need for energy is increasing worldwide. Energy engineers acting as designers, decision-makers and leaders are needed to transform the society through sustainability energy solutions to overcome environmental problems, mitigate the impacts of climate change and increase the welfare of people and the planet. Energy is produced by non-renewable and renewable energy sources. In the future, the non-renewable energy sources should be replaced by renewable energy sources and by more sustainable energy system solutions. Sustainable energy solutions have been understood as a combination of renewable energy sources and improvements in energy efficiency, according to a definition presented in the literature. However, sustainability has a more complex nature that includes social and economic dimensions in addition to environmental and technical dimensions. The decisions around sustainable solutions are also dependent on the attitudes, motivations and life situations of the decision-makers. Therefore, sustainability in energy education plays a crucial role in providing the students with the necessary sustainability knowledge and skills necessary to understand local and global demands as well as the limitations of sustainable energy systems. This thesis argued that sustainability skills are in their infancy and are poorly integrated into energy degree programmes, a situation which calls for guidance in improving sustainability teaching in energy education. One overall aim of this dissertation was to propose the necessary changes to curriculum planning to integrate sustainability as a tangible part of the courses in the energy degree programme.

All the papers of this dissertation dealt with sustainability and energy education from different perspectives. The sustainability concepts and tools were explored to combine and create appropriate sustainability teaching and learning methods for the classroom. The review of the LCA studies provided examples of how the use of LCA could promote students' understanding of the sustainability assessment of product systems. Sustainability was mostly understood from the environmental point of view in the energy degree programmes, despite the fact that LCA has been connected to teaching sustainable development and global challenges, according to a teacher survey at technical universities. Therefore, more attention is needed to improve the visibility of the economic and social dimensions in addition to the environmental dimensions of teaching the sustainability of energy systems. Moreover, the use of the same LCA framework for all the dimensions of sustainability would facilitate the interpretation of sustainability assessment results, given that the selected energy teachers were provided with sustainability training to use LCA software and databases. In addition to the use of traditional LCA, there is also a growing need to train teachers to use consequential LCA when the sustainability of the energy systems and their investments are planned at the societal level.

Learning outcomes have an important role to play in the integration of sustainability into the courses taught. Therefore, it is necessary to analyse the present sustainability content

and define a sufficient level of sustainability in the learning outcomes of the energy courses. The content of the learning outcomes was analysed to demonstrate a method of measuring the existing sustainability content of the learning outcomes, using an energy degree programme as a case study. The demonstrated method measured the sustainability content of the learning outcomes. These measures are useful in planning and discussing the desired sustainability levels of the learning outcomes in the energy courses of the energy degree programme. The teachers need support and resources to be committed to the implementation of sustainability learning outcomes and to choose the appropriate teaching and learning methods to provide their students with sufficient sustainability and LCA skills during the energy courses. Moreover, it is important to intensify collaboration between the university staff and key stakeholders to continuously update the future needs of sustainability content in the energy degree programmes.

In the future, more LCA and energy experts are needed in society. For this reason, the use of LCA should be promoted in energy education. LCA educational studies showed that LCA is used more in other engineering disciplines than in energy engineering. Experiences in the use of LCA clearly indicated that LCA promotes the problem-based learning skills of students. On the other hand, LCA energy studies provided useful examples of how to calculate the environmental impacts of energy systems and also of how to compare the results from the sustainability point of view. In the classroom, these LCA studies are relevant teaching and learning materials to generate discussion of the sustainability performance of energy systems. In particular, a holistic understanding of the different energy technologies, energy systems and LCA methodology is needed for making decisions on the sustainability of energy systems. Moreover, LCA assignments and group work enable students to get valuable practise to help them grow as energy engineers by solving real-life problems of sustainable energy solutions before entering the working life.

Sustainability can be enhanced in energy education by applying pedagogical teaching and learning methods to combine energy, sustainability and education. Carefully selected teaching and learning methods and suitable sustainability teaching materials and tools provide students with formal, informal and non-formal skills to achieve an understanding of the complexity of sustainability so that they learn to act as responsible energy engineers and decision-makers in working life. This thesis proposes that an efficient way to teach and learn the sustainability assessment of energy systems is to combine the use of LCA with research activities in the classroom. In summary, this dissertation introduced a teaching concept, sustainability learning outcomes, and the use of LCA in research-based teaching for the purpose of guiding teachers to incorporate sustainability as a permanent part of selected energy courses. However, there are still many obstacles to be overcome which must be taken into account in the integration of sustainable development into energy education. For example, teachers must be provided with adequate teaching resources and sustainability training as well as necessary support by the head of the energy degree programme and the university management.

8.1 Recommendations for further research

The barriers hindering the integration of sustainability into energy education should be explored and related appropriate action plans should be prepared to overcome these obstacles. Sustainability in education has been boosted by individual teachers, sustainability initiatives, and commitments of the higher education institutions (Karvinen, Mälkki, et al. 2016). However, in spite of the sustainability initiatives and an increased role of education, sustainability goals and targets challenge policy-makers, educators and actors in business life to search for new ways and actions to implement sustainable solutions in real-life environments. Case-by-case action plans should be developed for each university because the obstacles may differ from university to university, as identified in the results of the Nordic questionnaire (Karvinen, Löyttyniemi et al. 2016). For example, the barriers should be explored and the incentives should be strengthened to provide sufficient resources in sustainability teaching, to support the sustainability strategy in energy education, to increase the visibility of sustainability learning outcomes in the energy degree programmes, to provide teachers with sustainability training in energy issues, and to ensure the sufficient support of the directors and responsible teachers of the energy degree programmes.

The potential use of LCA in energy education should be explored to produce more practical interventions combining sustainability assessment and research-based teaching. The use of research-based teaching should be applied more efficiently and combined with systemic and scientific sustainability tools in the classroom. For example, student-centred learning activities in sustainability should include experimental and social aspects of energy systems, using real-life cases. Life cycle-based sustainability tools should be made familiar to the students in energy education for assessing the comprehensive sustainability of energy systems. It was shown that life cycle approaches enabled the systemic sustainability assessment of energy systems; however, there are still challenges to improve the use of LCA in energy education, e.g., in planning useful assignments and project work in order to provide students with practise related to the principles and methodology of LCA in sustainability assessment. Students especially need competencies to understand why the results of different LCA energy studies vary in the same kind of energy systems. Moreover, students should be prepared to explicate their sustainability thoughts and ideas in real-life situations together with the different stakeholders of working life.

More research is needed to explore what an appropriate level of sustainability is in a single energy course and at the level of an entire energy degree programme. The sustainability content of the learning outcomes of energy courses may differ due to the different nature and knowledge requirements of those energy courses. Therefore, it is necessary to identify, measure and discuss the sustainability content of all the energy courses in the energy degree programme. The sustainability content method and its quantified measures could be used to discuss and plan the necessary sustainability levels and content of each energy course in the energy degree programme. However, the final level of sustainability

in each course should be confirmed and regularly controlled by the director of the energy degree programme in order to maintain the continuity of sustainability teaching.

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Appendix A: Supporting articles of the dissertation

In addition to the six papers of this dissertation, the author was also involved in the following articles. They were used to support the views and ideas in the integration of sustainability into energy education. Some of them were also referenced in this dissertation.

i. Karvinen, M., Lundgren, U., **Mälkki, H**. & Sorvari, J., 2016. The implementation of sustainable development in the Nordic Higher Education Institutions (HEIs). In Filho, W. L., Mifsud, M., Shiel, C. and Pretorius, R. (eds.), *Handbook of theory and practice of sustainable development in higher education: World sustainability series. Vol. 3.* Springer International Publishing AG, 169–187.

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xii. Peltonen, P. & **Mälkki H**., 2007. Overview on ProDesign principles of the environmentally sustainable products. The 13th Annual International Sustainable Development Research Conference, Track 11: The Sustainability of New Product Development Projects, 10–12 June 2007, Västerås, Sweden.

Publication I

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Energy Engineering Students on Their Way to Expertise in Sustainable Energy

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Energy Engineering Students on Their Way to Expertise in Sustainable Energy

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***Abstract* – Energy engineering is facing new challenges in educating experts in sustainable energy. The aim of this paper is to characterise expertise related to sustainability in higher education. Future challenges and required skills are explored through recent studies, which have listed key competencies that engineers need in their working life. Sustainability and expertise are discussed on the basis of literature and energy curricula are explored on universities' internet pages.**

***Keywords* – energy engineering, expertise, curriculum, competencies, life cycle assessment, sustainable energy**

I. Introduction

Sustainable energy solutions are important for all sectors of industry and human life for many local and global reasons. The main global challenge is to tackle climate change, greenhouse gas emissions and their post Kyoto targets beyond 2012. It is generally agreed that fossil fuels cause global warming [1] and [2]. Increasing awareness pushes energy producers as well as users to choose more sustainable energy alternatives and to save non-renewable energy resources. Global demand for green solutions and the economy are creating opportunities for new technologies, investment and jobs. New skills required for green jobs also mean new requirements for the education in adopting new technologies, meeting new environmental regulations and shifting towards renewable sources of energy. [3]

Energy expertise is essential when making decisions about future energy choices, for example. These choices have consequences on the whole society where energy is used. Even though both energy and environment are closely linked to each other in politics and strategies, increasing environmental awareness and systems thinking still present challenges for teaching energy engineering. This was also identified in the Aalto University Teaching and Evaluation report published in 2011 [4]. The report has presented the same development needs as other national and international analyses of research and higher education in Europe and Finland. The main challenges are increasing internationality, career systems, research infrastructure and academic leadership [4]. These challenges should be observed in research based university education. This development of higher education and research is as an important part of public responsibility in the Bologna Process [5]. Expertise is called employability in the Bologna process and a definition is agreed on this term: "*A set of achievements – skills, understandings and personal attributes – that make graduates more likely to gain employment and be successful in their chosen occupations, which benefits themselves, the workforce, the community and the economy*."

A university should educate high-level professionals to work as energy and environment experts and to make research- and knowledge-based decisions. In this sense, university education should help students in developing their expertise to be able to make the best decisions at work after their graduation, taking into account both energy related and environmental viewpoints. Sustainable use of energy, natural resources and human living environment are key focus areas set out in Aalto University's strategy. These issues have been pointed out to be the main objectives in contributing to sustainable development. Actions to enforce the plan of sustainable development are already under way [6].

In this study, the role and demands of know-how in sustainable energy engineering are investigated through recent Finnish studies [7], [8] and [9], which have listed key competencies that engineers need in working life. Finnish technical universities are aware that sustainability must be incorporated into the energy engineering curriculum in order for the future graduates to acquire these competencies and cross-curricular needs. However, this remains to be implemented in the energy degree programmes. This kind of situation seems to be true also in other universities outside of Finland. Batterman et al [10] have reviewed more than two dozen energy-related programmes in U.S. and European universities and they identified no comprehensive set of educational competencies in the area of energy and sustainability. A current situation of sustainability and energy degree programmes will be mapped in a follow-up study to European universities. This paper discusses teachings in sustainable energy engineering and focuses on elements which are useful for students on their way towards sustainable energy expertise.

II. Development of Expertise

Expertise can be developed in formal and informal settings [11]. Education provides basic skills to people who are able to function independently, perceptively and effectively, allowing them to excel in their field of work [12]. Developing the skills of students is an important goal for teaching and preparing students for professional life. However, developing skills is not enough. Barnett & Coate (2005) [13] suggest that there are three dimensions to developing curriculum in higher education, that is, knowing, acting and being, all of which should be considered. This refers to the fact that in formal higher education, learning of new knowledge is usually well

represented, and the development of certain skills is also considered. However, the dimension of being is often not that well integrated into the curricula."Being" refers to the view growing up to be, for example, an energy expert. Nevertheless, teaching approaches should include the investigation of societal and working life challenges in open interaction with stakeholders like industry and employers. Expertise also requires mastering the working environment and the tools. Students could enhance their skills by putting them into practice during their education. Expertise does not end with graduation from higher education institutes, universities and polytechnics, but it continues throughout the whole working career.

Developing perspectives is of great value for an expert and it might take a number of years before a person is considered to be a real expert [14]. Klein and Hoffman have emphasised that continuous challenges are more relevant than the time spent on the job to develop expertise. They have stated that different domains have different requirements for expertise, but they all have common skills, which are observation of performance, assessment, modelling, relieving anxiety and developing a professional identity. There is also a progression of five levels of expertise, ranging from the beginner to the master and they are novice, advanced beginner, competent, proficient and expert. "*Novices see only what is there and experts see what is not there*" describes the difference between the lowest and highest level of expertise [14].

The Oivallus final report which was initiated by Finnish working life stakeholders has listed the teacher directed and learner cantered practices presented in Table 1 [8]. According to them, the goal of education should be a better balance between the different ways of learning. Future teaching methods do not mean that the old ones must be totally replaced with the new ones, but they could involve simple improvements and new arrangements. For instance the chairs and tables should be movable in the learning room so that the learners could see each other. The report has also recommended that learning practices could closely match the reality of the working environment.

TABLE I

VARIOUS TEACHING AND LEARNING PRACTICES [8].

Teacher directed	**Learner cantered**
direct instruction	interactive exchange
knowledge	skills
facts and principles	questions and problems
theory	practice
curriculum	projects
one size fits all	personalized
competitive	collaborative
classroom	global community
summative tests	formative evaluations

In the future, experts will be working in networks, through which the members will interact and provide interdisciplinary solutions to problems. The political road map for the European Higher Education Area in 2012-2015 focuses on three main goals in the face of the economic crisis: to provide higher quality education to more students, to equip students with better employable skills, and to increase student mobility [15]. Expertise should be based on broad multidisciplinary and interdisciplinary competences from the perspectives of working life [7]. This kind of working is necessary to adapt to the shift from an industrial society towards an information and experiential society [8]. Expertise in all sectors of higher education is at the moment commonly based on knowledge-driven research and relevant practices and their evaluation. This knowledge-driven education gives the student the basic skills to understand research knowledge and also to produce new knowledge in his own field according to approved procedures. However, expertise is not the only quality of individuals since expert knowledge should be learned and shared with others in an interactive community.

III. SUSTAINABLE ENERGY IN EDUCATION

Sustainability is one of the main objectives in the Europe's energy policy [16]. The above paper highlights a strategy for sustainable, competitive and secure energy where sustainability is connected to renewable and other low carbon energy sources and carriers. Also carbon free nuclear energy and clean coal technologies can be sustainable energy. The definition of energy from renewable sources includes wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases in the European Union Directive on the promotion of the use of energy from renewable sources [17]. This definition excludes energy from fossil sources. This directive introduces also the sustainability criteria for biofuels. These energy issues are crucial in sustainable energy education.

Sustainability includes a challenging combination of economic, ecological and social dimensions and needs interdisciplinary co-operation in education [18] and [19]. The teachers have to plan in cooperation with the other teachers, how they could put sustainability aspects into context within the curriculum and their courses. In universities the goal of teaching should be the students' education, which promotes expertise in tackling global ecological challenges.

Expertise in sustainable development means understanding the relationships and conflicts between the various actors' parties and technical solutions. The holistic view of the energy systems, the deep know-how on energy engineering and the ability of critical and creative thinking are basic skills for promoting sustainable energy. The sustainable solutions should be based on long-term goals of ecological, socio-economic, energy and material efficiencies. Decision making for sustainable solutions might take more time than expected when changes of mindset are needed. Table 2 presents the

current state of sustainable development in higher education of technology [20].

TABLE 2

CURRENT STATE OF SUSTAINABLE DEVELOPMENT IN HIGHER EDUCATION OF TECHNOLOGY [20].

Views of sustainable development	**Current state**
Strengths	many individual solutions, many enthusiastic teachers and researchers
Weaknesses	no uniform view, different technology actors, low visibility
Opportunities	a good basis for the systemic and life-cycle based development, strong problem solving skills
Challenges/ Threats	taken for granted, system-level solutions

In the coming decades, renewable energy sources will not be able to satisfy the total demand for energy [1]. Environmental degradation and especially climate change is also challenging the education of energy engineers.

IV. FUTURE TRENDS IN ENERGY ISSUES

When educating future energy engineers it is important to consider the future trends in energy issues in different industrial sectors. Following future trends in energy issues are mostly based on the FinnSight 2015 report [7]. This report's main conclusion is that research and innovation activities have to be strengthened in the areas of energy systems, entire production-consumption chains and energy and material efficiencies. There is growing interest to focus on the security of energy supplies and on renewable and clean energies. Efforts in these fields could combat climate change and scarcity of raw materials. Policy innovations and voluntary agreements could also improve the use of sustainable energy and awareness in environmental impacts. Environmental awareness grew during 1980 – 1990, but the climate change became widely recognized first in the beginning of the 21st century [9]. Recognized climate impacts are mainly mitigated through various attempts to decrease the emissions of greenhouse gases by reducing the use of fossil fuels. These efforts promote the global transition to renewable fuels. Emission trading introduced by the EU increases the cost of using fossil fuels which is also a driver for new decentralized power generation technologies. Moreover, energy and material efficiency have potential for improvement throughout the society. Sustainable energy solutions are also relevant for instance in the waste management and transport sector. [7]

The forest industry is also facing global changes. The change will focus on renewable raw materials and the shift from the paper and cellulose industry to special chemicals and technologies. The use of wood in energy production will bring the actors of energy and forest industries together. Nuclear energy technology will gain ground because of its carbon dioxide emission free heat generation process. Fuel cells and solar energy face high expectations, but advances are needed in material and manufacturing technologies. Renewable energy production methods are nevertheless evolving rapidly. Driving forces are needed for sustainable development, security of supply, political agreements and emerging markets. New solutions must be developed in the field of decentralized energy systems including the entire supply and demand chain starting from production to energy use. The FinnSight 2015 report has emphasized the need for strong cooperation between the different technology developers. [7]

These future trends also require continuous adjustments to be made to the energy engineering programmes. Higher education should educate energy engineers in different industrial sectors so that they are able to act and make the correct sustainable choices in tomorrow's environment. In Barnett's & Coate's terms [13], these engineers ideally see themselves as part of the whole society, and build their identity as engineers with respect to sustainability in whatever they do.

V. FUTURE EXPERTISE IN `ENVIRONMENT AND ENERGY

Today, students and engineers are facing increasingly complex tasks in energy issues. Energy engineering education normally prepares students to develop technical competences in the energy sector. However, policies and the society are emphasizing life cycle thinking and system approach in preparing long-term energy decisions. The new items integrated in energy engineering education should involve sustainability aspects of energy systems. An energy engineer requires analytical methods and tools to implement the concepts and best design practices in sustainable energy systems. The life cycle based approaches incorporated in energy engineering education would provide the ideal skill set for tackling a wide range of energy problems. Life cycle assessment (LCA) has become a core element in environmental policy and a critical analysis tool to provide broad perspectives needed to address complex problems of systems [21] and [22]. LCA is based on internationally agreed environmental management standards ISO 14040 [23] and ISO 14044 [24]. According to these ISO standards, LCA can be used in many applications of society to assess environmental aspects and potential environmental impacts in different phases of product systems. These outcomes are useful in seeking for balanced sustainable solutions to optimize use of natural resources and environmental consequences along an energy product's life cycle.

Skills of life cycle thinking and systems approach are necessary in preparing long-term energy decisions. In the coming decades, renewable energy sources will not be able to satisfy the total demand for energy [25] and [1]. The Finnish book *Energy Visions 2030 for Finland* states that there are still negative environmental impacts although all energy would be produced using renewable and sustainable energy sources especially in the case when energy consumption increases continuously. The book gives examples:

- wide utilisation of biomass as an energy source requires the use of large land areas, and effective cultivation may cause serious changes in the soil nutrient cycle

- renewable energy technologies also require non-renewable material inputs [1].

The FinnSight 2015 project [7] has studied the future needs of competencies in science, technology, society, business and industry. The Environment and Energy panel have brought up the ten important areas of expertise [7]:

- ecosystems,
- environmental management in Finland and globally,
- urban environments,
- water systems and water purification systems,
- biomass as an energy resource and their production systems,
- more efficient use of energy, negawatts,
- new energy production systems and their integrations,
- new technologies: production and use,
- logistics, distribution and
- mobile and distributed technologies as a platform for energy and environmental services.

Future expertise on environmental management of energy engineering should involve awareness of global problems in mapping and foresight of the environmental risks. Life cycle and systems thinking would increase environmental awareness in screening the systems. Future skills in energy education should also include the set of different sustainability tools [26] and [27].

VI. Conclusions and Discussion

Energy engineers need expertise to solve global and local environmental problems. They need a holistic view on energy systems, a deep know-how of energy engineering and the ability to think critically and creatively to sustainably solve these problems. Regarding future trends in energy issues, sustainable solutions should be based on long-term goals for the ecology, the economy and for energy and material efficiencies. It is also important to address other environmental risks and impacts than global warming when considering energy solutions in education. The environmental impacts should be calculated through whole energy production chain from raw material acquisition to the end use of waste. Expertise in sustainable energy faces complex environmental, economical and societal issues and the advancement in expertise requires competencies to understand and manage different tools and various cognitive perspectives when seeking for the sustainable solutions.

A better balance is needed between various teaching and learning practices in addition to the skills and educational learning outcomes in building the students' future careers. However, it seems that developing teaching practices is not enough. Future education should support identity development and collaboration by working in groups instead of working alone. Also, it could be helpful if the structures of education would support collaborative teaching and life cycle thinking integration in all energy engineering issues. In addition to formal education, the use of more informal learning environments, such as workplace-learning could motivate students to acquire deeper understanding of the role of sustainability in energy engineering and to learn how to use life cycle approaches in authentic environments. Integrating various learning environments would help the students to enhance their sustainable energy expertise and possibly develop multidisciplinary and interdisciplinary skills for sustainable energy solutions throughout their education. After having graduated, expertise should continuously be developed throughout the entire working career. The integration level of energy and sustainability still seems to be low in the curriculum. This research will continue by investigating practices and a current situation of sustainability in energy related degree programmes in Finnish and European universities.

