Journal of Cleaner Production 126 (2016) 643–653

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Ecodesign framework for developing wind turbines

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ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
28 January 2016
Accepted 22 February 2016
Available online 27 February 2016

Keywords:
Ecodesign
Life cycle management
Sustainable innovation
Stakeholder participation
Iterative design
Wind power

ABSTRACT

Despite a wind turbines perceived environmental benefits, there are still many improvements that can be made in the product development process to improve its environmental performance across life cycles. This is especially important as the wind power industry continues to grow, both in volume and size, in response to increasing global market demands. Planning, implementing, monitoring, documenting and communicating product related environmental activities of wind turbines in a life cycle management context is the focal point of this article. The development and application of an ecodesign framework specific to the organizational context of Siemens Wind Power is described. The framework was developed using an iterative, action research design approach which relied on the participation of cross-functional employees. Five iterations occurred over a four year time frame and methods such as workshops, pilots, interviews and life cycle assessment were applied. The ecodesign framework was aligned with the company's formal product lifecycle management process. When combined with life cycle assessment, the framework can identify potential environmental improvements and contribute to coherent and transparent environmental target setting. Examples of this are demonstrated at the technological, organizational and societal levels of the company. Lessons learned obtained during the design iterations call for assigned responsibility through key performance indicators at project and functional levels; adaptive learning approaches to ecodesign based on continuous improvements; and additional capacity building amongst employees in life cycle thinking. The article proposes that a life cycle based ecodesign framework can be a driver for sustainable innovations in components, product systems, technologies and business models.

1. Life cycle management in the wind power industry

Today's energy systems are transitioning to deploy high shares of renewable energy (EWEA, 2014; REN21, 2015). For example the global installed wind capacity had a 23% annual increase rate in the period 2005–2014 (GWEC, 2014). According to the International Energy Agency wind power could generate up to 18% of the world's electricity by 2050 compared with 2.6% in 2013 (IEA, 2013). On a European level wind power is the frontrunner among renewable energy sources and is supported by regulatory and economic measures (EC, 2009a; Mulder, 2008; TPWind, 2006). Following the sector's growth, an increasing number of assessments related to wind power technologies have been performed by authorities, technology developers and other stakeholders to evaluate their environmental and societal consequences (Angelakoglou et al., 2014; Martínez et al., 2009; Premalatha et al., 2014; Wüstenhagen et al., 2007). Apart from documenting the environmental, social and economic impacts, these assessments can contribute to product related improvements in the context of life cycle management (LCM) and ecodesign.

LCM is a broad management framework to assist companies in mapping, assessing and managing their operations with respect to sustainability related criteria across entire value chains (UNEP/SETAC, 2007, 2009a,b). There are two fundamental LCM principles:

- Inter- and intra-organizational stakeholder participation;
- Life cycle thinking.

Correspondingly, ecodesign refers to the systematic integration of environmental aspects in product design and development in order to reduce the adverse environmental impacts associated with

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http://dx.doi.org/10.1016/j.jclepro.2016.02.093
0959-6526/

a product across its life cycle (ISO, 2011). The first principle calls for a participative approach which accounts for multiple stakeholders taking decisions across this value chain (Sarmah et al., 2015; Vezzoli et al., 2015). Participation can be expressed through varying forms and allows for increasing levels of involvement e.g. information, consultation, collaboration, partnership and self-mobilisation (IPCC, 2007). Literature highlights the risks and benefits of stakeholder participation in the decision making process related to sustainability and innovation (Bano and Zowghi, 2015; Reed, 2008). Reported advantages of participation include: tacit knowledge acquirement, new innovations, stakeholder satisfaction, reduced risk, improved brand image, and increased transparency (Luyet et al., 2012; UNEP/SETAC, 2007). Participation from internal stakeholders, specifically cross-functional employees, is the focus in this article.

The second principle is a conceptual approach which attempts to capture the entire life cycle of a product or system from cradle to grave (Remmen and Munster, 2003). This becomes relevant in today's economy where environmental and social impacts expand across globalised value chains. To account for such impacts life cycle thinking can be operationalized through ecodesign. Ecodesign is defined as the systematic integration of environmental aspects in product design and development in order to reduce the adverse environmental impacts associated with a product across its life cycle (ISO, 2011).

Ecodesign also shares these principles but is more an operational approach to LCM. Much literature exists on ecodesign practices and tools (Brezet and van Hemel, 1997; Domingo et al., 2015; Tischner et al., 2000) and many sources reference specific industries i.e. automotive and electronics that apply ecodesign tools such as life cycle assessment (LCA) and environmental target setting (Alves et al., 2010; Muñoz et al., 2005). Yet, most examples occur on an insular level where pilot demonstrations outnumber systemic changes where ecodesign is an integrated aspect of organizational behaviour. The need for company and industry transitions towards more sustainable behaviours becomes prominent in order to achieve global policy targets such as Sustainable Consumption and Production which represents one of the 17 Sustainable Development Goals (UNDP, 2015). This challenge is also faced by the energy sector which has been identified as a priority production area by the UNEP (2010). The wind power industry is experiencing exponential growth which has implications on material use across all life cycle stages, despite the benefits associated with the production of renewable energy. The purpose of this paper is to explore the application of ecodesign principles and methods within a wind power manufacturer who is responsible for the design, manufacture, construction, and maintenance of wind turbines.

1.1. Research goals

With this background, the authors aim to investigate how ecodesign and LCM concepts can be incorporated in product development for wind power technologies to support sustainable innovation. The research goals are to:

1. Analyse how an ecodesign framework was developed according to a specific organizational context and the LCM principles. This aim is addressed in Section 2 of the article.
2. Present the ecodesign framework and indicate how it was aligned with existing product development processes in the case company. This aim is addressed in Section 3 of the article.
3. Indicate how the ecodesign framework can be applied in combination with LCA methodologies and communicate lessons learnt from the ecodesign framework's development and pilot within the case company. This aim is address in Section 4 of the article.

This research has been conducted in the applied setting of the Wind Power and Renewables division of Siemens AG, hereafter referred to as Siemens Wind Power (SWP). The setting provides a generative opportunity to pursue the research objectives since the company a) is a major player that is ranked amongst the three largest wind turbine manufacturers globally (BTM, 2013) and operates within a range of activities spanning across a wind turbines life cycle, b) is already engaging in activities that support ecodesign and environmental awareness across the value chain according to the European legislation (EC, 2009b), and c) is relatively young meaning organizational aspects are not yet fully established and are thus conducive to standardization improvements.

2. Methodology for developing the ecodesign framework

The ecodesign framework was iteratively developed in four years using a multimethod approach to facilitate stakeholder engagement. The framework is also aligned with the LCM principles related to stakeholder participation and life cycle thinking.

2.1. An iterative research design

The research process followed a non-linear and iterative methodology (Blessing, 2009). The ecodesign framework was designed with constructive and reconstructive iterations of Lewin's (1946) plan-act-observe-reflect spiral. Developing the ecodesign framework involved planning the framework based on document analysis, applying the framework by putting ecodesign into action, observing the outcomes by gathering user feedback and then re-formulating the framework based on user inputs. The ecodesign framework was designed within the period 2011–2014, evolving over five iterations. The latter iterations are thus based on a combination of user inputs and the self-reflective learning gained from previous iterations. The spiral's cycles of planning, acting, observing and reflecting do not always occur in a linear or simultaneous fashion but rather overlap and sometimes run in parallel which is a common characteristic of iterative designs (Blessing, 2009).