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Publication II

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An overview of life cycle assessment (LCA) and research-based teaching in renewable and sustainable energy education

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An overview of life cycle assessment (LCA) and research-based teaching in renewable and sustainable energy education

1. Introduction

Sustainable development is defined as “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” to quote the Brundtland Report [1]. Interpretations of this definition refer to the three dimensions of sustainability, namely, environment, society and economy. Sustainability of energy systems is commonly combined with the joint use of those renewable energy sources with low emissions and new technologies with improved energy efficiency [2,3] Sustainable energy and the use of renewable energy sources have been important elements in national and international research programmes and energy policy strategies in recent years [2,4–8]. New sustainable energy solutions are expected to create opportunities for new jobs and challenge the current expertise in sustainability and renewable energy [9–11]. Due to the increasing needs of such expertise, educational institutes and providers of training have an emerging task, which is to educate students and retrain workers for coming needs in expertise and the future employment opportunities related to renewable energy [12–14].

Education has been recognised to be a driving force for sustainable development (SD) [12]. Recent studies have identified sustainability as an essential part of teaching at higher education institutions (HEIs) [15–18]. The UNECE Strategy [19] for Education for Sustainable Development (ESD) introduced specific objectives, such as the use of formal, non-formal, and informal learning and the training of educators with SD competences so as to embed sustainable development (SD) in education. Research on and development of ESD was also mentioned among the objectives of UNECE. The UNECE strategy was followed by the United Nations Decade for Education for Sustainable Development (UN DESD) 2005–2014, encouraging governments and organisations to integrate the principles, values, and practices of sustainability into all aspects of education and learning [20]. The final DESD report included new challenges, such as the changes in attitudes, values, and lifestyles, and the strengthening of people's capacities to bring about desired change [21,22].

Findings on the learning processes during UN DESD showed that HEIs were re-orienting their education, research, operations, and community outreach activities toward sustainability [18]. These findings indicate that sustainability-oriented learning is a challenge for an entire educational system in many schools, universities, and companies. Therefore, the importance of promoting integration and understanding of SD in education at universities has been mentioned in several studies [2,23–25].

Kandpal and Broman [13] reviewed the global status on renewable energy education and identified a variety of challenges in energy education, including the unavailability of well-structured curricula, lack of motivated and competent teachers, the unavailability of adequate funds, and the uncertainty of employment prospects for students. They also identified that renewable energy courses are missing needed links to environmental interactions and sustainable development. They proposed that both energy and environmental education should be provided in a synergetic manner. Dincer [26] studied the relationship between renewable energy and sustainable development, using practical cases from both the current and future perspectives. He revealed essential factors, such as public awareness, environmental education and training, innovative energy strategies, the promotion of renewable energy resources, and evaluation tools were needed to integrate sustainability in energy programmes. In spite of the many ways to promote sustainability at universities, environmental issues seemed to remain a constant ongoing challenge in energy engineering education [3,27–31].

Specific life cycle approaches, tools, programmes, and procedures have been developed to support decision-making and evaluate the holistic impacts of the system [32–34]. Curran [35] reviewed life cycle based tools for assessing the environmental sustainability of biofuels in the United States. She pointed out that the use of renewable resources does not automatically mean the same as sustainability. She studied and compared ten tools, namely, Carbon Management, Ecological Footprint, Exergy Analysis, Fuel Cycle Analysis, Greenhouse Gas Life Cycle Analysis, Life Cycle Assessment, Life Cycle Risk Assessment, Material Flow Analysis, Net Energy Balance, and Sustainability Indicators. Findings for Curran [35] showed that a life cycle view is needed to be able to holistically assess biofuels. Moreover, she indicated that active co-operation within the scientific community can develop a consensus with the necessary scientific approaches to support policy-makers in delivering the information about sustainable energy systems.

The purpose of this review then is to seek greater understanding of how LCA can be useful in (higher) energy education, particularly as a research-based approach for the assessment of the comprehensive sustainability of renewable energy systems. The findings of this review are discussed in terms of a research-teaching nexus with the aim to identify those learning approaches that enhance students´ sustainability competences to act as decision-makers following graduation. To that end, this paper deals with the aforementioned topic of the use of LCA in energy education from two perspectives, namely, analytically surveying i) the LCA studies in renewable energy and ii) examining the LCA applications in education.

The procedure of this paper starts in Section 2 with a description of the theoretical background for life cycle assessment (LCA), life cycle sustainability assessment (LCSA), and sustainable and renewable energy in the context of LCSA, and research-based teaching. A literature review of

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the LCA studies is presented in Section 3. Findings, recommendations and new research needs and recommendation are presented in the discussion and conclusion Sections 4 and 5.

2. Theoretical background

2.1. Life cycle assessment (LCA)

Life cycle assessment (LCA) is a systemic research method used for compiling the environmental impacts of product systems from raw material acquisition to waste utilisation [36]. LCA has consolidated its position in environmental research since the beginning of the 1990's. From this moment, the first LCA guidebooks, e.g. [37–40] and the first LCA standards [41–44] were published to guide the use of LCA in research and education.

Methodology, databases and software have been continuously developed to improve the scientific use of LCA. The development of LCA has been supported by the UNEP/SETAC Life Cycle Initiative so as to enhance decision-making supporting more sustainable product systems and processes [45,46]. Moreover, the established local and global LCA networks have been sharing knowledge and experiences with LCA practitioners in the use of LCA. In spite of these continuous developments of LCA, Finnveden et al. [47] indicate that further developments are needed to improve databases, quality assurance, consistency, and harmonisation of methods. Conventional LCA (also called attributional LCA) quantifies physical flows and does not take into account the consequences related to changes in demands of the product systems. Therefore, Earles and Halog [48] reviewed a consequential life cycle assessment (CLCA) to integrate economic modelling approaches into LCA for policy-making and environmental strategy planning by corporations. Due to the growing information needs of decision-makers in different sectors of society, there is also an urgent need to extend the use of LCA to harness the economic and social dimensions of sustainability [49]. Ness et al. [50] highlighted the need for the environmental-focused realm of LCA to be expanded to a broader interpretation of sustainability. LCA was found to work as a desired framework for developing a life cycle sustainability assessment (LCSA) that can combine the environmental, economic, and social dimensions of sustainability [51,52].

Life Cycle Assessments (LCAs) are conducted according to LCA standards 14040 and 14044 published by the International Organisation for Standardisation [36,53]. The framework of LCA has four phases (see Fig. 1): 1) Goal and Scope Definition, 2) Inventory Analysis, 3) Impact Assessment and 4) Interpretation. In the goal and scope phase, all general decisions on setting up the LCA system are made and defined taking into account the purpose, intended application and audience. This phase also includes the decisions on the description of the whole system and its boundaries, the selection of the impact categories and methods, and agreement on data quality requirements and their limitations. In the inventory phase, the collection and compilation of the data are done in an iterative process, taking into account the goal and scope decisions. The inventory phase involves the quantification of inputs and outputs for a given product system throughout its life cycle as measured by the selected functional unit. In the impact assessment phase, potential environmental impacts are calculated based on the results of the inventory analysis. The impact assessment categories are selected to increase the understanding of the magnitude and significance of the inventory results and the intended goal of LCA. In the interpretation phase, all results are studied against the requirements of the intended application in order to draw conclusions, explain limitations, and provide recommendations. This framework for LCA is presented in Fig. 1. The four phases of LCA, described above, form a systematic way to calculate the environmental burdens and impacts during the entire life cycle of systems to be used in different applications.

2.2. Life cycle sustainability assessment (LCSA)

Many studies have used LCA as a framework to develop LCSA to combine the environmental, economic and social dimensions of sustainability [54–58]. In LCSA, the life cycle approach helps identify the dependencies between sustainability components to avoid problem and burden shifting from one part of the system to the other part [59]. Singh et al. [60] pointed out that sustainability indicators and composite indexes are useful for policy making and public communication because they simplify, quantify, analyse, and communicate otherwise complex information on sustainability. Klöpffer [61] proposed that LCSA be a combination of an LCA, a life cycle costing (LCC) and a social life cycle analysis (SLCA), using the equal and consistent system boundaries for all these dimensions for assessing sustainability. Heijungs et al. [62] further proposed that LCA, LCC, and SLCA provide three different ways to look at the same system.

Sustainability is more than an aggregation of these three sustainability dimensions, and therefore, interlinkages and dynamics between the used sustainability assessment methods are needed in LCSA [50,57,63]. Jorgensen et al. [57] argued that the goal of sustainability is often seen to

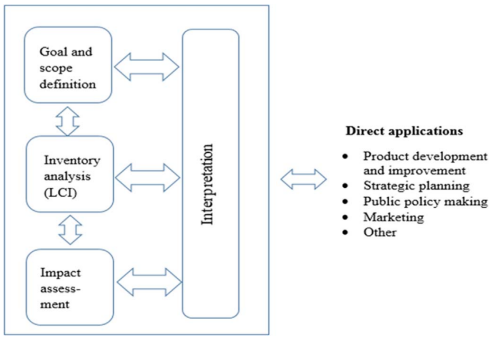

Fig. 1. The LCA framework and its four interactive phases with examples of direct LCA applications according to ISO 14040 (2006) [37].

reconcile the conflicts between environmental protection, social equity, and economic growth in a balanced way. The complex nature of SLCA has been also pointed out in many studies [51,57,63,64]. Lehmann et al. [65] studied the social aspects in decision- making suing two waste management case studies. Their findings showed that social aspects will benefit from LCA and LCC in decision-making despite their methodological differences and practical restrictions.

Many initiatives, projects, and researchers have taken part in the development of LCSA to increase the consensus and understanding of the sustainability dimensions within the same LCA framework [66–71]. Development of sustainability tools is crucial in order to enhance the sustainability content in teaching because education has been highlighted as being an important incentive that provides students with the knowledge, skills, and values needed for implementing sustainable decisions and solutions in society. As decision-makers, energy engineers need core skills and competences in the renewable energy technologies, the nature of energy efficiency, and an awareness for the environmental aspects of energy systems [72–74].

2.3. The LCSA framework for sustainable and renewable energy

Energy plays an essential and challenging role for sustainable development and poverty eradication according to many initiatives and conferences of the United Nations. The UN 2030 agenda introduced 17 sustainable development goals and 169 targets to be met by 2030, including the goal for energy to be affordable, reliable, sustainable and modern energy for all [75]. In 1992, the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro suggested the current levels of energy consumption and production are unsustainable [76]. Agenda 21 of UNCED presented and adopted the principles for the Sustainable Management of Forests. In 2002, energy was addressed in the context of sustainable development in the Johannesburg Plan of Implementation (JPOI) [77]. In 2011, the initiative of Sustainable Energy for All was introduced to ensure there will be universal energy access to modern energy services, double the global rate of improvement in energy efficiency, and double the share of renewable energy in global energy use by 2030. In 2012, the Rio+20 Conference highlighted the fact that energy plays a critical role in global sustainable development processes and offered the report titled, “The Future We Want” [78]. The role of new and renewable sources of energy was further emphasised as being global challenges of sustainable development by a report from the UN Secretary-General [79]. Finally, the decade of 2014–2024 was declared as the United Nations Decade of Sustainable Energy for All in order to increase the use of new and renewable energy sources and meet the declared sustainable development goals and targets by 2030.

Indicators, approaches, and frameworks are needed to assess the sustainability of solutions [69,80]. For example, poverty was revealed as a relevant energy-based indicator of sustainability in the developing countries [81]. The World Economic and Social Survey [7] identified multiple pathways toward sustainable energy, including many existing energy technology options for mitigating emissions and increasing social welfare. The Renewable Energy Directive (RED) introduced obligatory sustainability criteria at the EU level in order to keep a minimum level of sustainability [4]. Future global trends are also needed so as to plan and make decisions on sustainable and secure energy solutions [75]. Buytaert et al. [82] highlighted the integrated sustainability assessment for energetic use of biomass and used such sustainability assessment tools as Criteria and Indicators (C & I), Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), Cost Benefit Analysis (CBA), Exergy/Energy Analysis (EA) and System Perturbation Analysis (SPA). They detected significant differences between the sustainability tools and proposed developing a toolbox that combines the procedural parts of C & I and EIA, supplemented by calculation algorithms of LCA and CBA for integrating the sustainability assessment tools, respectively.

Coyle and Rebow [2] proposed that students need a framework containing systemic concepts and methods in order to understand the elements of sustainability in complex systems. In implementing sustainability through teaching, teachers need a framework to use to guide students to take into account the contents of the different sustainability dimensions. The sustainability framework presented in Fig. 2 can help teachers and students design sustainability of these energy systems. First, life cycle thinking (LCT) helps them study the whole energy system and every part of it and get a holistic view of the sustainability elements needed in any sustainability assessment. LCT prepares students to identify the phases of LCSA, and gather necessary data to produce quantitative and qualitative indicators for the separate methods of LCA, LCC, and SLCA as part of LCSA.

As a qualitative approach, LCT helps to define the up- and down-streams of the whole system to identify possible problems at an early stage in

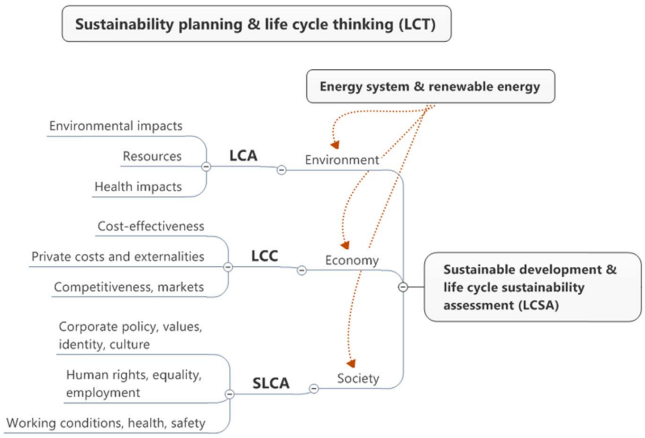

Fig. 2. LCSA framework for planning sustainability of energy systems.

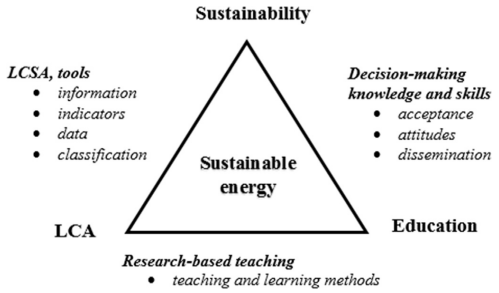

Fig. 3. A concept connecting sustainability, education and LCA in sustainable energy education.

the evaluation process. LCA used as a quantitative approach produces numerical data and indicators to evaluate the used resources and environmental and health impacts of the energy systems. LCC produces cost indicators to evaluate, e.g., cost-effectiveness, competitiveness in the marketplace, and private costs and externalities of the energy systems. SLCA produces social indicators to evaluate, e.g., corporate policy, values and culture, human rights, and the working conditions of the energy systems.

This framework for LCSA is presented in Fig. 2. It combines LCA, LCC, and SLCA and helps teachers to design the content of teaching they need to produce sustainability indicators for comparisons of energy systems and discussions by students. This LCSA framework (see Fig. 2) is a crucial part of the teaching concept for sustainable energy presented in Fig. 3 that needs to combines LCA with sustainability research activities, teaching and learning methods and knowledge of sustainability.

2.4. Research-based teaching in education

Research is one of the main mechanisms through which teachers in higher education update their knowledge and maintain and improve the relevance of their teaching. Universities have pointed to the strong connection between research and a high quality of teaching. Brew [83] referred to the political, institutional and disciplinary factors that affect the relationship of research and teaching, whether the aim is to integrate teaching with research or to integrate research with teaching. Horta et al. [84] indicated that universities, schools, departments, and staff have to make organisational efforts to better integrate teaching and learning activities and change teaching practices.

Many studies have reported the benefits found in the integration of research and teaching and proposed that traditional lecturing needs to change in the relationship between teachers and students [85–87]. The research by Chickering and Gamson [88] suggested that good teaching and learning can be encouraged by using structured exercises, challenging discussions, team projects, and peer critiques to improve the interactions between teachers and students. Co-operative teaching and learning methods and also problem-based learning are mentioned as examples for good teaching methods, while preferring the latest research in the report to the European Commission to improve the quality of teaching and learning [89]. Findings by Spronken-Smith [90] highlighted the fact that open-discovery and inquiry-based learning (IBL) develops better inquiry and research skills than traditionally taught courses. Griffiths [91] distinguished four types of knowledge, namely, empirical science, interpretive inquiry, applied inquiry, and integrative scholarship, to be able to produce knowledge for research-based teaching in the already built environment disciplines of higher education.

The use of research in teaching has inspired many authors to apply their own case studies and develop research-based teaching at their universities [92–95]. Healey [96] studied different concepts for bringing teaching and research together in the teaching and learning environment. He presented four ways to integrate research and teaching, namely, using research-led, research-oriented, research-tutored and research-based teaching methods. The use of research was dependent on the level of participation of the students and teachers where students were either audience or participants in the classroom. Research-led and research-tutored methods emphasised the use of research content. Research-oriented and research-based methods emphasised the use of research processes and problem-solving in teaching. These research categories are further described and listed as follows:

- Research-led: Teachers use research and case studies to teach students about current issues,
- Research-oriented: Teachers teach research skills and techniques to students,
- Research-based: Students learn to do research as a member of a group,
- Research-tutored: Students engage in research discussions based on research case studies.

Many studies have used Healey's model to further develop detailed applications for enhancing the integration of research and teaching [93,97–99]. Based on Healey´s model, Visser-Wijnveen et al. [99] presented five profiles for the research- teaching nexus, consisting of teaching research results, making research known, showing what it means to be a researcher, helping to conduct research, and providing research experience. Mälkki et al. [100] used Healeys´s model to analyse the LCA teaching and learning methods used in the energy degree programmes. Their findings indicated that LCA was taught using a large variety of teaching and learning methods in addition to traditional lectures in the research-teaching nexus. Brew [83] proposed that research-enhanced learning and teaching is a strategy that can better meet the needs of students in the twenty-first century. Xia et al. [101] indicated that research-based projects allowed students and faculty to combine teaching with research, thus leading to academic outcomes, such as papers and funding for future projects. In spite of the benefits of the research-teaching nexus, Bak and Kim [102] revealed that the financial incentives for research rather than teaching may redirect the attention of some professors from teaching to research. They indicated that the increasing emphasis on faculty research in universities might even harm the research- teaching nexus in higher education.

Teaching and research can be brought together by employing the concept of learning and teaching and using research-based assignments and

projects both inside and outside the classroom [97,98]. Xia et al. [101] demonstrated that a win-win situation is created for students, academics and industry partners when synthesising work-integrated learning, research, and teaching. Life cycle approaches have been used in research projects to calculate sustainability indicators to use for assessing the sustainability of systems. However, LCA energy studies [82,103–105] indicated that it can be complicated to assess the comprehensive sustainability of systems, especially when including environmental, economic, and social perspectives. In order to enhance the sustainability skills of students to become future decision-makers after their graduation, teachers need effective concepts and tools for how to implement research, teaching, and sustainability for students in sustainable energy education [106,107].

A concept to guide teachers in sustainable energy education is presented in Fig. 3. This concept demonstrates sustainable energy education through the knowledge of fundamental principles of sustainable development (Sustainability), appropriate teaching and learning methods (Education), and comprehensive sustainability tools (LCA). This combination of sustainability, education and LCA aims to provide students with the desired competences, skills, and awareness needed for planning, decision-making, and sharing information about sustainable energy solutions both locally and globally. This concept also trains students how to use softer skills, such as communication, problem- solving, and teamwork, and be better prepared to face different attitudes and acceptance levels of different stakeholders regarding renewable energy solutions both locally and globally [12].

Brew [83] highlighted that the skills of critical inquiry are central to a super-complex society that demands the ability to deal with complexity and uncertainty. Effective skills to communicate and share best practices are needed in the rapidly evolving field of renewable energy [9]. In particular, public acceptance plays an important role when implementing new energy solutions. For example, local inhabitants are a key audience to use to debate local installations of renewable energy plants [108]. Especially, this concept (see Fig. 3) guides both teachers and students to use life cycle-based sustainability tools and related research activities in energy education and acquire knowledge, skills and competences for dealing with sustainable energy aspects of their future challenges in their working lives.

3. Literature review of LCA studies

A literature review included the LCA studies that focused on the LCA studies in renewable energy and the LCA studies in education. A search of the LCA studies was carried out on the Internet from common databases and specific journals using critically selected keywords and their combinations. The final selection of LCA studies for this review paper was based on the LCA and renewable energy contents of these LCA studies.

3.1. An overview of LCA studies

An Internet search from the common databases (Aalto-library, ProQuest, and ScienceDirect) was done in June 2015, using keywords, such as life cycle assessment, LCA, life cycle thinking, education, learning, teaching, pedagogy, energy, engineering, and their combinations. Statements such as AND, OR and LIMIT-TO were used to limit the search results and better match them with the intended goal of the literature review. The results of the Internet searches of the LCA studies are presented in Table 1.

The search results from these common databases produced an extensive number of studies. Going through the databases and studies therein, one by one, however, turned out to be problematic. Therefore, it was necessary to undertake more detailed and targeted searches for specific journals. The overall search results for LCA studies from the common databases, including the selected journals, are presented in Table 1. The selected LCA studies on renewable energy are presented in Table 2, and the selected LCA studies for education are presented in Table 3.