2.2. Participatory and multimethod elements

The ecodesign framework follows suggestions by social theorists like Ho (2005) and Reckwitz (2002) who place routinized practices and their construction at the centre of behavioural analysis. Social units with common basis for practice, described as "communities of practice" (Wenger, 2000) go through a participatory process. Participation is described as "*a process of investigating, understanding, reflecting upon, establishing, developing and supporting mutual learning between multiple participants in collective 'reflection-in-action'*" (Simonsen, 2012). To establish the ecodesign framework in a participatory way, the authors use action research which involves team work as part of a community of practice to improve the way solutions are reached (Chevalier, 2013; Lewin, 1947; Susman and Evered, 1978).

To enable a participatory approach various methods were applied during the design process. Some iterations used quantitative approaches in order to investigate the degree to which phenomena occurred while in other iterations qualitative approaches were used to investigate the nature of things (Blessing, 2009). The use of multimethod tools such as the ones listed bellow and further detailed in supporting information (Table A) facilitated the environmental and technical employees to construct a common understanding of ecodesign.

- Document analysis e.g. company process diagrams, procedures, organizational charts
- Workshops (supporting information Table B)
- Semi-structured interviews (supporting information Table C)
- Questionnaires
- Visualization materials e.g. conceptual models of life cycle thinking
- Canvas mapping e.g. stakeholder mapping, functional mapping, rating scales
- Pilot projects to test tools and approaches
- LCA and Life Cycle Costing

Employee inputs were collected through continuous dialogue in an informal setting and through a series of activities ranging within the scale of stakeholder involvement: a) participation i.e. workshops, b) consultation i.e. interviews, and c) information i.e. training. The participatory nature enabled an open and responsive approach for the various inputs from the employees, it aimed to ensure feasibility of the outcomes and facilitated engagement and ownership as literature suggests (Bano and Zowghi, 2015). It also led to capacity building on life cycle thinking and ecodesign. The involved stakeholders, participatory methods and the corresponding iterative outputs for each iteration are also outlined in Table 1.

Based on the combination of user inputs, the research design can be further classified as critical participatory action research (Kemmis et al., 2014). This is due to the participatory approach in the iterations, the social and educational process for those collectively involved, and the degree of evolution in practice.

2.3. Life cycle based elements

The participatory design process previously described stems from a qualitative perception of sustainability and is in line with the argument that sustainability is about more than just the fulfilment of indicators; instead it is about the way individuals engage with each other (Scerri and James, 2010). However ecodesign also needs to rely on quantitative approaches for target setting. Facts based evidence is needed to direct environmental target setting and answer questions such as "*how* to assess the environmental impacts?" and "*which* of these impacts are deemed relevant for setting and measuring improvement targets?". LCA is a scientific methodology, which can be used to answer such questions (EC, 2010).

LCA quantifies environmental inputs and outputs in the life cycle of products. It further employs natural science to identify and describe causal links between these and the related environmental impacts. LCA ensures scientific robustness, assists in identifying the products largest impacts, compares alternatives, and thereby sets the focus right for ecodesign (Hauschild et al., 2004). For these reasons LCA was the preferred methodology for environmental assessments at SWP and has been used within the ecodesign framework development to support environmental target setting in the product development process when relevant.

Life cycle based elements were employed from the first to the last design iteration evolving and expanding in scope and goals. In I-2 (of Table 1) an LCA and Life Cycle Costing method was performed for a rotor blade, which is a key component of a wind turbine. The results were presented to employees from engineering, project management and communication functions to gather input on the tools application. In I-5 four full scale LCAs were performed which covered a large percentage of SWPs product portfolio and

Table 1
Ecodesign iterations applied at Siemens Wind Power.

Iteration	Timeframe	Methods and outputs	Internal stakeholder participation
I-1	2011	Suggestions for environmental review points in PLM (gates/milestones)	EHS specialists (2)
		Workshop with EHS specialists to specify environmental review points in PLM (gates/milestones)	EHS and Quality specialists (20+)
		Refinement to suggested environmental review points in PLM (gates/milestones)	Quality specialist (1)
I-2	2012	Eco Care Matrix (combining LCA and Life Cycle Costing) applied to a product component (Wegener et al., 2011, 2009)	EHS specialists (6)
		Workshops (3) with cross-functions to determine Eco Care Matrix applicability	EHS specialists (6), Sales, Marketing, Communication specialists (5), PLM, Project Managers, Design Engineers (13)
I-3[a]	2012–2013	Suggestions for environmental review points in PLM (gates/milestones) and instruction with appended checklist and target setting guide	EHS specialists (2), Project Manager (1)
		Workshop with Project Managers to gather feedback for environmental review points and instruction	Project Managers (8), EHS specialists (5)
		Pilots with six component projects	Project Managers (6), EHS specialists (4)
		Questionnaires to gather feedback on process one year post implementation	Project Managers (10)
		Refinement to Instruction with checklist and target setting guide to include health and safety	EHS specialists (4), Project Managers (1)
I-4	2013–2014	Semi-structured interviews with cross-functions to determine 1) environmental and life cycle relevance in current product development practices, and 2) stakeholder participation in current product development practices (Table C, supporting information)	PLM, Project Managers, Design Engineers (10), Procurement specialist (1), Quality specialist (1), EHS specialists (2)
		Suggestions for Ecodesign Framework including environmental review points in PLM (gates/milestones)	EHS specialists (5)
		Workshop with Design Engineers to gather feedback for Ecodesign Framework (applied in another division of Siemens AG)	EHS specialists (4), Design Engineers (3)
		Pilots with two product platform projects	EHS specialists (3), PLM, Design Engineers (6)
I-5	2014	LCAs performed on four product platforms and EPDs compiled (Siemens, 2014a)	EHS specialists (5), Design Engineers (+20), PLM (3)
		Workshops (4) with Sales and PLM specialists to educate about LCA and LCA results, and to discuss external communication of LCA results	EHS specialists (3), Sales, Marketing, Communication specialists (60), PLM specialists (30)
		Extension of I-3 where environmental information and the target setting guide were integrated in a pre-existing design manual (company-wide); and health and safety information in was integrated in the instruction with appended checklist and target setting guide (specific to the one business unit)	EHS specialists (4)

[a] The third iteration was applied to one business unit while the other iterations were company-wide.

presented in the form of Environmental Product Declarations (EPDs) (Siemens, 2014a). The LCAs covered the entire life cycle encompassing raw material extraction, materials processing, manufacturing, installation, operation and maintenance, and dismantling and end-of-life. Analyses were also carried out for both onshore and offshore wind power plants. The project took two years to complete, it involved a number of cross-functions and it had a steering committee designated that consisted of six product managers. The project was successful from an ecodesign practice perspective, in that it:

- Initiated constructive dialogue with external stakeholders of the extended value chain i.e. suppliers and customers;
- Informed multiple employees and managers from different functions outside of Environment, Health and Safety (EHS); and
- Increased the motivation and initiated momentum for further product related environmental activities.

3. The resulting ecodesign framework in an organisational context

The ecodesign framework was aligned with SWP's existing processes in order to reduce the gap between the framework developers and end users. This validates the ecodesign framework and its accompanying tools in an applied setting. The framework's association with established company processes related to product development are detailed in Sections 3.1 and 3.2. The final ecodesign framework described in Section 3.3.

3.1. Existing process for product development

Product Lifecycle Management (PLM) is the overarching process for all other product development activities in SWP (Fig. 1). It includes the customer-oriented strategic planning, design and development, monitoring and phase-out activities of the whole product life cycle. The goal of the process is to increase customer value and profit through the development of products and does so by combining various people, processes, information and tools (Stark, 2011). Products in PLM represent new or revised products, components, technologies or services hereafter called product.