3.2. LCA studies in renewable energy

A literature review of the LCA studies on renewable energy was based on the LCA studies in the *Journal of Renewable and Sustainable Energy Reviews* (RSER). Two Internet searches were done in November of 2015 and August of 2016. The first search resulted in 32 LCA studies, a third of which represented the construction industry and building sector, using the keywords of review, life cycle assessment and renewable energy. The second search produced 411 studies, using the keywords of LCA and energy. The final selection of relevant LCA energy studies was done manually, focusing on the sustainability assessment of renewable energy and LCA for renewable energy sources, such as wind, solar, biomass, geothermal, and hydro. LCA energy studies on fossil fuels were omitted in this current study. The selected studies were used to identify experiences and recommendations for the use of LCA in research. Specially, these findings were aimed at guiding teaching in the use of LCA for assessing the sustainability of renewable energy systems.

Altogether, the manual selection resulted in 52 renewable energy studies to use to review the use of LCA in the field of renewable energy research. Finally, 24 studies in renewable energy focusing on LCA and sustainability were selected; the short descriptions of these studies are presented in Table 2. Additionally, 14 LCA studies were selected to represent bioenergy and biofuels, including different sources for bioethanol, biodiesel, and biogas [109–122]. Six (6) LCA studies for wind energy ([123–128], seven (7) LCA studies for solar photovoltaics (PV) systems [129–135], and one (1) LCA study for geothermal power generation [136] were selected in order to review the use of LCA in renewable energy production. The hydro power options were embedded in many of the selected LCA renewable energy studies [26,103,124,137–139]. These selected LCA renewable energy studies also included some comparisons between renewable and fossil fuels [138–144].

The following examples of the LCA renewable energy studies described the experiences when compiling LCA studies and identified deficiencies for further improvements. Arvesen et al. [124] critically reviewed the LCA studies on wind power, addressing the life cycle environmental impacts of wind power. They identified weaknesses and gaps in knowledge, assumptions and considerations of offshore operations for wind farms in ocean waters. They recommended the use of hybrid LCA methodologies and broadening the scope of environmental impacts in order to consider toxicity and mineral resource depletion in particular. Asdrubali et al. [137] reviewed the LCA results for solar energy, wind power, hydropower and geothermal power. They argued that the variability in LCA results limited the utility of LCA by policy- makers, thus hindering getting both information and a full awareness of sustainable energies. Therefore, they introduced a methodology to harmonise the published LCA data to get a more reliable comparison of the environmental consequences of the different energy technologies. For that comparison, they used a comprehensive set of environmental indicators and parameters. The harmonisation results showed that wind power had the lowest impact values and the narrowest ranges of variability.

Bayer et al. [136] presented an overview of potential life cycle environmental effects from geothermal power plants. Moreover, they defined an approximate universal case to represent an expected average geothermal power plant. They indicated that LCA studies on geothermal energy were

Table 1
Overview search results for LCA studies with keywords and statements.

Databases	Keywords (source)	Statements	Results
Aalto-library (353 databases)	Energy education AND life cycle assessment	AND	205419
ProQuest (all databases)	(Energy education AND learning OR teaching OR pedagogy) AND ("life cycle assessment" OR LCA) OR "life cycle thinking"	AND, OR	235
ProQuest (ERIC database)	(Energy education AND learning OR teaching OR pedagogy) AND ("life cycle assessment" OR LCA) OR "life cycle thinking"	AND, OR	28
ScienceDirect (all databases)	(Energy education OR learning OR teaching) AND ("life cycle assessment" OR LCA OR "life cycle thinking")	AND, OR	4685
ScienceDirect (all databases)	(Energy engineering education OR learning OR pedagogy OR teaching) AND ("life cycle assessment" OR LCA OR "life cycle thinking")	AND, OR	3124
ScienceDirect (all databases)	(Energy engineering education LCA "life cycle") AND ("life cycle assessment")	AND	926
ScienceDirect (all databases)	(Energy engineering education AND learning OR pedagogy OR teaching) AND ("life cycle assessment" OR LCA OR "life cycle thinking")	AND, OR	788
ScienceDirect (all databases)	(Energy education AND learning OR pedagogy OR teaching) AND ("life cycle assessment" OR LCA OR "life cycle thinking") AND LIMIT-TO(topics, "energy, life cycle")	AND, OR, LIMIT-TO	178
ScienceDirect (all databases)	(Energy education AND learning OR pedagogy OR teaching) AND ("life cycle assessment" OR LCA OR "life cycle thinking") AND LIMIT-TO(topics, "energy, life cycle") AND LIMIT-TO "Journal of Cleaner Production, Energy Policy, Renewable and Sustainable Energy Reviews, Biomass and Bioenergy, Energy Procedia, Applied Energy, Energy and Buildings, Energy for Sustainable Development, Energy, Sustainability and the Environment"	AND, OR, LIMIT-TO	45
Journal Renewable and Sustainable Energy Reviews (RSER)	LCA, energy ("life cycle assessment") AND review AND LIMIT-TO(cids, "271969","Renewable and Sustainable Energy Reviews") AND LIMIT-TO(contenttype, "JL, BS", "Journal") AND LIMIT-TO(topics, "life cycle").	AND, LIMIT-TO	411 32
International Journal of Life Cycle Assessment (Int. JLCA)	Education, teaching, life cycle assessment, student, energy (The International Journal of Life Cycle Assessment)		15
Journal of Engineering Education Research (JEER)	Education, teaching, life cycle assessment, student (Journal Environmental Education Research)		114
European Journal of Engineering Education (EJEE)	Education, teaching, life cycle assessment, student (European Journal of Engineering Education)		194
The Journal of Education for Sustainable Development (JESD)	Education, teaching, life cycle assessment, student (DESD special-Journal of Education for Sustainable Development)		20

Table 2
Selected examples of the LCA and sustainability studies for renewable energy from the *Journal of Renewable and Sustainable Energy Reviews*.

Authors	Research, LCA studies	Use of results
Asdrubali et al. [137]	100 different LCA case studies for solar energy, wind power, hydropower, and geothermal power.	To make comparisons and harmonisation of the LCA results.
Awan and Khan [165]	Renewable energy technologies and potential capacities in Pakistan.	To increase the share of renewable energy.
Buytaert et al. [82]	Biomass. Sustainability assessment tools, sustainability issues, tool attributes, model structure, area of application. A statistical analysis.	To report differences between sustainability tools. An integrated sustainability toolbox is needed.
Cambero and Sowlati [166]	Forest biomass supply chains.	To highlight the economic, social and environmental perspectives.
Choi et al. [167]	Environmental impacts of a product system using an energy-economic model with a life-cycle assessment.	To guide industry in energy policies.
Descateaux et al. [168]	Carbon taxes and environmental benefits, North-eastern American electricity market. Example: GHG emissions of a wind turbine.	A model to estimate market price and GHG emissions in two clean air policies.
Evans et al. [103]	Sustainability indicators. 50 LCA case studies for greenhouse gas emissions (PV, Wind, Hydro, Geo, Coal, and Gas).	To compare renewable energy technologies based on sustainability indicators.
Fthenakis and Kim [140]	Studies of water use in US electricity generation and full-life cycle accountings for conventional- and renewable-electrical power plants.	To conserve water supply by moving to technologies like photovoltaics and wind.
Hanff et al. [141]	Biofuel opportunities in technical, agronomic and land potentials in a Sahelian country, Burkina Faso.	To substitute fossil fuels with biofuels, diversification of energy resources.
Hong et al. [169]	Life cycle cost analysis and LCA of the renewable energy system in educational facilities.	To select the optimum new renewable energy system for educational facility.
Liu [104]	The methods of selection, quantification, evaluation and weighting of the basic and general sustainability indicators.	To guide the development of sustainability indicators for various renewable energy systems.
Liu et al. [170]	Different measurement methodologies and standards for carbon labels. Standards of LCA, PSA 2050, Greenhouse Gas Protocol, and ISO 14067.	To implement carbon labelling approaches.
Lähtinen et al. [171]	Indicator sets for sustainability of forest-based bioenergy production systems. Ecological, economic, social and cultural sustainability.	To enhance the local sustainability goals.
Mangoyana et al. [105]	Systems thinking, indicator selection processes, life cycle of biofuels.	To establish holistically the sustainability of biofuel systems by the integration of social, economic and environmental issues.
Markevičius et al. [146]	Different initiatives and sustainability criteria for biofuels. Total 35 criteria for assessing sustainability, 12 environmental issues, 4 social and 1 economic (low food security).	Sustainability criteria for biofuels. Conflicts between various ecosystem services (economic production of food, fodder and fuels, biodiversity, social and cultural values).
Marvuglia et al. [145]	Many methodological studies with specific focus on bioenergy. Life cycle inventory (LCI) and consequential life cycle inventory (C-LCI).	Approaches for C-LCI, socio-economic mechanisms, economic modelling.

(continued on next page)

Table 2 *(continued)*

Authors	Research, LCA studies	Use of results
Milazzo et al. [147]	30 life-cycle analyses (USA, Brazil, Argentina, PR China), soy biodiesel production. Ecological and socio-economic consequences of large-scale renewable energy action plans for soy biodiesel.	To mitigate the use of resources and the potential environmental and social consequences.
Ozturk and Yuksel [142]	Environmental pollution, energy consumption, conventional and renewable energy technologies, renewable energy potential (Turkey).	To be used in assessment of green energy systems by researchers, engineers, decision and policy makers in industry and government. Sustainable development and solution.
Pant et al. [172]	LCA, wastewater treatment plants, organic waste fraction, energy, savings.	To propose a methodology for LCA of the bio electrochemical systems (BESs) converting organic waste fraction into useful energy such as electricity or hydrogen.
Pietrapertosa et al. [143]	Environmental damages, externalities of local and global air pollutants (NO_x, SO_2, VOC, particulates and GHGs). A national case study with the NEEDS-TIMES Italy model.	To focus on the changes in energy fuel mix, in local air pollutants and GHG emissions in terms of policy strategies. Different scenarios, strategic environmental targets.
Radovanović et al. [144]	28 European Union countries 1990–2012. Environmental and social aspects.	To define a new Energy Security Index with the long-term sustainability.
Turconi et al. [138]	167 LCA case studies of electricity generation (hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, solar photovoltaic (PV) and wind). Ranges of emission data for GHG, NO_x and SO_2 related to individual technologies.	To demonstrate the variability of existing LCA results for electricity generation. Environmental consequences of new technologies for decision making purposes.
Varun et al. [139]	10 LCA wind energy studies (1981–2005). 9 LCA solar PV studies, (1992–2006). 3 LCA solar thermal studies (1990–2006). 5 LCA biomass studies (1999–2005). 3 LCA hydro power studies (1996–1997).	To explore the LCA studies. To compare carbon emissions of renewable and conventional energy sources for choosing energy supply systems.
Varun et al. [173]	Sustainability indicators: electricity from renewable technologies (literature data).	To propose a new figure of merit linking GHGs, energy pay-back time and cost of electricity from renewable energy sources.

scarce, life cycle fugitive emissions were highly variable, and the collected data was still incomplete. For example, estimates for carbon dioxide, methane, and critical substances, such as mercury, arsenic and boron, were found. As a result of this review, they expressed the need for more transparent reporting and more assessment of local and regional environmental consequences so as to better demonstrate the sustainability of geothermal power as a renewable energy source. Evans et al. [103] reviewed renewable energy technologies against each sustainability indicator. They used indicators, such as price of generated electricity, full life cycle greenhouse gas emissions, availability of renewable sources, and efficiency in energy conversion, land requirements, water consumption and social impacts. For example, they proposed that the inclusion of social impacts would be necessary in order to identify and quantify the human risks and consequences for the acceptance and understanding of renewable energy technologies. Their findings showed that there was a wide range of differences for each technology. According to their ranking results, wind power was the most sustainable, followed by hydropower, photovoltaic, and s geothermal.

The bioenergy review by Marvuglia et al. [145] showed that LCA studies generated different outcomes due to real-world differences, data uncertainties and methodological choices. They pointed out that LCA had limitations for assessing complex systems, such as acro-systems. Hence, they recommended that consequential life cycle inventories (C-LCI) should be used to integrate socio-economic considerations and economic models. Due to the differences between LCA and the consequential life cycle assessments (C-LCA), they claimed that C-LCA´s context supports better decision-making because it takes into account the changes from possible future actions. Varun et al. [139] reviewed the LCA studies to compare energy and CO2 emissions of electricity generation systems based on renewable and conventional energy sources. These findings showed

Table 3
The selected LCA studies in education.

References	Target group, Discipline, Country.	Applications of LCA	Teaching and learning methods	Conclusions
Juntunen and Aksela [155]	Teachers, Chemistry, From elementary to high school, Finland.	LCA and IBL (inquiry-based learning), Environmental literacy, Sustainability, Socio-scientific issues.	Project-based, Student-centered, Inquiry concept, Problem solving.	Teaching concepts of LCA-IBL, Scientific literacy and sustainability competence, Combine social and personal teaching strategies.
Balan and Manickam [154]	Students, Course, Chemical engineering, Malaysia.	LCA assignment, Sustainable energy, Sustainable business, Sustainability principles (recycling, cleaner production and triple bottom line).	Multi-disciplinary, Research-based project, Individual and group work. Classroom activities.	Design of the LCA assignment, Holistic education, Sustainability principles in practice, Active learning and motivation.
Meo et al. [159]	Students, Course, Geography, USA.	LCA software, LCA case study, Overall environmental quality.	Projects, Lectures, Discussions, Hands-on activities, Individual work, Group work.	Understanding of LCA, Cradle to cradle thinking, Career options, Arouse interest in the new degree program.
Harding [151]	Students, Course, Manufacturing engineering, USA	LCA approach (streamlined LCA), SLCA tool, LCA for DfE, LCA analysis.	Project, Hands-on activities, Team-based learning, Team work, Problem solving.	Motivation, Role of engineer in preserving the environment, Learning from lectures, Awareness of non-technical issues.
Crossin et al. [156]	Students, Course, Civil, environmental and chemical engineering, Australia.	LCA, LCA-software tool, LCA learning outcomes	Lectures, Group activities, Computer-based tutorials, Minor project, Major project.	Positive feedback, Overall satisfaction, Good teaching scale results, Limited access to LCA software, High workload, Scientific methodology, LCA skills, LCA knowledge, Teaching practices.
Masanet et al. [162]	Students, Massive open online course (MOOC) on LCA, Any discipline, USA, China.	LCA, Introduction of LCA, A complete LCA model.	Lecture videos, Weekly homework Assignments, In-video quizzes, Project, Hands-on application, Interactions with instructors, Online discussion forums.	Motivation to online LCA courses, Basic analytical skills, The next generations of LCA analysts, Scientific development, Best practice teaching methods and materials.
Weber et al. [157]	Students, Sustainable development module, Engineering, USA.	LCA study, LCA game, LCA of everyday products, Environmental sustainability issues, LCA methodology, Components of products.	Lectures, Hands-on activities, Guest lecturers, Participatory exercises, One overall project, Presentation, Online activities, Working in teams.	Students' awareness and understanding of environmental issues, Changed misconceptions of environmental sustainability, Skills of engineers, First step in the curriculum reformation.
Vallero and Braiser [158]	Students, Two courses, Engineering, USA.	LCA of biofuel, LCA software, Current policy issues, Societal and geopolitical aspects.	Lectures, Discussions, Studio projects, Problem solving, Teamwork, Group presentations.	Interactive pedagogies, Effective in green engineering and sustainable design, Application of specific lessons to open-ended problems.
Olsen [160]	Students, Courses, Different technological domains, Denmark.	LCA and tool, LCM and tool, Sustainability assessment.	Theory lectures, Problem oriented, Case projects, Project learning, Individual assignments, Team work, Project reports.	Understanding of the engineer's role, Responsibility in a sustainable society, Barriers in terms of organisational, academic and engineering culture.

that the conventional energy sources had high life cycle carbon emissions. They pointed out that the carbon emissions from renewable energy systems are not zero, as is assumed for carbon credits. The results favored renewable energy technologies, particularly small hydro plants without the storage of water. As a conclusion, they proposed that mixed technologies would provide an optimal composition of electricity sources and reduce the environmental impacts and ensure electricity distribution.

Buytaert et al. [82] indicated that there is need for a comprehensive and reliable sustainability assessment tool to evaluate the environmental, social, and economic performances of biomass in energy production. Markevičius et al. [146] claimed that the use of biomass does not automatically imply that its production, conversion, and use are sustainable. In order to avoid conflicts between various ecosystem services, they proposed developing a balance between the economic production of food, fodder and fuels, biodiversity, and social and cultural values. Their findings on the different initiatives and sustainability criteria for biofuels indicated that energy balance and greenhouse gas balance were perceived as especially critical, the ranking of social criteria was generally low, and the ranking of food security was very low. Milazzo et al. [147] highlighted their finding that sustainability is more than just greenhouse gas savings. They identified the major sustainability concerns were associated with specific resource use and the potential environmental and social consequences of soy biodiesel. They analysed and compared the existing sustainability tools and explored the opportunities for mitigating these concerns. They also indicated there were significant differences between the sustainability tools.

Turconi et al. [138] reviewed 167 LCA case studies of electricity generation based on fossil and non-fossil fuels to demonstrate the variability of existing LCA results. Their findings aimed to guide decision-makers in avoiding conflicting decisions regarding the environmental consequences of implementing new technologies. Their findings showed that GHG emissions could not be used as a single indicator to represent the environmental performance of a system or technology. In their review paper, they identified and reported on the most critical methodological aspects as they related LCA studies.

Additionally, two other LCA renewable energy studies outside of the RSER journal are selected and presented here to support the general findings of the LCA studies for renewable energy. Matthews et al. [148] reviewed the literature on biogenic carbon and life cycle assessment of forest bioenergy. They indicated that LCA is an appropriate methodology for the assessment of GHG emissions of the forest bioenergy system. Their review included both attributional (also called conventional) LCAs and consequential C-LCAs, resulting in a large range of possible scenarios for forest bioenergy. They also estimated the forest bioenergy sources to achieve the reduction goal of the overall GHG emissions by 2050. Their findings showed that the LCA results varied considerably due to different goals, scopes, and research questions. For example, the GHG emissions of forest bioenergy were sensitive to the scenarios for land use. They proposed that the consequential LCA (C-LCA) would be better than the attributional LCA for assessing the impacts of the GHG emissions if there were changes in the use of forest bioenergy. Alsema et al. [149] reviewed energy pay-back times and life cycle environmental impacts of different PV (Photovoltaics) electricity technologies. They made comparisons of GHG emissions with energy supply options. Their findings showed that PV technology held a good position in a portfolio of low-carbon energy

technologies for a future sustainable energy supply. However, further LCA studies of thin film technology are still needed to contribute to greater transparency and gather more information to improve the options for PV technologies.

Findings of the LCA review studies on renewable energy showed that a large number of LCA studies were available (see Table 2). Moreover, the LCA results had a wide range of differences for each technology due to different goals, scopes, and research study questions. The LCA studies revealed weaknesses and gaps in the knowledge, data, assumptions, and considerations. The findings indicated that LCA had limitations when assessing complex systems, such as acro-systems. In order to take into account the changes from possible future actions, the use of the consequential life cycle assessment (C-LCA) was recommended so as to integrate socio-economic considerations and economic models' supporting decision-making and policy purposes. The results favored renewable energy technologies. However, further LCA studies are necessary to contribute to greater transparency and get more information on the sustainability of renewable energy options. Many of the selected studies (see Table 2) reviewed the existing tools and indicators to assess the sustainability of renewable energy. A significant amount of information was detected as being available on biofuels and their sustainability. Due to incomplete and inconsistent data, as well as tools, these studies call for new integrated and comprehensive life cycle-based approaches and tools to assess all the dimensions of sustainability of renewable energy systems.

3.3. LCA studies in education

A literature review of the LCA studies in education included journals, such as the *International Journal of Life Cycle Assessment*, the *Journal on Environmental Education Research*, the *European Journal of Engineering Education* and the *Journal of Education for Sustainable Development*. An Internet search was done in June of 2015 using the keywords, education, teaching, life cycle assessment, student and energy. The Internet search resulted in a large number of journal articles (see Table 1). However, there was a scarcity of studies that focused on the use of LCA in education. Therefore, a separate Google search was done to map more LCA studies in education using the Internet. Besides direct LCA courses, LCA and SD also appeared in the courses focusing on, for example, sustainable engineering, green design techniques, sustainable material science, environmental sustainability, and sustainable building [150–153]. After a thorough investigation of the LCA studies, nine (9) different LCA studies from a variety of sources were manually selected as examples of the use of LCA for teaching students (see Table 3). Most of the selected studies came from the US, but others were from Australia, Malaysia, Denmark, and Finland. The findings showed that the selected LCA studies focused on education in different engineering disciplines, including chemical, manufacturing, civil, and environmental engineering.

Selected LCA studies implemented LCA at the course level. LCA assignments, practical activities, and related teaching concepts were well planned and documented to achieve the planned educational goals in scientific literacy and sustainability competence [154,155]. For example, LCA activities were aimed at increasing students´ awareness and understanding of environmental and social issues, professional skills in problem-solving and teamwork and soft skills in communication [151,155–157]. LCA projects were used to solve problems in product development and guide current policy issues [158]. Additionally, a feedback survey at the beginning and at the end of the LCA course was carried out to detect changes in students´ threshold concepts and any of their misconceptions surrounding sustainability [157].

Meaningful and effective assignments made chemical engineering students more interested in sustainable development when applying LCA and industrial ecology [154]. LCA was identified as an integral part of green engineering that provided information for engineering decision-making on societal issues, such as energy sources and environmental quality [158]. Meo et al. [159] claimed that the use of LCA helped students clarify attractive career options. For example, the use of LCA in education improved student appreciation of the role of an engineer in preserving the environment and taking responsibility for a sustainable society [151,157,160]. Moreover, the LCA course prepared students for the LCA community and for more advanced LCA courses that would educate them to be new LCA analysts for future needs [161]. However, there was a need for further LCA studies in education so as to enable scientific development and the sharing of best practices for effective teaching approaches, methods, and materials [155,161]. Juntunen and Aksela [155] proposed that more research was needed to investigate what kind of learning outcomes best promote students' scientific literacy and advance moral awareness to empower students to act more responsibly. Moreover, Masanet et al. [161,162] pointed out that any LCA education would benefit from LCA content development for learning outcomes.

The findings of LCA studies on education showed that the use of LCA enabled students to create new knowledge, learn critical thinking, and solve problems (see Table 3). Students used LCA tools, LCA software, LCA assignments, case studies, and projects. LCA projects, combined with Social Life Cycle Assessment (SLCA) and Design for Environment (DfE), involved real-life problems and hands-on activities to work individually or in groups. In spite of the high workload and limited access to LCA software, LCA teaching and learning methods did activate and motivate students to achieve professional knowledge and skills in practice. Problem-oriented projects helped students understand the role and responsibility of engineers in a sustainable society.

4. Discussion

This review revealed that the LCA studies were not reported in the research-teaching nexus in energy education. In order to find greater understanding for how LCA could be useful in renewable and sustainable energy education, this review explored two kinds of LCA studies, namely, 1) LCA studies in renewable energy and 2) LCA studies in education. These studies are discussed in terms of LCA-based sustainability assessment and the use of LCA in research-based teaching in order to produce recommendations on how to enhance the integration of LCA, research, and sustainability in renewable and sustainable energy education. In spite of the difficulties in using LCA in education, the findings of this literature review indicated that there is an increasing need for future LCA experts. Therefore, LCA is indeed a relevant topic for research-based teaching.

The reviewed LCA studies in renewable energy offered examples of how LCA was used for assessing the environmental sustainability of renewable energy sources. Many studies called for better integration of the economic and social dimensions into comprehensive sustainability of renewable energy systems. In the scientific field, LCA has been actively used to compile the environmental impacts of energy systems, and the use of LCA has been broadened to address integrated sustainability assessment (LCSA). In research-based teaching, these LCA study examples allow students to experience the real-life problems and practice the sustainability assessment of the renewable energy systems in their own LCA projects. In addition to LCA books, the case studies were experienced as an important learning material for students for obtaining knowledge from research [163,164].

The LCA studies in renewable energy revealed relevant research items that are useful for students to use to practice LCA, such as using their knowledge of renewable energy technologies, building whole chains of energy systems, acquiring LCA data from the field and the databases, and interpreting the results calculated by LCA software. Therefore, teachers should use the current research in renewable and sustainable energy to

identify the problems present in real-life cases. On the other hand, LCA and LCSA seem to be demanding tools to use for teaching and learning. Therefore, teachers should be further encouraged and trained to use LCA-based sustainability tools in energy education. Moreover, teachers should carefully plan their LCA projects and estimate the reasonable amount of work their students need to do. In addition, teachers should ensure that students have the necessary access to LCA software and the required databases in order to facilitate the most efficient working environment for these LCA projects.

The LCA studies in education underscore the role of learning outcomes in curriculum planning that can ensure that the knowledge and skills of LCA are taken into full account then teaching these courses. More field research is still needed to define the relevant learning outcomes for LCA and how it changes teachers´ willingness to use LCA and related sustainability methods in their courses. However, the use of LCA as a research-based and sustainability teaching method depends on the teachers´ choices and decisions for how they apply different teaching and learning methods, the current research, and their available teaching resources. The training of teachers in the knowledge and skills of LCA and sustainability is thus crucial to achieve the necessary competences to guide and teach students in the use of LCA projects that is based on LCA research in renewable and sustainable energy education.

5. Conclusion

This paper sought synthesize the use of LCA for sustainable and renewable energy education by reviewing LCA as a research tool for assessing the sustainability of renewable energy systems. An extensive review of LCA studies applicable to renewable and sustainable energy revealed that LCA is widely used in energy research for assessing environmental sustainability and compiling sustainability indicators of the renewable energy systems. A thorough selection of the LCA studies in education revealed that there has been an intention to use LCA in chemical, manufacturing and environmental engineering. In these studies, LCA was perceived as motivating students to understand the comprehensive sustainability of the systems when they were doing problem-based projects in the classroom. LCA strengthened the integration of the research-based teaching in the courses where it was applied. However, a diverse review of the LCA studies indicated that there are sparse LCA studies on energy education. Therefore, more published studies are need to share the various LCA experiences between teachers and motivate teachers to use LCA in energy education.

In particular, the variability of the existing LCA studies on renewable energy should be efficiently noted and utilised in research-based teaching and classroom learning. These studies produced unsolved research issues in the sustainability assessment of renewable energy systems. For example, the sustainability assessments of the different bioenergy systems would be useful cases for students to use to learn from real-life research problems. In the research-teaching nexus, students would learn a systematic way for acquiring knowledge from the existing LCA research studies to use to conduct their own LCA energy research studies. Moreover, students would learn to work as a member of a group/team and gain valuable experience from project management. Above all, LCA and these student projects would bring research and teaching together to implement stronger co-operation between university and industry, as the process improved the desired quality of teaching at universities.

In conclusion, LCA should be integrated into the learning outcomes of energy degree programmes to ensure that their teachers are committed to using LCA and LCA-based sustainability assessment tools in their energy courses. However, more research is still needed to increase and strengthen the use of LCA in energy education via exploring students' working life skills and their LCA expertise after graduation from an employer's point of view. The demands for greater student' employability competences in LCA and sustainability knowledge will provide a justified foundation for teachers to make the needed changes for the best learning outcomes in renewable and sustainable energy education and thus more student-focused learning regarding the use of LCA-based practices in a research-based curriculum and its instruction.

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Publication III

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Selected emissions and efficiencies of energy systems based on logging and sawmill residues

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Selected emissions and efficiencies of energy systems based on logging and sawmill residues

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Abstract

Bioenergy has an important role in the implementation of the Kyoto agreement in Finland. The main sources of wood residues for energy production are logging areas and sawmills. The use of forest chips can be of great significance in reducing carbon dioxide emissions by replacing fossil fuels. Increasing the use of forest chips has environmental benefits, but it also includes possible environmental disadvantages. Therefore, system research is needed to assess the forest chip utilisation prospects for their environmental quality to secure sustainable forest management. Life-cycle methodology was developed and applied to assess environmental burdens and impacts of the logging and sawmill residues throughout the whole fuel chain from the forest to energy production. According to the study, the energy efficiencies of the forest chip systems are quite high. Net CO_2 emissions of the systems are low owing to the low input of external primary energy required to operate the systems. Although wood energy is renewable, it has many similarities with fossil fuels, e.g. as the emissions of the conversion phase are significant.

Keywords: Life cycle assessment; Greenhouse gases; Environmental emissions; Environmental impacts; Logging residues; Sawmill residues; Bioenergy

1. Introduction

Bioenergy can be of great significance in reducing carbon dioxide emissions by replacing fossil fuels. According to the Kyoto protocol, the EUs commitment is to reduce greenhouse gas emissions by 8% from the level of 1990. The EUs burden-sharing agreement allows Finland to keep emissions at the 1990 level (77.1 Mt CO_2 eq.) over the commitment period of 2008–2012. The carbon dioxide emissions of the Finnish energy sector were 54 million tonnes in 1990. In 2001 carbon dioxide emissions exceeded by about 11% the emissions in 1990, according to the Preliminary Energy Statistics 2001 of Statistics Finland [1]. The total electricity consumption was 81.6 TWh, which is 1.3% more than the year before [1].

Many proposed changes to reduce emissions have already been taken into use in Finland, which limits its possibilities in the energy sector. Use of the co-generation of heat and power and biofuels is more extensive in Finland than in any other country [2]. However, the potential to increase the utilisation of bioenergy is great. The National Action Plan for Renewable Energy Sources has set a 30% target value for biomass use in 2025 [3], which means a 10% increase in biomass use in primary energy consumption.

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The target of the National Action Plan for Renewable Energy Sources is to increase the annual use of forest chips to 5 million m^3, corresponding to about 10 TWh by 2010. The use of forest chips amounted to 0.93 million m^3 solid in 2000, according to the statistics of the Finnish Forest Research Institute. The total annual potential of forest residues from logging is estimated to be about 29 million m^3 solid, but the annually recoverable amount of forest residues from that total potential is estimated to be about 8.6 million m^3 solid [4]. In Finland, the promising bioenergy potentials lie in forest chips. This is largely applicable to large power plants, which use forest chips in co-combustion together with bark, sawdust, peat, recycled waste and fossil fuels.

1.1. Goal and scope of the study

The goal of the study was to produce relevant life-cycle-based information on the environmental burdens and impacts of the use of forest chips in energy production to facilitate decision-making and communication on the environmental arguments between the interested parties.

The targets were to model four relevant forest chip and two sawmill residue energy systems, to identify and quantify the emissions of the burning of forest chips and sawmill residues by means of emission measurements in a typical power plant, and to compile a systematic and transparent data set of key environmental arguments, i.e. greenhouse gas emissions, acidic emissions and energy efficiencies, for the studied systems.

1.2. System boundaries and the functional unit

The main phases of the forest chip production take place in Finland. The main functional unit of the study is 1 MWh of total useful energy produced. An overview of the forest and sawmill chip systems is given in Fig. 1. The life cycle begins in the forest, and proceeds to the power plant where the chemical potential of the wood biomass is converted to useful energy. In addition to the processes of the main cycle of the chips, the overall life-cycle system includes the transportation of the machines between logging lots, and the sub-system for the fuels used by the machines and the transport vehicles. Manufacturing of the machines and facilities is not included in the system.

Many important issues needed to be excluded from the agenda of the study, such as the processes and the time span of the forestry, nutrient economy of the forests including the various options of nutrient generation, recycling and compensating fertilisation, soil emissions, carbon cycle, radiative forcing, and biodiversity. Moreover, the manufacturing chains and the life-time questions of the machinery, health impacts of particulate matter and heavy metal emissions, impacts of the oil releases, and the physical effects of machines on the forest ecosystems were not addressed in the study.

2. Material and methods

Life cycle assessment (LCA) methodology [5] was applied to assess the environmental burdens and impacts of the logging and sawmill residues throughout the whole fuel chain from forestry to energy production. Environmental aspects of the sawmill residue chains and the terrain and the roadside chipping chains for logging residues, including both the fresh and the dry chipping options, were analysed considering a variety of air emissions from the logging, chipping and transportation machinery [6]. Data for conversion were acquired with emission measurements and the material balance calculations made for a typical wood energy plant [7]. The forest residue calculations are based on Norway spruce stands with 200 m^3/h solid stem wood yield, with 390 kg/m^3 stem wood density and with 155 kg/m^3 logging residue to stem wood ratio [8]. The recovery rate for logging residues was 70% [9]. The emissions of forest machinery and road transport are calculated using models and data developed in VTT [10,11].

3. Results

The results of the forest and sawmill residue systems are presented in the following tables. They include selected emissions, energy efficiency indicators and produced energy amounts in different functional units. The energy efficiency indicators of the systems are presented only for the off-road and

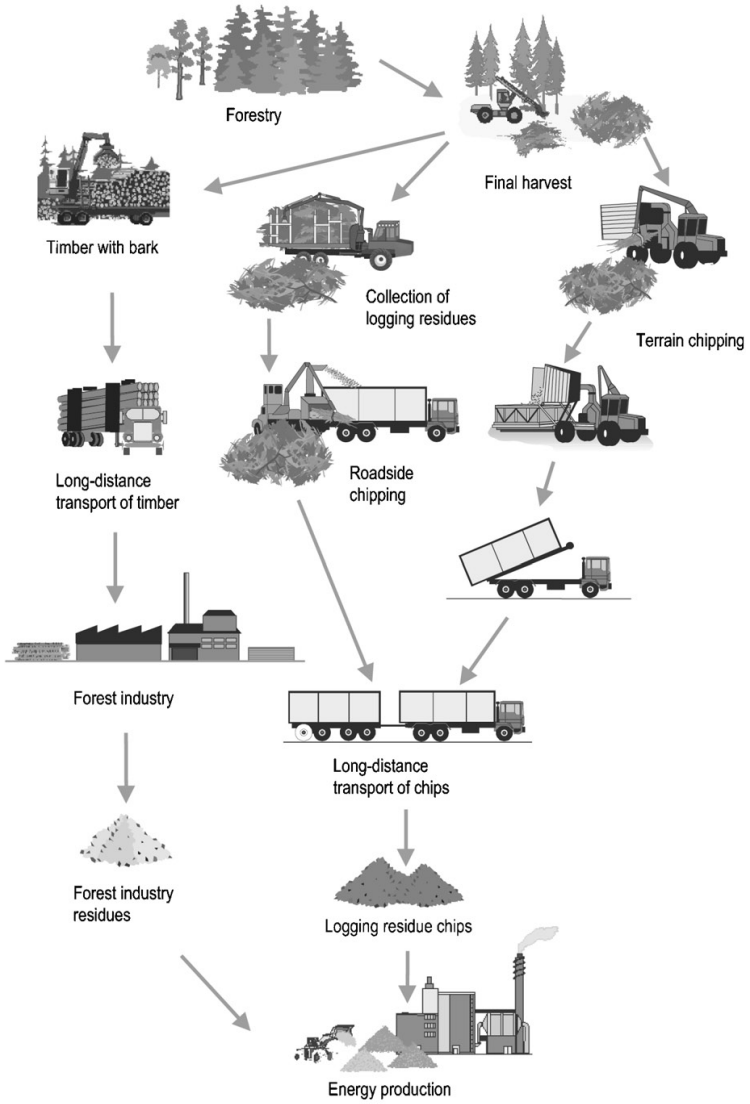

Fig. 1. An overview of the system model for the energy utilisation of forest and sawmill chips.

Table 1
The gross unit factors calculated per 1 MWh of useful energy produced are presented for the greenhouse gas emissions, acidic emissions, particulate matter emissions, and oil releases to the ground. The gross CO_2 emissions include the emissions of the combustion phase. The CO_2 emissions of the combustion phase are assessed to be zero in the calculations of the net CO_2 emissions

Type of emission	Off-road, brown kg/MWh	Roadside, brown kg/MWh	Off-road, green kg/MWh	Roadside, green kg/MWh	Small sawmills kg/MWh	Big (industrial) sawmills kg/MWh
Greenhouse gases	540	541	534	535	556	493
N_2O	0.002	0.003	0.002	0.003	0.002	0.001
CH_4	0	0	0	0	0	0
CO_2 (gross)	540	541	534	535	556	493
CO_2 (net)	7.728	9.191	6.951	7.874	10.727	6.659
Acidic emissions	0.526	0.559	0.653	0.674	0.374	0.385
NO_x	0.510	0.541	0.617	0.637	0.340	0.365
SO_2	0.016	0.018	0.036	0.037	0.033	0.020
Particulate matter	0.020	0.022	0.028	0.028	0.018	0.030
Oil releases	0.025	0.022	0.021	0.017	0.035	0.024

roadside chipping chains, because the sawmill residue chains include allocation problems in sawmill processes, mostly owing to insufficient data.

3.1. Emissions and environmental impacts

Unit emission figures (per 1 MWh of useful energy produced) for the studied forest chip and sawmill residue systems were calculated for carbon dioxide, nitrogen oxide, sulphur dioxide, and particulate emissions as well as oil releases of the forest machinery to the ground. These results are presented in Table 1.

Note that the gross value of CO_2 in Table 1 means that the fixation back to the tree biomass has not been taken into account.

The results show that the off-road chipping chain is a more favourable chain than the roadside chipping chain from the emission point of view. The results of sawmill chains show that the big sawmill chain is more favourable in greenhouse gases than the small sawmill chain.

3.2. Contributions of the unit processes to the unit emissions

Contributions of the unit processes to the unit emissions for the studied forest chip systems are shown in Table 2. Most (98%) of the gross carbon dioxide emissions come from the energy production phase. The sulphur dioxide emissions come mostly from the energy production and the forest machines. The share of machine emissions is bigger for the brown logging residue chain than for the green logging residue chain. The nitrogen oxides come mostly from the energy production. The oil releases to the ground come from the harvester, chipper and forwarder. The gross carbon dioxide emissions of the chains, excluding combustion, come mostly from the chipper.

3.3. Indicators of energy efficiency for forest chip systems

The energy efficiencies of the studied forest chip systems are presented in Table 3. The produced energy, relative to the effective total heat value of the input dry matter varies between 34% and 50%. The losses take place in the collection phase and in the power plant, and during the drying period of the brown residues.

Table 3 also shows the proportions of the external primary energy input to the useful energy produced. The external primary energy input comprises mainly fuels used by the forest machinery and transport vehicles. This indicator varies from 2.8% to 3.7% of the total useful energy produced.

3.4. Amounts of produced energy from the systems

Table 4 indicates the useful energy amounts produced for five size-scales of forest and sawmill residue

Table 2
The breakdowns of the gross unit emissions are presented by the phases of the forest chip system (brown chips)

Phases of the forest chip system	CO_2 (%)	SO_2 (%)	NO_x (%)	TSP (%)	CO (%)	Oil, release (%)
Harvesting of timber and logging residues	0.1	3.0	1.6	3.4	1.7	31.0
Transportation of harvester to the logging lot	0.005	0.002	0.07	0.03	0.01	0
Chipping of logging residues	0.8	30.3	15.5	31.9	30.5	69.0
Transportation of chipper to the chipping site	0.1	0.0	1.6	0.6	0.2	0
Transportation of chips to the power plant	0.5	0.2	7.3	5.1	2.5	0
Energy production at power plant	98.4	58.4	73.5	58.1	64.8	0
Sub-system for machine and vehicle fuels	0.1	8.1	0.6	0.9	0.4	0
Total	100	100	100	100	100	100

Table 3
The indicators of energy efficiency for roadside and off-road forest chip systems

Energy efficiency indicators	Brown logging residue		Green logging residue	
	Off-road chipping	Roadside chipping	Off-road chipping	Roadside chipping
The proportion of the external primary energy used in the logging residue chain to the produced energy (%)	3.1	3.7	2.8	3.2
The proportion of the produced energy to the effective heat value (dry) of the logging residues before losses (%)	33.8	33.8	50.4	50.4

Table 4
The amounts of useful energy produced (MWh/TWh), calculated according to the harvested area, annually recoverable amounts of logging residues in Finland and yearly produced amounts of sawmill residues in Finland

Produced useful energy[a]	1 ha (MWh)	5.6 million m^3 solid (TWh)	8.6 million m^3 solid (TWh)	1.5 million m^3 solid (TWh)	3 million m^3 solid (TWh)
Logging residues, brown	58	10			
Logging residues, green	86		15		
Small sawmills[b]	158			2	
Industry sawmills[c]	47				6

[a]Assumed harvesting method and species: final felling, spruce.
[b]All residues to energy production: sawdust, sawmill chips and bark.
[c]Only bark to energy production.

energy systems. The calculated energy amounts also show the differences and potentials of forest and sawmill residues in producing bioenergy. The results can be used, e.g. in further estimations of total energy and greenhouse gases on a national level.

The energy output figures for forest chips are calculated for three functional units: (1) one hectare with yield of 31 000 kg residue dry mass; (2) for 5.6 million m^3 solid brown forest residues, and (3) for 8.6 million m^3 solid green forest residues. The two latter values represent the amounts of forest residues estimated as annually recoverable from the logging sites in Finland. This includes all species of wood harvested, of which the share of spruce is about 68%. Because of simplification, the spruce share per hectare in the calculations of this study is assumed to be 100%.

The results of useful energy produced per hectare of brown forest chips are 58 and 86 MWh for green forest chips. The energy yield of brown logging residues is less than for green logging residues, because needles drop during the drying period. For the annual recoverable logging residue potentials, the calculations give a produced useful energy amount of 10 TWh/year when the residues are recovered brown, and 15 TWh/year when the residues are recovered green.

The green logging residues are collected fresh from the logging lot and transported without storing to the power plant. Fresh chips include the needles. The brown logging residues include storing and during the storage period they dry and lose most of their needles before chipping.

Table 4 shows the energy outputs of sawmill residues calculated for three functional units: (1) residues for one hectare with 200 m^3 solid stem wood yield; (2) for 1.5 million m^3 solid small sawmill residues, and (3) for 3 million m^3 solid big industrial sawmill residues. Small-sawmill residues are not recycled back to the forest industry and thus they include all residues (resulting in 55% residues from solid stem yield) as sawdust, sawmill chips and barks directed for energy production. Big sawmills are normally in the neighbourhood of pulp and paper mills and the most part of the sawmill residues are recycled back to forest industry; only bark is available and left for energy production.

The results of useful energy produced per hectare are 158 MWh for residues from small sawmills, and 47 MWh for residues from industrial sawmills. All residues from small sawmills normally go to energy production, which is why the produced energy per hectare is higher than for industrial sawmills, where only bark goes for energy production. Industrial sawmills handle bigger volumes of timber. Thus, the annual energy amount produced is larger (6 TWh/year) than that of small sawmills (2 TWh/year).

4. Discussion

The study provided a good database for the life cycle assessments of wood-based energy. Four different systems for logging residues and two systems for sawmill residues were studied. According to the study the energy efficiencies of the forest chip systems are quite high. The input of external primary energy required to operate the systems is very low. It follows that also net CO_2 emissions are low (7–9 kg/MWh). The results of other logging residue studies are not directly comparable to this study, because the system boundaries and allocation principles are different. The net CO_2 emissions according to a Finnish study [12] are between 5.6 and 7.8 kg/MWh and according to a Swedish study [13] they are 17 kg/MWh calculated for the domestic case.

The proportion of the external primary energy used in the logging residue chain is between 3% and 4%. The proportion of the produced energy to the effective heat value of the logging residues before losses is 34% for brown and 50% for green logging residue chain. The green systems seem to be better for energy efficiency and emissions from the forest machinery and transportation. According to Forsberg [13] 6–11% non-renewable energy is regarded for delivery of one MWh (electricity) of renewable energy.

The results of the logging residue systems are reported widely, because the data were more accurate than in the sawmill residue systems. The uncertainties in the sawmill processes concerned mostly the allocation problems. However, the emissions and amounts of the useful energy produced in different functional units are reported as a basis for discussions. The sawmill residues do not directly facilitate the increase of bioenergy, because the residues are today already almost totally utilised in industry. The amounts depend on the demand of timber. The logging residue potentials are dependent on timber, too.