The company's PLM consists of four stages and seven substages:

Define: A new or revised product is defined and strategically planned. This stage, often termed the Fuzzy Front End, represents the time between when a product idea is conceived and when resources are given to its formal development (Gassmann and Schweitzer, 2014). It is characterised as an unstructured and informal period because information is more important than a structured approach (Barquet et al., 2013). During scoping product ideas and market trends are acquired and evaluated and a product requirement specification is formed. During feasibility a product design specification is iteratively defined and different technical solutions are evaluated based on feasibility. The requirement and design specifications are than aligned and the Product Development Process is employed.

Realize: In contrast to the Fuzzy Front End, the Product Development Process represents the time where the tangible changes in product development occur. It is characterized as a structured and formal period. Product design is carried out and a number of prototypes are built for test and evaluation. Progress in product development is controlled through gates and milestones following the Stage-Gate system (Cooper, 1990).

Commercialize: The product design is transferred to the supply chain for serial production, product monitoring and servicing.

Phase Out: The end of PLM signifies the closure of production and marketing followed by the end of guarantee and service time.

3.2. Need for alignment

Alignment with the PLM was a natural choice for two main reasons:

- Ecodesign literature supporting alignment with formal product development processes; and
- SWP being a very process oriented company. Further explanations are provided below.

A number of authors suggest the need for environmental checkpoints within the product development process (Bras, 1997; Johansson, 2002). Aligning environmental reviews in the already established and formalised PLM via a number of gates and milestones is thus a logical way to organize and manage product related environmental activities at SWP and satisfy the integrated management system requirements. Lindahl (2006) also indicates that ecodesign should be adjusted to different company contexts and to different communities within a company because they possess different cultures and have different practices for performing tasks. A decision to have a flexible method linked to the PLM was made by environmental specialists in I-1 and was later reinforced by engineers in I-3 and I-4 (Table 1). It ensures ecodesign will remain in the context of SWP's innovation activities and it attempts to reduce the gap between the framework developers i.e. EHS functions and the end users i.e. engineers and project managers.

SWP considers processes the backbone of its operations. Processes are a main entry point into the integrated management system and act as a compliance measure with internal and external stakeholder requirements. Furthermore, processes maintain product excellence in respect to quality, environment, health and safety. Processes are used to document workflows; describe tasks, deliverables and interfaces; and assign roles and responsibilities at SWP.

The ecodesign framework correlates best with the PLM stages when the Product Development Process is employed. This is because the Product Development Process:

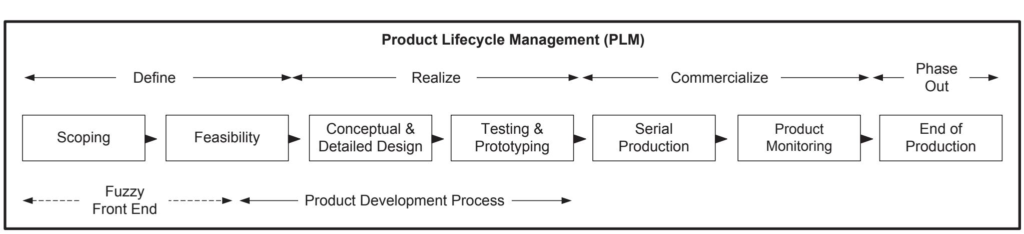

Fig. 1. Overview of Siemens Wind Power's product lifecycle management process.

- Has the broadest scope of all sub-processes covering all critical aspects of product development, involves both strategic and tangible aspects and the largest number of cross-functional stakeholders;
- Is based on a number of sequential phases that must be approved via a milestone or gate review;
- Is defined more extensively than the other sub-processes and undergoes a revision process every year; and
- Is the most referenced sub-process by cross-functional employees.

3.3. The ecodesign framework

The ecodesign framework presented in Fig. 2 was designed based on the international standards for ecodesign, specifically ISO/TR 14062:2002 and ISO 14006:2011. After which, it was aligned with the PLM process, or more specifically the Product Development Process.

In line with Birch et al. (2012) the terms *ecodesign* and *design for environment* are used synonymously. This article uses the term ecodesign but SWP's ecodesign framework uses *design for environment* in its title and descriptions. This is because the *design for X* (where X can be **S**erviceability, **D**isassembly, **R**emanufacturing, etc.) concept is well known to a number of disciplines due to its practitioner focus and has experienced a high success rate in industrial applications (Dombrowski et al., 2014; Huang and Mak, 1998). Using *design for environment* is thereby an attempt to decrease the division between product development and environmental functions, who have traditionally operated separate from one another, by giving more meaning to the end users (Ehrenfeld and Lenox, 1997).

The ecodesign framework can run on three levels:

Product: Ecodesign decisions begin in the Fuzzy Front End (scoping and feasibility in PLM) and can affect one or a range of products in the portfolio e.g. substitution of material x for all wind turbines by 20xx.

Component: Ecodesign begins in the early Product Development Process stages (feasibility and design in PLM) and affects one or more components e.g. reduction of process waste during blade y production, reduction of parts for nacelle z.

Systems: Ecodesign decisions are driven outside PLM on a project basis and affect cross-functions other than engineering and project management e.g. environmental targets related to suppliers, project installation, service, etc.

Furthermore, it is divided into seven stages, encompasses the full product life cycle and correlates with specific gates and milestones throughout PLM:

Environmental requirements: The framework begins by identifying, evaluating and prioritizing environmental requirements according to significance and improvement potential. Examples include legislation, stakeholder requirements, strategic goals, high impacts realized in former LCAs, annual targets and market analyses.

Environmental strategy: A reference product is selected, cross-functional team designated, and environmental product strategy formulated based on the prioritized requirements.

LCA decision and **eKPIs***:* An explicit decision whether an LCA, EPD, or other forms of communication are necessary. Environmental improvement targets (eKPIs) are formulated and responsibility is assigned. There are minimum requirements of one LCA and one EPD per product platform and one environmental improvement target per project. These steps are to be performed in parallel to the PLM and recorded in the requirement specification.

Preliminary data collection: In relation to these decisions preliminary data is collected.

Implementation, evaluation and preliminary results: The LCA methodology and ecodesign framework are iteratively applied and evaluated after the product design specification is defined.

Final results: Design changes during prototyping, simulations or tests are compared against the reference product e.g. via bills of materials, design drawings, supplier specifications, waste measurements, etc. Final results and environmental effects are documented, including trade-offs prior to serial production.

Communication: Relevant aspects and improved environmental features of the product should be included in an environmental communication plan that can be directed at external stakeholders for informative purposes or used internally for management and employee motivation.

To address the environmental assessment and improvement needs, methods and tools that serve different purposes accompany the ecodesign framework (see Table 1 and supporting information). For example, guidelines, which are also known as process descriptions, were created to facilitate ecodesign, conduct LCAs and compile EPDs. A checklist is used to ensure management involvement i.e. checklists are to be completed and filed alongside other PLM documentation by the project manager. An environmental target setting guide encompassing all life cycle stages of a wind farm project ensures focus in life cycle based improvement targets and enforces capacity building (I-3 of Table 1). Use of such methods and tools is also in line with literature (Byggeth and Hochschorner, 2006; Karlsson and Luttropp, 2006).

4. Results after applying the ecodesign framework

The discussion in this section on the usefulness of the ecodesign framework are based on the authors' empirical work throughout the four years and are synthesized based on the iterations from Table 1 i.e. inputs from cross-functional employees during the workshops and semi-structured interviews and outputs from the application of LCA. The empirical results are also supplemented with literature. Section 4.1 discusses the benefits of combining the ecodesign framework, which is a qualitative element, with the quantitative elements of LCA. Section 4.2 highlights some lessons learned based on the iterations and may prove useful to other companies interested in ecodesign.