The impacts of wood energy are site-specific and diverse. Although wood energy is renewable, it has many similarities with fossil fuels. The emissions of the conversion phase are significant. When wood energy replaces fossil energy, it mitigates the global climate change provided that the re-growth of wood is not disturbed. A combined production of heat and power increases the positive effect. However, utilisation of forest residues raises questions about the effects of the nutrient loss on the growth of trees and vegetation. Ash recycling returns the mineral nutrients to the soil, but not nitrogen, which is released with air emissions during combustion. Nitrogen losses can be compensated for by fertilisation, but also ash

recycling for fertilisation could be a relevant option for forest management.

Finland and Sweden are pioneers in the field of forest residues. The great interest in utilisation of forest residues began in the beginning of the 90s and accelerated in the late 90s. Feasibility increased owing to the reduced production costs. The forest and transportation machinery has been developed and logistics has been improved. Conversion has been adapted to be suitable to burn forest residues. The logging residues are at the moment almost an unutilised resource. The Kyoto protocol underlines the reduction of greenhouse gases, which helps to promote renewable energy sources. The national energy taxation together with the coming CO_2 trading favours bioenergy. A good environmental image is important. Altogether, these factors have resulted in a lot of technological, economic and environmental research worldwide.

Among other ecological studies, studies dealing with timber, transportation and forestry are valuable in supplementing the research of logging residues. However, utilising logging residues has its special characteristics. Moreover, the management of complex systems also raises new needs to improve knowledge and data, and to develop compatible research methods in order to plan sustainable systems as well as to combine industrial ecology aspects.

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Educational initiatives

Curriculum planning in energy engineering education

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ABSTRACT

Curriculum is a key factor in defining programme outcomes. It typically consists of modules and courses, which should be linked together to produce the desired learning outcomes for students. This work aims to explore the practical and theoretical principles of curriculum-centred strategic planning and to inspect how curriculum planning and its implementation are visible in the corresponding teaching structures and student experiences. The research approach used in this paper includes a student survey, teacher interviews and core content analysis. The paper demonstrates that when addressing only a cluster of courses, a relatively simplified approach provides sufficient information for identifying existing strengths and good practices that can be built upon as well as key areas that need further improvement. In addition, the key observations and best practices can also be utilised within any engineering education context.

1. Introduction

Curriculum is a key factor in university teaching. It reflects the university's rules and course content and it defines programme outcomes. Curriculum reform offers an opportunity to make desired changes to the degree programmes. A successful curriculum planning process seems to take time and cooperation between many stakeholders both inside and outside of the university (Gunnarsson, S., 2010; Desha and Hargroves, 2010; Sng, 2008). Many authors have called attention to the need for better interaction between universities and those involved in working life in order to provide industry-relevant competencies (Jackson, 2010; Tynjälä et al., 2003). In connection with successful curriculum planning, a university needs to simultaneously follow its mission and strategy, pass programme quality accreditations, meet the needs of interested parties, be consistent with respect to the outcomes and objectives of its programmes, and, in the European Union (EU), harmonise its education so that it conforms to the Bologna Process directives (Dolence, 2004; Hakula et al., 2013; Sursock and Smidt, 2010).

This paper discusses course-level curriculum planning at Aalto University's Department of Energy Technology. It focuses on a Master's level energy programme that includes five major subjects. In particular, it focuses on the Urban Energy Systems and Energy Economics (UESEE) module and the four courses comprising it. The authors have three primary goals: to identify the coherence of curriculum planning at the module level, to identify applied teaching methods and to increase student-centred learning practices within the module. Their overall goal is to identify best practices and compile recommendations for strategic planning and teaching in the energy engineering degree programme. These best practices and recommendations can be utilised within any engineering education context.

The research methods employed to achieve this goal are as follows: a student survey, semi-structured teacher interviews and core content analysis (Lindblom Ylanne and Hamalainen, 2004). These methods are employed to obtain an in-depth understanding of the pedagogical approaches applied in the teaching and evaluation of the courses that are a part of the module. Afterwards, the paper will discuss the curriculum planning process and best practices based on these results. To limit the scope of this paper, the authors have not included any interviews with representatives of working life. The findings presented in this paper are based on earlier, preparatory work done by the authors (Mälkki and Paatero, 2012, 2013). However, this paper is based on a broader set of data and presents more thorough observations and findings.

2. Background

Many researchers have focused on the strong connection between curricula development and learning outcomes (Batterman

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et al., 2011; Biggs and Tang, 2007; Wong and Cheung, 2009). Curriculum typically consists of modules and courses that are linked together to produce the desired outcomes. When moving towards larger wholes, Dolence (2003, 2004) uses the term 'strategic planning' to refer to the overall design process for curriculum, where each part of the plan is expected to be part of a larger whole that lasts for a longer period of time and includes all of the teaching done as part of the module. He proposes that the planning of teaching and research agendas should reflect new developments in existing fields and emerging areas of inquiry, with closer links between related or complementary fields. He believes that this would entail a more open approach to staff management, evaluation and funding criteria, teaching, curricula and research.

Exploring the issue further, Biggs (1996) has pointed out that the process of enhancing teaching includes teaching and learning activities that achieve the curriculum objectives for the whole system. Adding to this, Levander and Mikkola (2009) have introduced the idea that curriculum consists of interconnected courses along the learning path; as such, curriculum should include educational goals, educational content, working methods and learning outcomes. Furthermore, Edström et al. (2010) have suggested that learning outcomes are the foundation for curriculum planning. The planning process begins by reflecting on the pre-existing learning environment and then identifying the desired changes and outcomes. In a similar manner, strategic curriculum planning reflects national accreditation standards, university rules and programme traditions.

Biggs (2003) argues that a 'constructive alignment' approach is needed to combine all components of the teaching system so that they are properly aligned with one another. He lists curriculum and its intended outcomes, teaching methods and assessment tasks as parts of the teaching system that need to be aligned with learning activities. Segalàs et al. (2010) experimentally verified that students' learning outcomes could be enhanced by community-oriented and constructive learning approaches. Such learning activities could support high-level learning (Mälkki and Paatero, 2012); likewise, Litzinger et al. (2011) believe that effective learning experiences could be better integrated within the systematic curriculum design process. For example, including problem-solving activities, such as problem-based learning (PBL), in the course content could develop learners' understanding of the subject matter and real-life situations (Loyens and Gijbels, 2008; Mälkki et al., 2012; Tynjälä et al., 2003). Additionally, Lansu et al. (2013) have highlighted the need to rethink engineering education as a means of including the professional demands of stakeholders and academic quality standards in the process of curriculum planning.

The ways in which constructivist learning environments and knowledge building promote learning have also been discussed by Loyens and Gijbels (2008). Students' formal and informal skills are formed during their studies when they are attending courses that are a part of the programme. Hence, individual courses play an important role in building knowledge and working life-related competencies.

Levander and Mikkola (2009) have proposed the idea of using core curriculum analysis as a conceptual tool for analysing, describing, sharing and making the degree programmes understandable at the level of individual courses as well as at the level of the whole programme. Aalto University has been developing a computer-aided core curriculum analysis tool to help curriculum planning efforts (Auvinen, 2011). This tool will help teachers determine the learning outcomes for their courses and cooperate with other teachers in the programme.

In addition to core curriculum analysis, student feedback has been utilised when developing curriculum at Aalto University. Since late 2009, it has been mandatory for teachers to collect feedback; the process is automated, whereby students are asked to provide feedback using the same software platform they use for their individual curriculum plans. Mainly quantitative feedback data are collected using standardised or for the most part standardised forms at the end of each course. The forms also have a field for general remarks and opinions, resulting in qualitative feedback data. Richardson (2005) has explored the questionnaires used in North American, Australian and British studies, and he noticed that there is a clear need to collect more student feedback that can be used as research evidence about teaching, learning and assessment. The research-based results provided by such feedback can be used to improve teaching quality, but he warns that it is unlikely that simply collecting the feedback will lead to significant improvements.

The Bologna Process added external pressure to the need for European universities to use learning outcomes as a basis for establishing national qualification frameworks and arrangements for recognising prior learning (Reinalda, 2008; Rauhvargers et al., 2009). The outcomes and educational objectives of a particular programme are also stressed in the EUR-ACE accreditation process. The accreditation process includes the requirements specified in national legislation and by the university-level management system (EUR-ACE, 2008).

The degree reforms prompted by the Bologna Process began in 2005 and resulted in Finnish technical universities adopting a two-level educational system consisting of both a Bachelor's degree and a Master's degree. As a result, energy engineering was divided into two separate and independent parts: namely, the Bachelor's degree and Master's degree programmes. In addition, students now need to complete the Bachelor's level degree before beginning Master's level studies. The first wave of changes in the degree was implemented immediately after the Bologna reform; however, the reforms included mainly reorganising courses and only a limited number of revisions to courses or actual re-planning of courses. The current, more fundamental change includes a full re-evaluation of all of the teaching and course contents. This has implied a need for strategic curriculum planning for both Bachelor's level and Master's degree programmes. The ongoing curriculum reform of the Bachelor's and Master's degree programmes affects the status and role of every course in all of the programmes at Aalto University. Major changes are being made to previously existing courses and curriculum structures. Some of the courses will be discontinued and their content introduced to other, more comprehensive courses. For this reason, it is important to clarify the status and content of the energy courses before the new Master's level degree programme in energy engineering enters into force. To effectively improve the curriculum, it will be necessary to provide a comprehensive analysis of the courses being taught when aligning the existing courses and planning the new reformed curriculum (Eskandari et al., 2007).

In 2012, Aalto University's Master's degree programme in energy engineering (120 ECTS) included 3–4 teaching modules (20 ECTS each), with each module consisting of 3–7 courses. In addition, the programme included 40–60 ECTS of other coursework, including a Master's thesis (30 ECTS). The programme has a total of five specialisation options (major subjects), including Urban Energy Systems and Energy Economics (UESEE).

3. Research methods

To understand and document the current teaching and course planning practices that are a part of Aalto University's energy engineering education, it was important to focus on a module that serves a large number of energy engineering students. In addition, when the curriculum reform of the Bachelor's and Master's degree

programmes was at its initial stages, the Master's level modules were the most relevant area for pedagogical inquiry. For the Master's degree programme in energy engineering, Urban Energy Systems and Energy Economics (UESEE) is the most popular subject. In addition, the first Master's level module that the students specialising in UESEE take carries the same name as the major (Urban Energy Systems and Energy Economics, see Table 1).

The UESEE teaching module aims to provide students with a basic understanding of the types of energy technologies applied in an urban environment and of the urban energy infrastructure and urban planning and the ways in which they are connected to urban energy planning, energy investments, energy markets, district heating engineering and energy system models that are optimised at different levels. To analyse the content and teaching in the cluster of courses forming the UESEE module, an approach using three different methods and angles was utilised. The three selected methods consisted of a student survey, teacher interviews and core content analysis; the methods correspondingly shed light on student-centred, teacher-centred and curriculum planning views on the matter.

These methods yielded qualitative and quantitative information and also provided an in-depth understanding of the teaching and learning practices that are a part of this module. The student survey provided quantitative data on learning issues before students attend the courses, while the interviews provided qualitative information on the fundamentals of curriculum planning. The core content analysis yielded information on how the teachers rate the learning outcomes and workloads for the courses. This information established the general context for both the survey and interviews.

The core curriculum analysis for the UESEE courses was done using pre-existing curriculum planning documents from the summer of 2012. Many of these documents had been prepared for the 2009 re-audit of Aalto University (then Helsinki University of Technology) conducted by the Finnish Higher Education Evaluation Council (Karppanen et al., 2010) and the 2010–2011 Aalto University Teaching and Education Evaluation process (Levander and Koivisto, 2011). Also, part of this material has been produced using a computer-aided tool developed by Auvinen (2011). Although most of these documents were prepared with a 'core curriculum analysis' mind set, their quality and level of detail varied significantly between the different UESEE courses. In particular, there were major differences in the level of detail with respect to the learning goals.

The aim of the student survey was to obtain a representative sample of the students who are taking the UESEE module. Thus, the sample was collected from two simultaneously ongoing courses at the beginning of autumn 2012. In this way, the sample included a large part of the overall student population and the individual surveys had only a minimal effect on the student population during the survey period. Some students were taking both of the courses where the surveys were conducted and they were requested to answer the survey only once.

To obtain a high participation rate, the surveys were conducted at the beginning of the first lectures for the courses, where more than 90% of the students taking the courses that year were present. All (100%) of the students at the two lectures responded to the survey, resulting in 88 respondents, which comprises a good representative sample.

After establishing student profiles, the survey asked students about their perceptions of the specific knowledge and working-life competences pertaining to their personal UESEE module before the course began. The students were first asked to evaluate a select set of their current working-life competences and then to reveal their expectations about improving the competences while completing the module. In addition, students were asked about their preferred teaching methods and expectations about learning information specific to the UESEE module. Students were asked to rate their knowledge and competence levels using a four-point scale: 1 = 'nothing', 2 = 'basic level', 3 = 'intermediate level' and 4 = 'expert level'. A comprehensive list of the competencies and knowledge used in the questionnaire is provided in Table 2.

The interviews were designed to provide in-depth qualitative data about the course planning and implementation process that are part of the UESEE module. The courses in the module were managed by three teachers, while only two of them were available for interviews. However, one of the interviewed teachers was the person responsible for developing the courses in the UESEE module.

The interviews were conducted in the summer of 2012 and they focused on the courses currently being taught. They were conducted in a semi-structured format, using an indicative list of 13 main themes and questions to support the interviewer. The teachers were interviewed separately and asked about several aspects of the course and curriculum planning practices in the module, including goal setting, sharing of responsibility, levels of collaboration, use of feedback and documentation. Due to the small number of interviews, no formal method was applied in the analysis of the material. Instead, conclusions were made through reflective discussions by the authors.

Table 1
Urban Energy Systems and Energy Economics (UESEE) teaching module.

Minor in energy systems for communities and energy economics, module I (20 cr)	ECTS course points
Models and optimisation of energy systems	5
District heating engineering	5
Energy markets	5
Energy systems for communities	5

Table 2
List of working-life competencies and knowledge specific to the UESEE module used in the student questionnaire.

No	Competence	Knowledge
01	Basic natural sciences and mathematics	Conventional energy technologies
02	Analytical skills	Renewable energy technologies
03	Problem-solving skills	Modelling of energy systems
04	Critical thinking	District heating systems
05	Applying theoretical knowledge in practice	Cost accounting and investment analysis
06	Latest research knowledge	Economics
07	Creativity	Global energy markets (like oil, coal, natural gas)
08	Basics skills in entrepreneurship	Nordic electricity market
09	Project management	Energy policy
10	Leadership skills	Energy and greenhouse gases
11	Group work	Energy and sustainability
12	Social skills	Energy and urban planning
13	Dealing with international environments	Innovations in energy technology
14	Information retrieval skills	
15	Presentation, speaking and negotiation skills	
16	Skills with your best foreign language	
17	Writing skills	
18	Life-long learning skills	
19	Self-knowledge	
20	Ethical awareness	
21	Environmental awareness	
22	Sustainability awareness	
23	Life-cycle assessment skills	

4. Results

The core content analysis of the UESEE courses provided the background and context for the applied student survey and teacher interviews. It revealed the ways in which the content being taught were interconnected and thus highlighted whether or not the principles of curriculum planning were present in the content being taught. Partly due to the broad scope of the courses, the four courses are mainly independent and only connected to one another in a parallel manner. The courses do not build on one another; instead, they all focus on their own areas of energy engineering, which are not directly connected to the other courses within the module. The only exception is the course 'Models and Optimization of Energy Systems', where prior knowledge from the 'Energy Markets' course is required. Thus, there is only a limited possibility to build on the knowledge and experiences that students have acquired from the other courses within the module. The analysis also revealed that the learning goals of the courses were mainly defined in the form of core engineering skills, mathematical skills and analytical skills. There was very limited content and few goals concerning informal skills, such as teamwork and presentation skills. Overall, the analysis showed that while the teaching of engineering skills, mathematical skills and analytical skills was clearly planned for in the curriculum, most of the skills connected to 'professional identity' (e.g. leadership, presentation skills, social skills) were overlooked in the curriculum planning and alignment process.

The interviews with the teachers provided information about how the staff in general perceive of and implement the education services they provide. In practice, the results deal with the planning of courses and with applied teaching and evaluation methods. The interviews were also crucial for inspecting how curriculum planning and its implementation are manifested in the UESEE courses.

The interviews revealed that the content of the UESEE courses has been selected based on both the teaching needs specified in the module and curriculum and the interests of the responsible staff. At times, the choices have also been influenced by the already existing support materials for the course. Overall, we discovered that course planning has been influenced by curriculum-level teaching needs. However, the curriculum-level objectives have not been specified in detail and much freedom has been left to the teachers in terms of designing the contents of the courses and determining how the courses should be taught. In addition, the teaching and evaluation methods applied to the courses consisted mainly of traditional university teaching methods, such as lecturing, examinations, take-home assignments and exercise sessions. Innovative or novel teaching approaches were occasionally tested, but not in any kind of systematic manner.

The interviews also revealed that the planning process applied to individual courses has not been very systematic and that joint planning between teachers has only occurred on a rather random and inconsistent basis. Course feedback was collected systematically through the study planning software platform and also through direct contacts, typically initiated by the students. However, the use of course feedback was very much up to the teacher and there was no systematised manner for dealing with it. There was no other consistent source of feedback on the teaching content.

The results of the student survey provided a deeper understanding of how the students as participants perceive of themselves and the education they are receiving. Their professional identity and expertise can be viewed in terms of how the curriculum is planned and implemented. Their opinions thus provide a 'customer' viewpoint on the teaching process and its content. The results of the survey show that students have clearly distinguishable and consistent opinions about both the methods and the content of the education they are receiving. Thus, their voices should be considered when course content and applied teaching methods are being developed.

The background of the participating students was mixed: 63% of them were in Finnish degree programmes, 60% were completing a Master's degree and 63% were studying full time. The rest were mostly enrolled in Bachelor's degree programmes and English degree programmes and worked 25% of the time. However, they do represent a typical set of students taking the UESEE courses.

In the questionnaire, the students were asked to identify their own level of competencies (see Table 2). The results are presented in Fig. 1, which also includes the mean values for each category calculated based on the applied four-point scale. Based on the mean values, the students expressed the highest degree of competence in 'basic natural sciences and mathematics', 'critical thinking', 'social skills' and 'skills with your best foreign language', followed closely by 'group work', 'problem-solving skills' and 'writing skills'. They expressed the lowest degree of competence by far in 'latest research knowledge' and 'basics skills in entrepreneurship'. Some other low-hitting skills included 'project management', 'life-cycle assessment skills' and 'leadership skills'. Of the two highest ranked skills, more than 70% of the students identified their skill level as being at the intermediate or expert level. Correspondingly, with respect to the two lowest ranking skills, more than 67% of the students identified their skill level as non-existent or basic.

When asked what competences the students expect to acquire or would like to improve through attending the UESEE courses, almost 58% of them mentioned 'environmental awareness' and 'sustainability awareness', as seen in Fig. 2. The next most popular topics in ascending order were 'applying theoretical knowledge in practice', 'critical thinking', 'latest research knowledge' and 'life-cycle assessment skills'. The skills receiving the lowest level of interest and expectations were 'self-knowledge', 'basic natural sciences and mathematics', 'writing skills', 'leadership skills', life-long learning skills' and 'social skills'. While most of the low-interest skills mentioned by students were at the high end in terms of how they evaluated their own skills, 'critical thinking' received a high level of interest even though students also rated it as one of the skills they were already most competent in. In addition, students had low 'leadership skills' but also relatively little interest in improving such skills.

In their preferences for course teaching and evaluation methods, presented in Fig. 3, the students showed a strong correlation (0.77) between their earlier experiences with the methods and how much they wanted the same methods to be used in the future. The methods widely applied during the earlier part of their studies (lecturing, exercises) received a significant level of support (>64% want it to be used), while unfamiliar and little-used approaches (like reading circles and keeping lecture diaries) received low approval ratings (<12%). Clear exceptions were field trips, which students expressed a great deal of interest in (59%), even if only 38% had ever been on one. In addition, commonly used exams (68%) and take-home assignments (53%) were not particularly popular with students (with 40% and 41% of students wanting them to be used, respectively). While essay writing is also commonly used in courses (35%), the students expressed a strong level of disapproval for it as a teaching method: only 13% wanted it to be used as a teaching method.

Concerning the level of knowledge that students would like to be exposed to in the UESEE courses, the results (see Fig. 4) show a clear spread. Clearly, 'renewable energy technologies' was the most popular knowledge category, with 86% of the students saying that they want this topic to be taught at an 'advanced' or 'expert' level. Following close behind, 73–75% of students reported that they want 'innovations in energy technology' and 'global energy

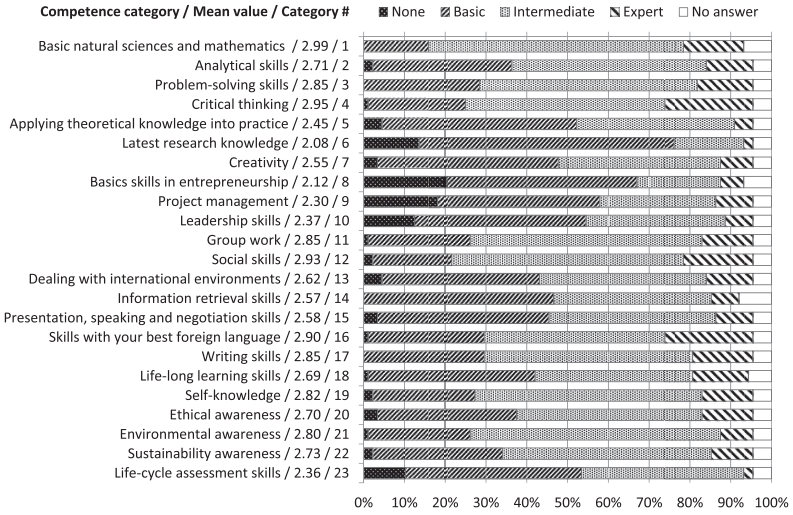

Fig. 1. Student estimates of their own level of competencies before the UESEE courses.

markets' to be taught at more of an advanced level. Correspondingly, they expressed the least amount of interest in the categories 'district heating systems', 'economics' and 'energy and greenhouse gases', with 40–42% of the students wanting to be exposed to either 'none' or only a 'basic' level of knowledge on these topics.

Overall, the core content analysis, teacher interviews and student surveys revealed both good practices and clear needs for improvement in connection with the UESEE module. Also, according to the Aalto Sustainability Report 2013 there are clear needs to intensify teaching and research on global warming, energy conservation and clean energy, and the sustainable use of natural resources (Aalto University, 2013). On this basis, the next section discusses a selection of the best practices.

5. Discussion and recommendations

Teaching should be managed and developed in accordance with the university's strategy, which aims to create high-quality learning

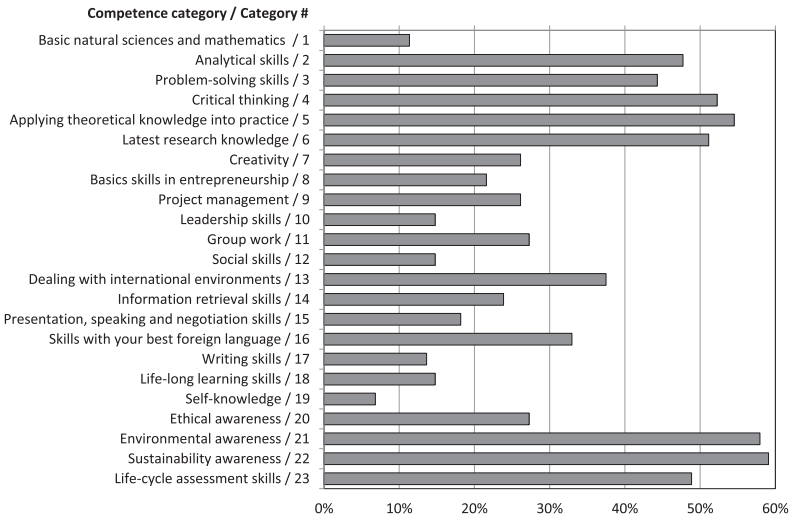

Fig. 2. Percentage of students expecting to acquire or wanting to improve the listed competences through attending the UESEE courses.

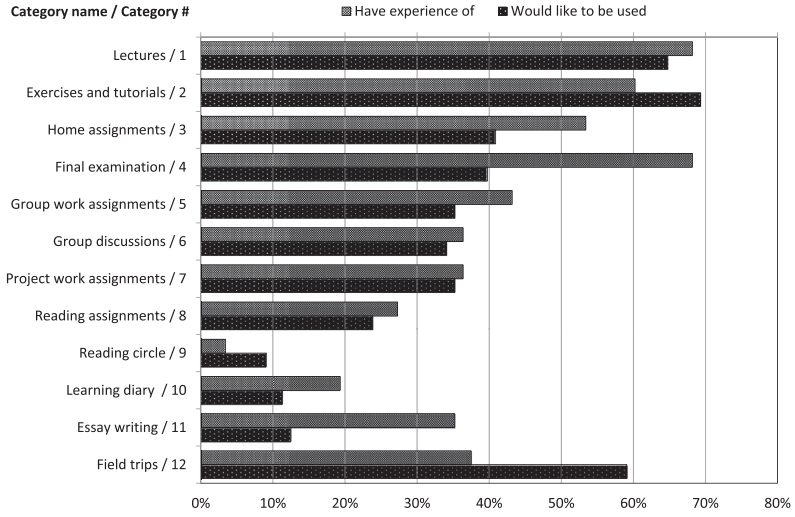

Fig. 3. Percentage of teaching and evaluation methods that students have had earlier experience with and would like to see used in the UESEE courses.

environments that meet the needs of society and the workplace. Although the entire degree programme will be subject to a planning process when developing curriculum, the practical actions should take place at the module and course level. Strategic efforts are needed to combine the objectives of the university and those for the entire programme, while at the same time systematically improving existing courses or planning new courses, taking into account the needs of stakeholders and ensuring that students acquire the skills they will need for their future careers. Much prior research suggests that this will be a challenging task (Eskandari et al., 2007; Lozano and Lozano, 2014).

One approach to manage teaching with close connection to the strategy of the university is to utilise strategic curriculum planning (Dolence, 2004), which should involve the overall alignment of teaching and learning practices throughout the entire degree programme. However, special attention should be paid to specifying learning outcomes, which are the fundamental elements of core content analysis and curriculum planning (Edström et al., 2010).

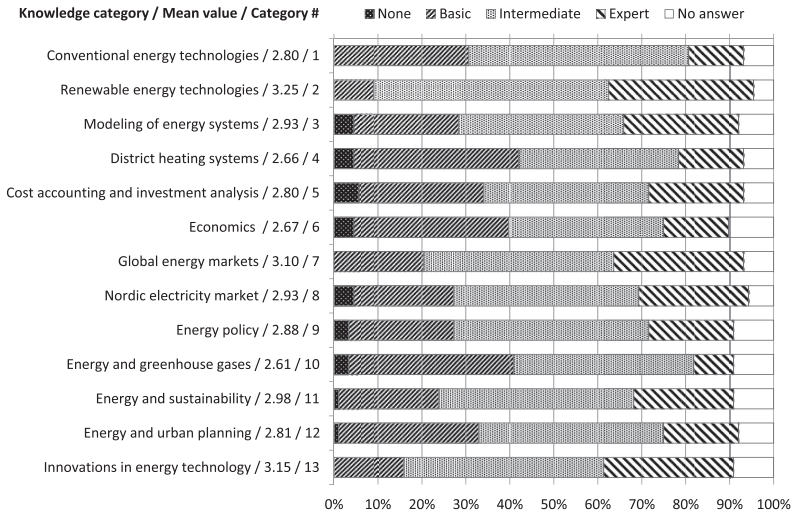

Fig. 4. Student preferences about the level of knowledge that they want to be exposed to in the UESEE module.

This approach could also be quite successful at Aalto University, since at least the Department Energy Technology staff already has experience with core content analysis (Auvinen, 2011; Levander and Koivisto, 2011). Thus the authors strongly recommend the use of strategic curriculum planning at Aalto University or any university where emphasis is wanted for overall alignment of teaching.

To construct student-centred learning environments, teachers should use teaching methods that are suited to the subject being taught and support different types of learners so as to ensure the participation of more students (Biggs and Tang, 2007; Segalàs et al., 2010). The contents of the course and the teaching processes should respond to the changes needed in working life, society and science (Gunnarsson, S., 2010; Tynjälä et al., 2006). As a research-oriented university, Aalto University has a solid foundation in providing up-to-date, research-based educational content. This in-house expertise is quite attractive to students and could be utilised more widely. In addition, the ways in which the course content is connected to the changing needs of society and working life is left very much up to individual teachers. Thus, systematic and university-wide practices should be developed and implemented to also ensure up-to-date teaching in this area. As an example, Tynjälä et al. (2003) have suggested utilising organisational or critical dialogue to bring higher education closer to the needs of working life. The authors recommend introducing this or similar practice to Aalto University or any university where better connection to practitioners is sought after.

Aalto University, including the Department of Energy Technology, has a widespread practice of collecting student feedback, but it still depends very much on the teacher how this information is utilised. This information should be systematically utilised to revise educational processes, as student feedback provides valuable evidence about the quality of the educational activities in question (Richardson, 2005). As an example, the feedback could be discussed by an expert group after each course and the resulting observations could then be reported to the responsible manager and teacher of the course. The feedback information could also be complemented with surveys and discussions focused on current needs in terms of the regional development of working life (Jackson, 2010; Lansu et al., 2013). Overall, the authors strongly recommend Aalto University to introduce a body, where student feedback will be systematically processed and utilised for curriculum development. Any university that lacks such body should consider its introduction as well.

Close collaboration within the university (e.g. by administrators, teachers, managers) is needed during every part of the curriculum planning process (Desha and Hargroves, 2010; Sng, 2008). This also applies to aligning the courses that are a part of the modules and the modules as a part of the degree programmes. Aalto University's Department of Energy Technology has previously allowed for the joint planning of courses and modules, but this has not been done in a systematic and consistent manner. However, there are clear signs that a more systematic approach to joint planning has been adopted in the ongoing reform of Bachelor's and Master's degree programmes. In addition, several members of the Department of Energy staff have taken part in the pedagogical education provided by Aalto University's Strategic Support for Research and Education (e.g. Hakula et al., 2013), where key skills for systematic curriculum and course planning can be learned. All of this shows the quite positive direction in which collaborative planning is headed, one that will result in well-aligned degree programmes. Thus the authors recommend that curriculum planning at Aalto University continues to build on such collaboration. However, special attention should be paid to introducing novel teaching methods, like problem-based learning, early on in the degree programmes so that the more conservative students will have time to adapt to these new methods.

Overall, special emphasis should be placed on the interest of students in environmental and sustainability issues. Even if there are specific programmes for these topics, energy engineering students still have a genuine interest in learning more about these themes. However, Lozano (2010) has pointed out that the successful integration of sustainability content also requires introducing balanced, synergistic, trans-disciplinary and holistic perspectives into the course content. It is thus recommended that such content, together with environmental and sustainability content, should be supplemented by the core content of the courses. This point should also be closely supported by the professional development of the staff of the Department of Energy Engineering. Barth and Rieckmann (2012) found that a staff development programme can result in more sustainability content being added to the curriculum. As a related teaching method, researchers recommend that student projects should include problem-based learning since such learning supports the integration of sustainability topics into the curriculum (Bacon et al., 2011). For a broader integration of sustainability issues, Ceulemans and De Prins (2010) recommend using a teacher's manual to motivate and guide teachers in integrating sustainable development-related content within the curricula. The authors recommend Aalto University to adopt the use of such manual to ensure the integration of sustainability related contents to its curriculum. Similar practices are recommended for any university seeking to introduce sustainability content throughout its curriculum.

6. Conclusions

High-level university education should be based on a well-planned curriculum produced by the collaborative efforts of key stakeholders. One approach to curriculum reform is to use strategic curriculum planning, as discussed by Dolence (2003, 2004), one that takes into account the perspective of the larger whole and always considers the courses and modules as a part of whole degree programme. In addition, aligning the curriculum is a central component of strategic curriculum planning, one which begins with identifying the learning outcomes at the level of the degree programme, such as key working-life competences and knowledge related to the degree programme.

At Aalto University, the major reforms being implemented for degree programmes offered a natural basis for examining the existing practices and updating the learning outcomes. The interviews with the teachers about planning and teaching practices at Aalto University's Department of Energy Technology showed that the staff already has experience with some of the key practices of strategic curriculum planning. However, stronger emphasis is needed on maintaining an active connection to the needs of working life and promoting planning collaboration between teachers, at least at the Department of Energy Technology. One approach would be a department-wide adaptation of the organisational or critical dialogue, as suggested by Tynjälä et al. (2003), together with systematic and regular use of working groups consisting of members of the teaching staff and representatives of working life.

The results of the student survey indicate that special attention should also be given to their natural interests and tendencies. At the Department of Energy Technology, this includes, for example, taking into account student interest in applying theoretical knowledge in practice and acquiring up-to-date energy expertise and learning about sustainability issues. In addition, the students tended to reject teaching methods that they have limited experience with. Thus, any changes in teaching and learning practices need to be

systematically planned and the use of alternative teaching approaches should proceed on a step-by-step basis within the curriculum. Hence, further studies could focus on the causes and background factors affecting the students' preferences. Analysis of these results could improve curriculum planning and the way in which the desired educational changes are implemented within the courses and the entire degree programme.

Overall, the paper demonstrated that through core content analysis, interviews and student surveys, a good understanding can be achieved about how to plan and implement new curriculum at the module level. Through this approach, we obtained enough information to identify existing strengths and good practices that can be built upon as well as key areas that need further improvement. In addition, the key observations and best practices can also be utilised within any engineering education context.

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Publication V

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A method to quantify the integration of renewable energy and sustainability in energy degree programmes: a Finnish case study

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Educational initiatives

A method to quantify the integration of renewable energy and sustainability in energy degree programmes: a Finnish case study

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ABSTRACT

The key factors affecting the sustainability of our society are research, conversion, delivery and the efficient use of energy resources. The expertise, attitudes and sustainability awareness of decision-makers determine far-reaching political decisions made regarding whole energy systems as well as the choices available for individual consumers. Despite the significance of education with respect to renewable energy and sustainability, the position of these topics remains unclear in degree programmes. Measuring the relevance of these subjects can be considered a central issue in terms of promoting a more sustainability-oriented perspective on education strategy formation. Therefore, this paper presents a new curriculum development method for stimulating discussions about the learning outcomes of the degree programmes. This method has been used to calculate a proposed relevance ratio (RR) index, which indicated the relative weight of renewable energy and sustainability topics for energy studies in Aalto University's energy degree programme. The benefits of this RR index include the ability to reveal the strengths and weaknesses of selected contents in the curricula. However, more research is needed to integrate wider working life skills with the students' learning path as a means of promoting student expertise. This new tool will be universally applicable and quantify the desired contents of learning outcomes in degree programmes at universities.

1. Introduction

World energy consumption is increasing in non-OECD countries by 90 percent between 2010 and 2040 due to the use of fossil fuels (IEO, 2013). Biofuel and food production compete with each other on the use of land area and threaten biodiversity at the global level (EC, 2006; EC, 2010; Uslu et al., 2010). In Europe, the use of energy from renewable sources is promoted by European Union (EU) energy policies (Beurskens and Hekkenberg, 2011; EU, 2009; Ruska and Kiviluoma, 2011). From these perspectives on energy issues, sustainability is a crucial component in educating engineers in energy conservation, improved technology, and increased use of energy sources with low emissions, and in building a foundation for sustainable consumption patterns for the world's growing population.

Many recent studies have identified the need for sustainability in curriculum and in higher education institutions (Adomβent et al., 2014; Hancock and Nuttman, 2014; Lozano and Lozano, 2014; Wals, 2014). The role of education for sustainability has been increased and perceived as a catalyst for innovation in education since the establishment of the United Nations Decade for Education for Sustainable Development (DESD) 2005–2014 (Nolan, 2012). Nolan (2012) has concluded that the challenge of sustainable development needs to be accompanied by changes in attitudes, values and lifestyles, and the strengthening of people's capacities to bring about change. Although these new challenges are recognised in sustainability education, there remain ongoing challenges in integrating sustainability and renewable energy into energy education (Acikgoz, 2011; Kandpal and Garg, 1999; Karabulut et al., 2011). Engineers need training to use renewable energy technologies (IRENA, 2011) and to be aware of the principles of sustainability (Littledyke et al., 2013; Lozano, 2010; Müller-Christ et al., 2014).

A diverse nature of sustainability does not only mean increasing the share of renewable energy or improving energy efficiency; economic, ecological and social dimensions also need to be addressed in education (Byrne et al., 2013; Svanström et al., 2008).

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Here, tools, good ways and systems' models are essential for assessing desired competencies for sustainability in curricula (Lozano and Lozano, 2014; Rorarius, 2007; Zamagni et al., 2009). Yarime and Tanaka (2012) have mapped sixteen sustainability assessment tools for higher education institutions. They stated that more work is needed to analyse the content of courses, to develop methodologies and to encourage efforts towards sustainability. The role of sustainability in its broader sense is still not clear in degree programmes and teaching about renewable energy and sustainability takes place at an 'encyclopaedic level' (Bojic, 2004; Karabulut et al., 2011). It seems that there is still a need for systematic methods to measure the extent to which degree programmes deal with renewable energy and sustainability.

The aim of a degree programme is to enable continuous learning and ensure that the prerequisites of the courses strengthen overall learning outcomes (Levander and Mikkola, 2009). Gradually, each course supplements and builds students' comprehensive competencies. This type of cumulative learning procedure is referred to as constructivist learning theory, which is based on understanding, knowledge, experience and reflection (Tynjälä, 1999). In comparison, Segalàs et al. (2013) have divided these competencies into three dimensions: 1) knowledge and understanding, 2) skills and abilities, and 3) attitudes. These competence dimensions have also been referred to as formal, informal and non-formal skills (Malcolm et al., 2003; MacVaugh and Norton, 2011). The aim of this paper is not to address the whole competence phenomenon. Instead, we focus on knowledge, and understanding and the formal contents of learning outcomes. We later use the term contents to refer to these viewpoints.

Students need appropriate teaching methods that embed theory, practice and self-reflection as well as the social environment to better develop their expertise (Barnett and Coate, 2005; Tynjälä, 2008). Eskandari et al. (2007) have identified a crucial need to revise curricula due to changes in the types of engineering roles and responsibilities within the field. Integrating both expertise and education is a multi-step, iterative and continuous process involving several stakeholders (Davidson et al., 2010; EHEA, 2012; Klen and Hoffman, 1992). Planning the content of curricula requires the commitment of the university community to collaborate with working life (Mälkki and Paatero, 2013; Barth and Rieckmann, 2012; Hirsto and Löytönen, 2011). For example, the results of regular surveys of students who have recently graduated offer a good basis for planning and developing working life competencies in engineering curricula (TEK, 2012b; Korhonen-Yrjänheikki, 2011; Oivallus, 2011).

According to a FinnSight 2015 report (2006), expertise in renewable energy and sustainability involves many elements, e.g. knowledge of ecosystems, criteria for the biomass, environmental management of the product systems, efficient use of energy and new technologies. This expertise is built on a solid basis of fundamental physics, field knowledge and practical skills. Expertise will be imparted in practical learning environments and through learning by doing, working on multi- and interdisciplinary teams and using problem-solving approaches (Crawley et al., 2007; Peltonen et al., 2013; Tynjälä et al., 2006). Fig. 1 shows the composition of a sample engineer's expertise, which is modified from a study by Mälkki et al. (2012).

Universities have a particular challenge when it comes to embedding sustainability-related knowledge and skills within courses and curricula (Desha and Hardgroves, 2010), and teachers need support and interdisciplinary co-operation in this endeavour (Allenby et al., 2007; Byrne et al., 2013; Davidson et al., 2010; Ferrer-Balas et al., 2008). Collaboration between teachers, academic staff and various stakeholders plays an important role in enabling the desirable changes within degree programmes (Barth and Rieckmann, 2012; Hirsto and Löytönen, 2011; Mälkki and Paatero, 2012). These changes within courses can be supported by using appropriate teaching and learning methods (e.g. Jennings, 2009; TEK, 2012a; Tynjälä et al., 2003). In particular, participatory student tasks are considered essential for internalising the concept of sustainability (Segalàs et al., 2008), as well as for facilitating students' development as experts (Litzinger et al., 2011). In terms of core curriculum planning, curriculum analysis has proven to be a useful tool for identifying and defining important and less important content for degree programmes and courses (Blom and Davenport, 2012; Carr et al., 2012; Miller and Crainn, 2011).

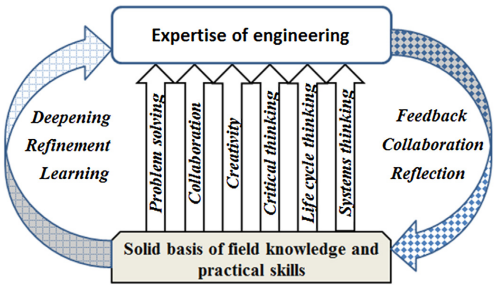

Fig. 1. Composition of an engineer's expertise, based on Mälkki et al. (2012).

European universities have implemented the Bologna model since 2005 in Bachelor's and Master's degree programmes, which has resulted in a need to intensify the development of degree programmes and their accreditations (Lindblom-Ylänne and Hämäläinen, 2004). Universities have also updated their course information in terms of curriculum development by defining the learning outcomes at the course and programme levels. The Finnish Educational system has been successful in the educational rankings of the OECD Programme for International Student Assessment (PISA). Finland is also well known for its innovations, such as mobile technology and computer games, which have maintained the country's economic competitiveness for several years. Sustainable forest management is essential for Finland's national economy due to its dependence on forests, forest bio-products and ecosystem services. Wood is used in the production of renewable energy and in construction. In addition to traditional forest industry products, there are also new wood-based bio-products, such as biodiesel fuel, composites, biopolymers, pharmaceuticals, cosmetics and well-being products (Forest Finland, 2011). Hence, education in renewable energy and sustainability is necessary in all sectors of society and as an essential part of product design.

Aalto University is one of the leading Finnish universities. Its goal is to become a world-class university by 2020. It has set an ambitious goal to integrate sustainability and responsibility into all teaching and research by 2015 (Aalto University, 2013). However, the position of these topics remains unclear in degree programmes. Measuring the relevance of these subjects can be considered a central issue in terms of promoting a more sustainability-oriented perspective on education strategy formation. To that end, an attempt has been made to promote curriculum development by developing a computer-aided tool called STOPS (Software for Target-Oriented Personal Syllabus for Students) in the School of Engineering at Aalto University (Auvinen, 2011; STOPS, 2011). The STOPS tool is described in Section 2, "The case study, material and methods".

In this paper, we propose a new method that includes a relevance ratio (RR) index, which generates added value for the use of

STOPS in curriculum development by quantifying the relevance of the content of the studied learning outcomes in a defined entity of the degree programme. One advantage of the RR index is that it gives a precise method for combining different qualitative and quantitative information in STOPS. For this purpose, we identified and quantified contents of learning outcomes in more detail by assessing four majors that are part the energy degree programme at Aalto University. Our case study focused on the learning outcomes embedding renewable energy and sustainability. Finally, this new RR index method is discussed as a systematic way to quantify the desired contents of courses within the degree programmes and to support teachers' commitment to curriculum development at universities.

2. The case study, material and methods

2.1. The case study method

The case study focuses on the four majors in the energy degree programme at Aalto University. This case study method proposes a relevance ratio (RR) index to quantify the relevance of the sustainability and renewable energy content of the studied learning outcomes in the four energy majors. Aalto University is a new foundation-based Finnish university, which was established in 2010 combining three universities of technology, business, and art & design, and encompassing six schools, 11,337 students and 4985 staff with 382 professors (Aalto University, 2014). Its mission is to contribute to a better world and to support Finland's success. In education, it focuses on students' new learning culture and approaches. Aalto University supports development of education and pedagogical training for staff. This is a significant change in the culture of the Finnish technical universities. Curriculum planning is a key factor in the improvement process, and it has been promoted by the STOPS tool at Aalto University (Auvinen, 2011). Our new method with the RR index combines qualitative and quantitative information in the STOPS environment. Thus, it provides added value to the use of STOPS by revealing the strengths and weaknesses of selected sustainability and renewable energy contents in the energy curricula.

At Aalto University, the O4 curriculum development project (Student Guidance Study Guide), was initiated by the Department of Civil and Structural Engineering and encompassed a detailed analysis of individual courses based on the learning outcomes, skills and competencies they produce. As an outcome, a computer-aided tool STOPS (Software for Target-Oriented Personal Syllabus for Students) was developed to improve the planning process of degree programmes and help students in their study choices (Auvinen, 2011; STOPS, 2011). Auvinen (2011) has explored intelligent tutoring systems (e.g. Hwang, 2003; Murray, 1999) and curriculum visualisation tools (e.g. Gestwicki, 2008; Zucker, 2009), and concluded that an advantage of the STOPS tool is that it provides interconnections of the learning outcomes and prerequisites between the courses throughout the degree programme.

In STOPS, teachers first define the learning outcomes, credit points and levels of knowledge for their courses. Moreover, teachers specify necessary and supporting prerequisites that the learner should possess before taking the course. These prerequisites are used to build and visualise dependencies between the courses in the degree programme. Fig. 2 illustrates a structure of the learning outcomes and interdependent prerequisites for the courses.

In the visualisation of the study paths, students can select required courses to cover their entire degree programme by following the prerequisite links. It also helps teachers to identify problems in the learning outcome links of the study path (Auvinen, 2011). However, teachers could find it useful to experience more specified methods in balancing the subject matters in the contents of the learning outcomes. Therefore, this new proposed method with the RR index could benefit teachers to quantify the relevance of the desired content of the learning outcomes in order to assess its share in the degree programme.

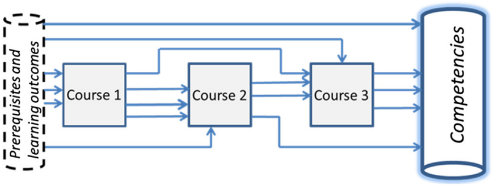

Fig. 2. An illustration of a competence path based on learning outcomes and prerequisites.

In STOPS, the levels of knowledge have been classified into five categories, each of which corresponds to a certain level in Bloom's taxonomy of educational objectives (Bloom, 1956; Krathwohl, 2002). The present implementation of Bloom's taxonomy at Aalto University separates knowledge into five levels: 1) remember, 2) understand, 3) apply and analyse, 4) evaluate and 5) create. It has been modified from the six levels originally presented by Krathwohl (2002). From the standpoint that learning is based on prior knowledge, building competencies can be viewed as cumulative in nature. This idea is described in the STOPS tool by both the workload invested in acquiring the learning outcomes and its level on Bloom's taxonomy.

2.2. Data collection

Both qualitative and quantitative data from the learning outcomes of the energy degree programme were collected utilising the outcomes of the curriculum development efforts at the Department of Energy Technology between 2009 and 2012. We analysed the contents of courses included in the study paths of the department's four majors:

1. Energy and Environmental Technology (EET)
2. Heat and Ventilation Technology (HVAC)
3. Urban Energy Systems and Energy Economics (UESEE)
4. Combustion Engine Technology (CET)

Table 1
Selected keywords, related terms and verbs in the identification of the sustainability and renewable energy content of the learning outcomes.

Sustainability/Renewable energy			
Keywords of sustainability	Keywords of renewable energy	Related terms	Related verbs
sustainability	renewable energy	energy resources	understand
climate change	biofuels	energy systems	know
emission control	biomass	energy processes	recognise
environment	fuel cells	energy technologies	identify
environmental impacts	geothermal energy	eco-efficiency	search
ecological impacts	hydropower	energy efficiency	compare
economic impacts	solar power	waste treatment	classify
social impacts	wave power		evaluate
global impacts	wind power		estimate
health	wood energy		Apply
life cycle assessment			Analyse

First, we identified the learning outcomes and prerequisites of the courses, including renewable energy and sustainability, by analysing the verbal appearance of the learning outcomes. Second, we calculated relevance ratios (RR) for renewable energy and sustainability on the basis of their cumulative competencies (CC). These calculation principles are explained in Section 2.2, "Calculation". The identification of the sustainability and renewable energy content was done using selected keywords, related terms and verbs presented in Table 1 (see an example in Fig. 3). An examination of the verbal descriptions against the selected set of words was carried out manually through all the learning outcomes and prerequisites. In principle, this search phase could also be programmed in the computer, e.g. in the STOPS environment.

These principles of the content identification were discussed with several teachers at Aalto University. However, this identification process includes uncertainties and subjective perceptions in the selection of the keywords, related terms and verbs, and also in the interpretation of the sustainability and renewable energy content. The scarce and limited descriptions of the learning outcomes do not always show the real situation in teaching. These uncertainties can be decreased by interviewing and discussing with the teachers in the energy degree programme, thus improving the visibility of the sustainability and renewable energy content in the verbal descriptions of the learning outcomes. Finally, this method with the RR index is an interactive tool for collaborative curriculum development.

2.3. Calculation

To make explicit the role of different contents, we suggest that cumulative competence should first be calculated according to Eq. (1) using the following definitions:

The energy degree programme				Major course: Power Generation from Biomass I					Cumulative Competence (CC)				Relevance Ratio (RR)			
				Learning outcomes												
Course: Energy Economics (3 cr)				Understands different power plant concepts	Knows the basics of boilers, gas and steam turbines	Can perform process calculations of a power plant	Can use mass and energy balances in calculations	Knows about biomass as a source for energy production	Necessary renewable energy	Supporting renewable energy	Necessary sustainability	Supporting sustainability	Necessary renewable energy	Supporting renewable energy	Necessary sustainability	Supporting sustainability
Learning outcomes	Credit (cr)	Bloom score (1 - 5)	CC	Prerequisites (N = necessary/ S = supporting)					CC	CC	CC	CC	RR %	RR %	RR %	RR %
Characteristics of energy and basics in energy technology	0.4	1	0.4	N	N	N	N	N	0.4				9			
Concise description of energy production technologies	0.4	1	0.4	N	N	N	N	N	0.4				9			
Energy use in Finland	0.5	2	1.0	S	S	S	S	S		1.0				22		
Energy resources globally and in Finland	0.5	2	1.0	S	S	S	S	S		1.0				22		
Environmental impacts and climate change	0.5	2	1.0	S	S	S	S	S				1.0				22
Costs of energy production	0.2	1	0.2	S	S	S	S	S				0.2				4
Energy markets	0.5	1	0.5	S	S	S	S	S								
Total	3	1 - 2	4.5	7	7	7	7	7	0.8	2.0	0	1.2	18	44	0	26

Fig. 3. An example of calculation principles used for the content analysis.

$$CC = \sum_{i=1}^{n} a_i b_i, \quad (1)$$

where CC is cumulative competence, n is the number of learning outcomes, a_i is the credit points invested in the i-th learning outcome and b_i is the level of Bloom's taxonomy assigned to the i-th learning outcome. This cumulative competence describes the values of the different learning outcomes within the context of the total cumulative competence at the course or programme levels.

To provide an easily understandable and comparable measure, we present the relevance ratio (RR) index. This *RR* index is now defined as the ratio of the cumulative competence for certain subject matter (A) (e.g. renewable energy) and the cumulative competence of the total study path (tot), including all subject matter, according to Eq. (2):

$$RR = \frac{CC_A}{CC_{\text{tot}}}, \quad (2)$$

where CC_A is the cumulative competence for subject matter A and CC_{tot} is the cumulative competence of the whole study path.

2.4. Calculation examples

Examples of calculation principles used for the content analysis are shown in Fig. 3. The course 'Energy Economics' contains learning outcomes that are prerequisites for the course 'Power Generation from Biomass I'. For example, the learning outcome 'Characteristics of energy and basics in energy technology' for the course 'Ene-59.2101 Energy Economics' is a prerequisite for the learning outcome 'Understanding different power plant concepts' for the major course 'Ene-47.4110 Power Generation from Biomass I'.

The data presented in Fig. 3 indicate that the course 'Energy Economics' has three credits and seven learning outcomes, which are divided into sub-credits and categorised by applying Bloom's taxonomy levels. Renewable energy is embedded in four of the seven learning outcomes and sustainability in two of the seven learning outcomes. In Fig. 3, the dark grey colour means that the learning outcome has renewable energy embedded in it, whereas the light grey colour indicates that the learning outcome has sustainability embedded within it. The explanations for the letters mean that *N* is a necessary prerequisite, *S* is a supporting prerequisite, *CC* is a cumulative competence and *RR* is the relevance ratio. Here, the total number of learning outcomes, including renewable energy, is four (4). The cumulative competence, *CC*, is calculated from Eq. (1): $CC = 0.4\ldots1 + 0.4\ldots1 + 0.5\ldots2 + 0.5\ldots2 = 2.8$. Consequently, the cumulative competence for the whole study path, CC_{tot}, is 4.5. Now, it could be concluded that the four learning outcomes embedded in renewable energy encompass 2.8 points out of a total of 4.5 points at the course level.

The relevance ratio of renewable energy is calculated using Eq. (2): $RR = 0.4/4.5 + 0.4/4.5 + 1.0/4.5 + 1.0/4.5 = 0.62$ (62%). The relevance ratio states that the four learning outcomes embedded in renewable energy cover 62% of the maximum theoretical relevance ratio (100%) for the course 'Energy Economics'. Similarly, the calculations for the content analysis are presented in Tables 3 and 4 at the energy major and programme levels.

3. Results

We conducted the data analysis individually for all four majors that are part of the energy degree programme. The analysis was based on the learning outcomes and prerequisites for the courses collected using the software tool STOPS. The findings of the content analysis are summarised in Tables 2 and 3. Table 2 presents the total numbers of courses, credits, learning outcomes and prerequisites for each major as well as the *CC* calculated for the total learning outcomes of each major. Table 3 presents the extent to which renewable energy and sustainability are included in the majors along with the number of corresponding prerequisites; the *CC* and *RR* are calculated for each learning outcome embedding renewable energy and sustainability.

Table 2
The overall results of the numbers and Cumulative Competence (CC) of the majors.

Overall results	Majors within the energy degree programme				
	EET	HVAC	UESEE	CET	Total
Number					
Courses	16	13	13	4	46
Credits	53	49	67	20	189
Learning outcomes	71	71	62	33	237
Necessary prerequisites	171	144	133	92	540
Supporting prerequisites	5684	662	158	495	6999
Cumulative Competence (CC)					
Learning outcomes	184	144	182	56	566

The data in Table 2 indicate that the Energy and Environmental Technology (EET) major had the highest score with respect to the total number of courses and the necessary and supporting prerequisites. The Urban Energy Systems and Energy Economics (UESEE) major had the largest number of credits, although fewer courses were offered than with the EET major. The Heat and Ventilation Technology (HVAC) major had more necessary and supporting prerequisites than the UESEE major. The Combustion Engine Technology (CET) major contained the fewest number of courses, but it had the most learning outcomes per course and credits, whereas *CC* was the lowest for this major out of all the majors. The *CC* for the learning outcomes included in the EET and UESEE majors was at the same level, in spite of the fact that the UESEE major had fewer courses and learning outcomes. The *CC* results revealed that the majors used different levels of Bloom's taxonomy and so the results were different in spite of the fact that they offered the same number of credits.

The data in Table 3 indicate that the EET major had the largest number of prerequisites as well as the highest *CC* and *RR* levels for renewable energy. The EET major had sustainability only as a supporting prerequisite, and it had no necessary sustainability prerequisites. The HVAC major had the largest number of prerequisites and highest *CC* for the necessary sustainability prerequisites, but no necessary renewable energy prerequisites. The UESEE major had both necessary and supporting prerequisites. The CET major had only supporting prerequisites and no necessary renewable energy and sustainability prerequisites. The relevance

Table 3
Renewable energy and sustainability content and results of the majors.

Renewable energy and sustainability content	Majors of the energy degree programme				
	EET	HVAC	UESEE	CET	Total
Number of prerequisites					
Necessary renewable energy	64	0	39	0	103
Supporting renewable energy	1742	90	56	64	1952
Necessary sustainability	0	26	2	0	28
Supporting sustainability	945	116	22	93	1176
Cumulative Competence (CC)					
Renewable energy	90	2	15	0	107
Sustainability	30	4	18	2	54
Relevance Ratio (RR) %					
Renewable energy	49	2	8	0	59
Sustainability	16	3	10	4	33

Table 4
A SWOT analysis of the new content analysis method with the RR index based on the STOPS tool.

Strengths	**Weaknesses**
• offers a tool to support discussion • supports cumulative learning • transparent and democratic in terms of content issues • quantification of relevance: results based on number of presentations • assists teachers • computer-aided tool • collaboration in curriculum development	• omission of non-transparent skills • not supporting discussion on how to learn necessary skills • lack of repetition in terms of relevance when progressing along the study path • lack of ways on how to support transformative learning
Opportunities	**Threats**
• makes the curriculum development process more efficient • identifies potential gaps in learning outcomes • enhances collaboration and discussion between teachers • allocates use of teaching resources • builds equality in degree programmes and in students' study path	• inconsistent learning outcomes • requires continuous discussions during the curriculum development process • lack of adequate instructions • misuse of the method; a purpose for which it is not suited • just another curriculum development method • does not improve teachers' commitment • not all teachers use the STOPS tool

ratio implied that the EET major embedded a 49% share of renewable energy and a 16% sustainability share out of the total *CC* for the major. The relevance ratio index indicated that other majors had only minor relevance in terms of renewable energy and sustainability.

The content analysis revealed remarkable differences between the majors. Only one major involved both necessary and supporting prerequisites for renewable energy and sustainability. The other majors had deficiencies in either necessary renewable energy or sustainability prerequisites.

4. Discussion

Working life requirements are constantly changing, which implies the need for continuous improvements in curricula. Future sustainable solutions are dependent upon the energy choices made by society. Thus, it is necessary for renewable energy and sustainability to be embedded within engineering education courses. To embed sustainability, many papers concluded that it is important to enhance collaboration of teachers, to develop participatory approaches and to adapt interactions between higher education, practitioners and stakeholders (e.g. Barth and Rieckmann, 2012; Davidson et al., 2010; Ferrer-Balas et al., 2008; Müller-Christ et al., 2014). Many papers emphasised that more work is needed in mastering the content of courses, in developing methodologies, in understanding concepts and in encouraging efforts towards sustainability (e.g. Barnett and Coate, 2005; Lozano, 2010; Segalàs et al., 2013; Svanström et al., 2008). They also identified the relevance of competence development with respect to sustainability related knowledge and skills in curricula Despite the importance of all these competencies, we did not address the whole competence phenomenon on the basis of the studied learning outcomes in Aalto University's energy degree programme. Instead, we focused on analysing knowledge, and understanding and formal contents of learning outcomes. For this purpose, we introduced a content analysis method to calculate a numeric relevance ratio (RR) index in order to quantify the integration of renewable energy and sustainability as a percentage of the contents of learning outcomes. This method can be used to reveal possible gaps and differences between the particular entities measured by key figures, cumulative competencies and relevance ratios.

The case study of the Aalto University Degree Programme in Energy Technology showed that both the integration of renewable energy and the status of related learning outcomes as prerequisites for other courses varied a great deal between the different energy majors. This is caused in part by the fundamental nature of the various majors. For example, the EET, HVAC and UESEE majors represent and teach environmental and systemic-oriented issues, while the CET major involves more technical fundamentals of engineering and unit processes. The results of the content analysis could not be generalised with respect to studies at the Bachelor's degree level because the data involved only energy majors at the Master's degree level at Aalto University.

The results of the content analysis also showed that there are more supporting than necessary prerequisites, and sustainability has a smaller role than renewable energy in the content of the learning outcomes. Because the learning outcomes and prerequisites have solely been determined by the teacher responsible for each course, the present structure of the degree programme includes a number of subjective evaluations. That is why, at least for teachers, continuous collaboration would be very important inside the degree programmes to balance the contents of courses and learning outcomes, to define appropriate levels of learning, e.g. according to Bloom's taxonomy, and to embed a sufficient number of prerequisites in the areas of renewable energy and sustainability. According to these results, there is a need to improve teacher interaction in the development process of the energy degree programme at Aalto University. In addition, there is a need for computer-aided tools to help develop the curriculum process and to help in collecting and sorting data. Universities could also benefit from computer-aided curriculum tools and methods that help monitor different quality aspects of degree programmes.

The real benefit of the content analysis method is its ability to efficiently reveal the strengths and weaknesses of the present status of the courses, which could help departments and teachers in developing the educational content of the energy degree programmes for future needs (Table 4). However, while this method includes numerous opportunities where it could be useful, there are also threats that must to be taken into consideration when quantifying and interpreting the results (Table 4).

This content analysis method is applicable whenever the learning outcomes, credits and Bloom scores are defined in a similar manner as in the STOPS tool. This tool could be further developed to integrate, e.g. this kind of content analysis method with an RR index, into the STOPS curriculum development model. Generally, this kind of relevance ratio (RR) index could help to quantify the systematic integration of the desired contents within the degree programmes, and thus, it could support curriculum development efforts at universities.

5. Conclusions

European Union energy policies have set targets to reduce CO_2 emissions, increase renewable energy and improve energy efficiency. Meeting these targets will require sustainable solutions for society. Thus, improving knowledge, skills and attitudes regarding sustainability and renewable energy should be an integral part of an engineering education. Here, we present a new curriculum development tool, which can be used to start discussions about how best to integrate renewable energy and sustainability within energy degree programmes. As part of the development process for this tool, we analysed the content of the courses based on their learning outcomes and suggested a numeric RR index to measure the extent to which renewable energy and sustainability are

integrated within the four majors that are a part of Aalto University's energy degree programme. Finally, this RR index was presented as a percentage.

As an example of how to use this tool, the results of the content analysis indicated that renewable energy and sustainability were unevenly embedded in the learning outcomes of the various energy majors that are a part of Aalto University's energy degree programme. The content analysis method revealed an urgent need for intensified collaboration in curriculum development between the teachers responsible for planning curricula for the energy courses. Teachers have an essential role in discussing and determining the necessary learning outcomes and prerequisites and how they should build upon one another from one course to the next. This kind of cumulative learning path is needed to provide the desired content competencies after graduation for students. A quantified and illustrative representation of the RR index would be a simple way to increase teachers' awareness of how to start discussing and collaborating with other teachers in the degree programme on how best to balance the subject matter in the contents of the learning outcomes.

The suggested content analysis method is not currently applicable for exploring skills other than content-based knowledge skills and revealing their strengths and weaknesses in the present curricula. Hence, more work is needed to further develop this method and tool to measure the informal and non-formal skills of the learning outcomes and to integrate them into the students' study path. According to the literature survey, a comprehensive set of skills is necessary to promote understanding of sustainability and students' working life skills. Thus, collaboration inside the university should be expanded so that other relevant stakeholders in society will be encouraged to take part in developing curricula at universities.

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Publication VI

Mälkki, H., Alanne, K., Hirsto, L. & Soukka, R.
Life cycle assessment (LCA) as a sustainability and research tool in energy degree programmes

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Life cycle assessment (LCA) as a sustainability and research tool in energy degree programmes

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1 INTRODUCTION

Energy plays a critical role in global sustainable development processes according to the United Nations (UN) report “The Future We Want” [1]. The UN 2030 agenda introduced 17 sustainable development goals and 169 targets to be met by 2030 including a goal for energy to be affordable, reliable, sustainable and modern energy for all [2,3]. In Europe, the use of energy from renewable sources is promoted by European Union (EU) energy policies [4].The UNECE strategy (2005) [5] highlighted the use of formal, non-formal and informal learning and the training of educators with

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the SD abilities in order to promote education for sustainable development (ESD). The UN Decade 2005 – 2014 for ESD (UN DESD) encouraged governments and organisations to integrate the principles, values and practices of sustainability into all aspects of education and learning [6]. However, sustainability still remained a challenge in education after the UN DESD. Therefore, a new action plan was launched to follow and ensure the implementation of ESD in all teaching and research [2]. Kandpal and Broman (2014) [7] reviewed a global status of renewable energy education and identified a variety of challenges in energy education including unavailability of well-structured curricula, lack of motivated and competent teachers, unavailability of adequate funds and uncertainty on the employment prospects of the student. They found out that renewable energy courses are missing links to environmental interactions and sustainable development. This paper introduced a teaching concept (Fig 1) to train and motivate teachers to integrate ESD into the energy degree programmes.

Life cycle assessment (LCA) is one of the techniques developed to increase the awareness of environmental protection, and the possible impacts associated with the product systems [8]. LCA is a systemic tool for comparing and identifying the best sustainable solutions to the product systems. Sustainable and secure energy solutions are needed to overcome environmental problems, mitigate the impacts of global warming and increase welfare of people locally and globally. The overall concept of sustainability is understood as sustainable development (SD) with the environmental, economic and social dimensions [9]. Sustainable energy and sustainability dimensions in teaching pose the challenges to energy education at universities in order to produce experts for the needs of the sustainable society. Education has seen as an incentive for people to use their individual potential and contribute to social transformation [2].

Teaching and research can be combined by employing the concepts of learning and teaching using research-based assignments and projects inside and outside the classroom [10,11]. The research-teaching nexus was further developed by Healey (2005) [12]. He presented a model of four research categories integrating research and teaching by using research-led, research-oriented, research-tutored and research-based categories. The research categories represented either content-driven research or focused on conducting research and its problems. In addition, these research categories included teacher-focused teaching and student-focused learning. All the research categories influenced the students' learning process. They enabled students to learn research skills and techniques, become familiar with current research, learn to be engaged in research discussions, learn to carry out research and act as a researcher. This model by Healey is used in this paper (Fig. 4) to explore how LCA-based research appears in the energy degree programmes.

A teaching concept (Fig. 1) helps teachers to combine LCA, sustainability and education by using teaching and learning methods connected with research and sustainability applications in energy education. Sustainability applications train students to understand, discuss and interpret the findings of the used studies. Students learn to identify the most significant sustainability aspects and environmental impacts of the case studies. They learn to identify the best life cycle phases of the systems for the optimisation of improvements. The use of LCA-based research helps students to recognise e.g. planetary boundaries, limits to growth, local conditions and the cost effectiveness of their solutions. First and foremost, students learn to know LCA and enhance their interpretation skills of LCA and sustainability and thus avoid misleading conclusions. In energy education, this concept enables critical debates about the current topics of the energy technologies and their local and global sustainable solutions.

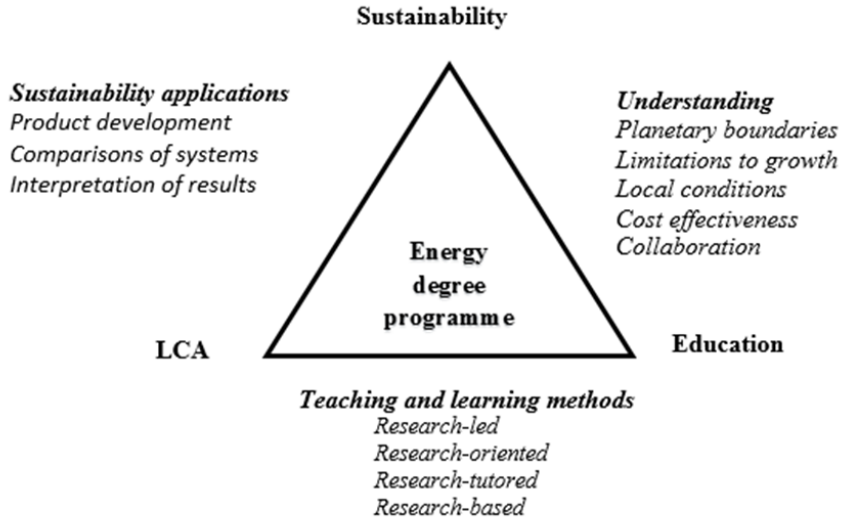

Fig. 1. A concept connecting sustainability, education and LCA in energy education.

In spite of the various uses of LCA in research and business, the role of LCA seems to be unexplored in energy education. Teachers lack information on how LCA is taught and how LCA is connected to SD in the energy degree programmes. Therefore, this study explored the use of LCA and LCA-based research in the energy degree programmes at Baltic, Nordic and Finnish technical universities. A survey was sent to the responsible teachers and professors focusing on the use, importance, incentives and teaching and learning methods of LCA. The results of the LCA teaching and learning methods of the survey were placed in a research-teaching nexus model applying the Healey model [12] in order to identify how LCA-based research manifests itself in energy education. The findings of this paper are presented and discussed for enhancing the use of LCA and LCA-based research in sustainability assessment in the energy degree programmes at technical universities to educate future LCA experts in sustainable energy for future needs of sustainable societies.

2 LIFE CYCLE ASSESSMENT (LCA) AS A SUSTAINABILITY TOOL

Life cycle assessment (LCA) has a following description in the ISO 14040 standard [1] "*LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)*." The framework of LCA consists of four phases, namely Goal and scope definition, Inventory analysis, Impact assessment and Interpretation. The inventory phase produces data to be used in impact assessment and in the interpretation of the overall results.

During the past few decades, LCA methodology, databases and software have been developed as well as LCA standards [1,13] and LCA guidebooks [e.g.14-16] in order to improve the scientific use of LCA. The development of the LCA has been supported by the UNEP/SETAC Life Cycle Initiative to enhance decision-making towards more sustainable product systems and processes [17,18]. For example, LCA-based indicators, eco-labels and carbon footprints support corporate strategic planning, product development and marketing in industrial, governmental and non-governmental

sectors [19]. However, all the uses of LCA do not aim to improve sustainability, e.g. the carbon footprints help to improve marketing and business but they do not provide information on how to tackle climate change. At the moment, the most typical sustainability applications of LCA addressed the product development and comparisons of systems.

Due to the growing information needs of decision-makers in different sectors of society, there was also an urgent need to extend the use of LCA to harness the economic and social dimensions of sustainability [20,21]. Ness et al (2007) [22] highlighted that the environmental-focused realm of LCA has to be expanded to a wider interpretation of sustainability. A life cycle sustainability assessment (LCSA) combines environmental life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (SLCA) [23,24]. The combination of LCA and LCC provides information to choose the most cost-effective solutions. The combination of LCA and SLCA provides information to identify the aspects threatening the social sustainability of the solutions.

Ever since the early years of LCA, LCA has been used to calculate the emissions and environmental impacts of the energy systems in order to make improvements in energy technologies and systems. In connection with LCA, the energy systems typically consist of the fuel chain and the production phase of energy generation in the power plant (i.e. cradle-to-gate) excluding infrastructures, buildings and machines. Recently, Asdrubali et al. 2015 [25] reviewed 100 LCA renewable energy case studies for comparing energy systems, Turconi et al. (2013) [26] reviewed 167 LCA energy case studies for comparing sustainability indicators, and Evans et al. (2009) [27] reviewed about 50 LCA energy case studies of greenhouse gas emissions. They all reported that there were weaknesses and gaps in the results of the reviewed LCA energy case studies addressing the used knowledge, data, assumptions and considerations of the energy systems. In order to ensure better data, transparent and precise information to assess and interpret LCA-based sustainability results, the training of students on LCA skills and energy knowledge is crucial.

3 RESEARCH METHODS AND MATERIALS

This study explored the use of LCA and LCA-based research in the energy degree programmes by using a survey and Healey´s model [12]. The survey was sent to the selected teaching staff at Baltic, Nordic and Finnish technical universities in the autumn of 2012. In total, the respondents consisted of 16 teachers and professors at ten universities. The number of the respondents varied in each issue and it was limited because the respondents were chosen with care highlighting the fact that they are aware of the actual situation of energy education at their universities. Therefore, the target group consisted of teachers and professors who were responsible actors in the energy degree programmes and courses therein. They were also supposed to know how energy is being taught. The chosen energy target group may have set limitations to the generalisation of the results and applying them in other disciplines.

The survey questions concerned the use, importance, incentives and teaching and learning methods of the energy courses in the energy degree programmes (Table 1). The survey included 16 incentives and 26 teaching and learning methods. The use of LCA in research was analysed by applying the Healey model that combines research and teaching that is described in the introduction section. The teaching and learning methods of LCA were analysed using the experience of the authors and the descriptions of the teaching methods [28] and thereafter they were placed in four research categories (Fig. 4) for further interpretation.

Table 1. LCA questions and answer options of the survey.

Questions	**Options**
Is LCA used in the bachelor and/or master energy degree programmes (majors/ minors/ elective studies/ no studies)?	*Yes/No*
What is the importance of LCA in the energy degree programmes and what are the future prospects for LCA and energy?	*Very high/ High/ Medium/ Low/ Not important/ I cannot say*
What are the main incentives to incorporate LCA into the energy degree programmes?	*Global challenges, Environmental problems, Public pressure, Demand from employers, Demand from students, University strategy, Learning outcomes, Engineering competences, Interdisciplinary education, Integration of research and teaching, Sustainable development, Economic awareness, Social awareness, Environmental awareness, Environmental politics and laws, Other incentives*
What are the main teaching and learning methods for LCA?	*Assignments, Debate, Drama pedagogy, E-learning, Exams, Exercises, Field trips, Group work, Independent studying, Learning by doing, Learning café, Learning diary, Lectures, Mind map, Panel discussion, Peer teaching, Preliminary test, Personal guidance, Presentations, Problem-based learning (PBL), Project work, Reading circle, Seminar, Supplementary reading, Workplace practice, Others*

4 RESEARCH RESULTS

Findings of the survey showed that the use of LCA varied in the energy degree programmes at the Baltic, Nordic and Finnish technical universities. According to the open ended comments, LCA was also used by doctoral students at universities. LCA was better used in the master than bachelor level energy studies (Fig. 2). Minor studies of the bachelor and master degree programmes dominated the use of LCA. LCA was less used in the major studies of the degree programmes. Additionally, LCA was used in elective studies and as a separate course in the master degree programmes. Findings also indicated that LCA was not used in all the bachelor and master energy degree programmes.

Respondents indicated that LCA was more important for the master than bachelor level studies. The importance of LCA varied from a high level to a not important level. Additionally, many respondents could not give any answer to the importance of LCA (Fig. 3). The future prospects indicated that LCA will have a high importance and energy a very high importance in the energy degree programmes in the future.

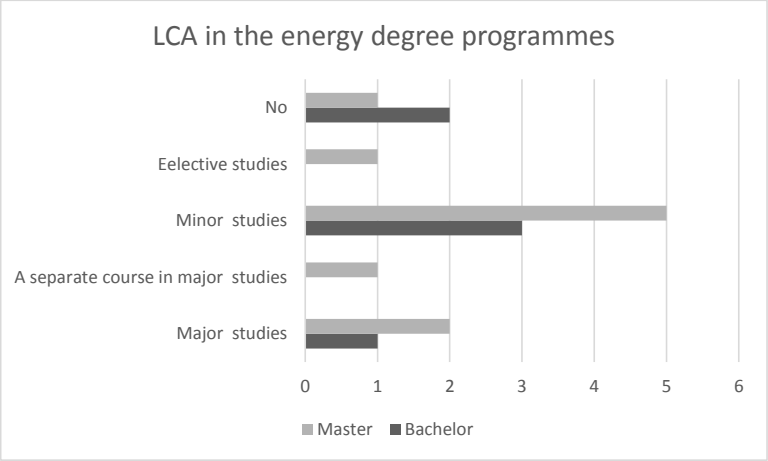

Fig. 2. The use of LCA in major, minor and elective studies and as a separate course in the energy degree programmes. N = 10.

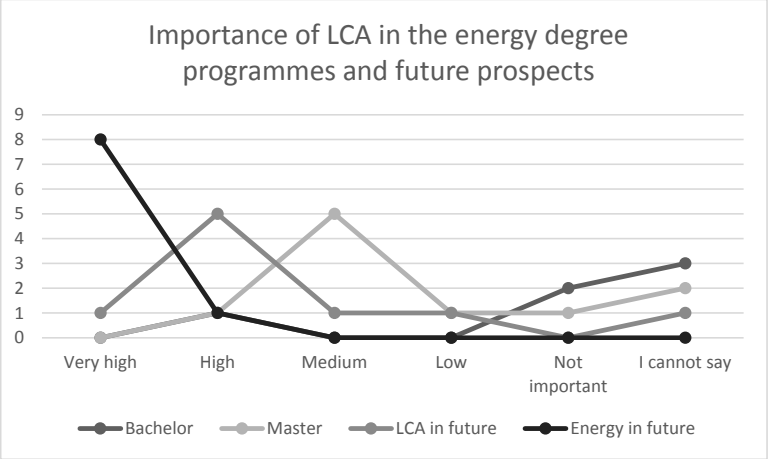

Fig. 3. The importance of LCA in the major subject studies of the energy degree programmes and future prospects for LCA and energy. N = 10.

Findings showed that sustainable development was the main incentive for the use of LCA in the degree programmes followed by environmental awareness, environmental problems, demand from employers and global challenges. Integration of research and teaching, engineering abilities, and environmental politics and laws were identified as moderately important incentives by the respondents. Only a minority of respondents recognised that interdisciplinary education and demands of students were incentives for the use of LCA. Findings revealed that social and economic awareness as well as public pressure, university strategy and learning outcomes were identified as the weakest incentives among all the presented incentives for the use of LCA. Results of the incentives in the use of LCA are presented in Fig. 4.

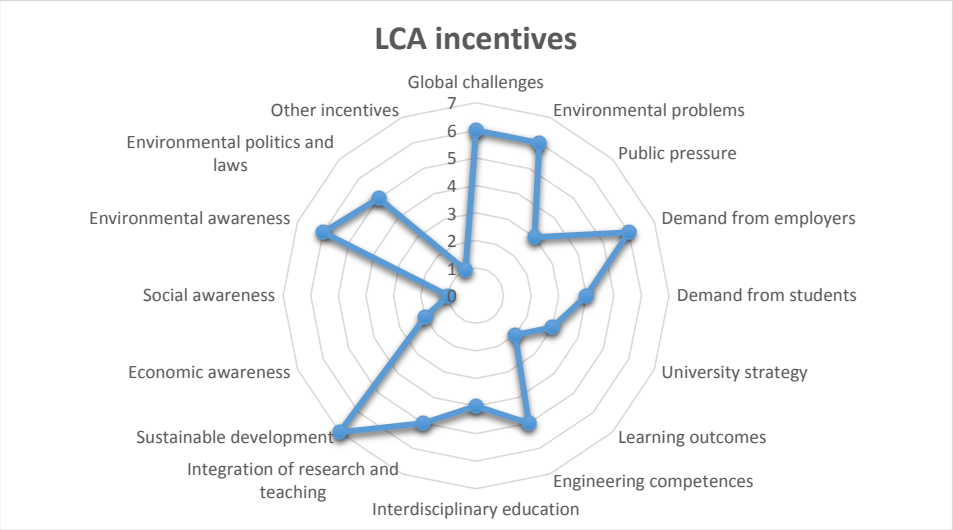

Fig. 4. The incentives for LCA in the degree programmes. N = 14, the respondents were allowed to give one answer per each issue.

26 teaching and learning methods included 93 responses. Results showed that LCA was taught with a large variety of teaching and learning methods (Fig. 5. Respondents identified that the most used methods were lectures, assignments and exercises in the use of LCA in teaching. The use of LCA was moderately recognised in debates, E-learning, exams, field-trips, group works, mind maps, panel discussions, peer teaching, problem-based learning, seminars and supplementary reading by the respondents. The least used methods included drama pedagogy, learning café, learning diary, reading cycle and workplace practice. The results of the responses are further analysed through the Healey model (Fig. 6).

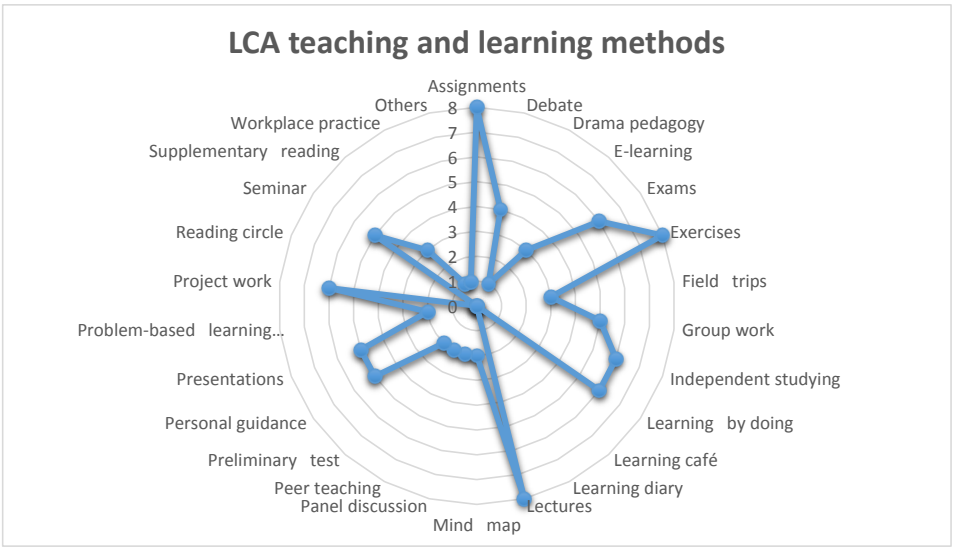

Fig. 5. The main teaching and learning methods used in the degree programmes. N = 14, the respondents were allowed to give one answer per each issue.

93 responses to the teaching and learning methods were placed in four research categories using the Healey model in Fig. 6. The results showed that the LCA teaching and learning methods were quite counterbalanced between the student-focused (46 responses) and teacher-focused categories (47 responses). Research content received 50 responses divided into research-tutored (18/93) and research-led (32/93) categories. Research processes and problems received 43 responses divided into research-based (28/93) and research-oriented (15/93) categories. The teaching and learning methods of LCA enabled the use of all the research categories in teaching in the energy degree programmes.

STUDENT AS PARTICIPANT

STUDENT -FOCUSED

46

Research-tutored Engaging in research discussions		**Research-based** Learning how to do research and be a researcher	
3	Supplementary reading		
3	E-learning		
2	Panel discussion	6	Learning by doing
0	Reading cycle	1	Workplace practise
4	Debate	6	Independent studying
1	Drama pedagogy	6	Project work
0	Learning café	5	Group work
0	Learning diary	2	Problem-based learning
5	Presentations	2	Mind map
tot.	**18**	**28**	**tot.**
EMPHASIS ON			**EMPHASIS ON**
RESEARCH CONTENT			**RESEARCH PROCESSES**
			AND PROBLEMS
5	Seminar		
3	Field trips		
8	Exercises		
8	Assignments	5	Personal guidance
2	Preliminary test	2	Peer teaching
6	Exams	8	Lectures
tot.	**32**	**15**	**tot.**
Research-led Learning about current research		**Research-oriented** Developing research skills and techniques	

47

TEACHER-FOCUSED

STUDENT AS AUDIENCE

Fig 6. The LCA teaching and learning methods of the survey in the four research categories of the Healey model [12].

As an example, the most common teacher-focused and student-focused methods were as follows:

- Teacher-focused methods: lectures, assignments, exercises and exams

    - Lectures have put an emphasis on research processes and problems.
    - Assignments, exercises and exams have an emphasis on research content.
- Student-focused methods: presentations, debates, independent studying, project work and learning by doing
    - Presentations and debates highlight research content.
    - Independent studying, project work and learning by doing emphasise on research processes and problems.

5 DISCUSSION AND CONCLUSIONS

Sustainable development is a challenge for teachers at universities. Teachers need training on SD skills and tools in the integration of all the dimensions of SD into energy education. However, the findings did not support the practice of using LCA as a broader framework for sustainability assessment (LCSA) in energy education. LCA has been typically used in assessing environmental issues such as the carbon dioxide emissions of the energy systems. Therefore, more attention needs to be paid to the enhancement of the social and economic incentives when using LCA and sustainability in energy education. The economic and social dimensions of SD are normally studied by using separate tools such as multiple forms of LCC and SLCA. Due to the complexity of sustainability assessment, it is important to train teachers and students in the use of LCA and related SD tools. Incompetent and inexperienced researchers might fail to interpret the study results and thus they might draw misleading conclusions. This is also identified by the reviews of the LCA energy studies highlighting the importance of the proper energy data for transparent and adequate information on the energy systems for decision-making purposes in politics and business.

This paper presented a LCA-based teaching concept (Fig. 1) for combining LCA, sustainability and education and placed the LCA teaching and learning methods of the survey on a research-teaching nexus model by Healey (Fig. 6) for exploring the use of LCA in the energy degree programmes. The findings of the survey showed that LCA was more common in the master than bachelor energy degree programmes. However, LCA was not used in all energy degree programmes at Baltic, Nordic and Finnish technical universities. Especially the bachelor energy students would benefit from LCA during their bachelor studies in order to become familiar with LCA before their master studies. In spite of the varying importance levels of LCA, the respondents indicated that the importance of LCA and energy will significantly increase in the energy degree programmes in the future. It might mean that the number of LCA and energy experts would also increase in the future to prepare sustainable solutions to decision-making purposes in society. Moreover, all over the world the SD and energy experts are needed to implement the global action plan to avoid climate change by limiting global warming and to implement the SD energy goal of the UN agenda 2030 for affordable, reliable, sustainable and modern energy for all.

The traditional teaching and learning methods such as lectures, assignments, project work and exams were used in LCA. In spite of the useful contributions to solving the problems, problem-based learning was less used in LCA in the energy degree programmes by the respondents. Therefore, the use of problem-based learning as a student-focused method should be enhanced as part of sustainable energy education in the future. Teachers are key actors in choosing the best appropriate teacher-focused and student-focused teaching and learning methods for the integration of ESD into their energy courses. The teaching and learning methods of LCA in the Healey model

revealed that LCA was perceived in all research categories and enabled students with diverse skills and learning.

The research-teaching nexus model (Fig. 6) by Healey helps teachers to use LCA-based research in teaching. The teaching concept (Fig. 1) guides teachers to combine LCA, education and sustainability in energy education. Sustainability applications help students to learn to do LCA and recognise the most significant sustainability aspects and impacts of their applications. Students learn to discuss and interpret the complexity of findings for improving the sustainability of the energy systems. In tackling the future challenges for SD and sustainable energy, universities have a vital role in educating future LCA and energy experts to be able to use LCA and LCA-based research in the sustainability assessment of the energy systems and services. Summing up, more research is needed to motivate teachers and increase the use of LCA as a sustainability and research tool in the energy degree programmes at technical universities to educate future LCA experts in sustainable energy for the needs of sustainable society.

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