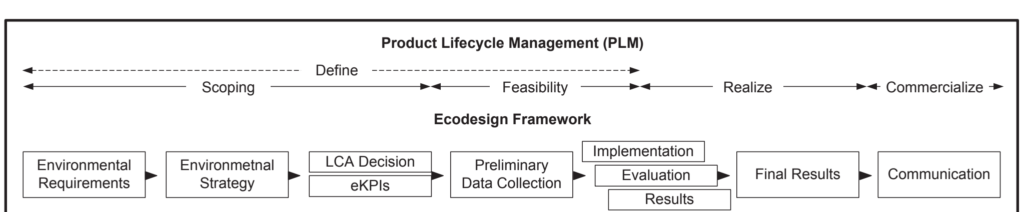

Fig. 2. Overview of Siemens Wind Power's aligned ecodesign framework.

4.1. Combining qualitative and quantitative ecodesign elements

LCA is used to show how quantitative methods can inform strategic target setting in SWP in the support of sustainable innovation. Sustainable innovation can occur at three levels:

- Technological (Section 4.1.1);
- Organizational (Section 4.1.2); and
- Societal (Section 4.1.3) (Eco-innovation Observatory, 2013; NBS, 2012).

The purpose is to identify the added value brought by LCA in product development throughout the ecodesign framework at these different levels.

The goal is not to extensively detail the inventory data or focus on the accuracy of the specific LCA results. For this reason, assessment results are shown at midpoint level and only for one impact category i.e. climate change (kgCO_2-eq). SWP also uses climate change in its EPDs because:

- Stakeholders are more aware of, and can more easily relate to, this impact category (Weidema et al., 2008);
- Energy systems are globally a main contributor to CO_2 emissions (Canadell et al., 2007); and
- Alternative energy sources are evaluated upon their contributions to climate change (Evans et al., 2009).

A full scale LCA was conducted for an average, European onshore wind power plant with 20 SWT-2.3-108 wind turbines. The system has been modelled in SimaPro v.8 software on the basis of ecoinvent v2.2 (Frischknecht et al., 2004) background data. The impact assessment has been done based on the recommendations by the International Reference Life Cycle Data System (EC, 2010). The details of the LCAs are reported in separate publication and it is beyond the scope to present them here. Instead the authors aim to showcase the value of the LCA results in initiating discussions towards sustainable innovation. For this reason Fig. 3 illustrates the contribution of the life cycle stages to climate change and presents the contribution of the different plant components to the impacts from the life cycle stage ‘materials’.

Materials and manufacturing account for more than 90% of a wind turbines impact. This is in line with literature, e.g. Haapala and Prempreeda (2014) report a 78% contribution from materials to the total impact for a two MW turbine while Guezuraga et al. (2012) report more than 84%. IPCC also identifies infrastructure the main culprit for a systems environmental performance (Wiser et al., 2011).

Conventional environmental target setting in SWP focuses on energy and waste reductions during the manufacturing stage. However, the manufacturing stage accounts for only 8% of the total impact in a life cycle perspective. Conversely, the tower is the most significant component in the materials life cycle stage. Ensuring steel recycling at the end of life would lead to environmental savings due to the avoided production of primary steel (negative values in Fig. 3).

This broad systems view identifies hot spots and the relative importance of different life cycle stages. It is particularly useful in the Fuzzy Front End of the PLM (Fig. 1) because it can be used for strategic environmental planning to indicate where efforts and resources can be directed to maximise improvements across the life cycle. Its use it thus, directed towards the top and middle management functions in product development that have the ability to make strategic decisions e.g. platform owners, chief technology officers, chief engineers. The next three subsections will position LCA within the technological, organizational and societal levels of sustainable innovation.

4.1.1. Technological level: sustainable innovation within the company

The technological level represents sustainable innovation on an individual component i.e. rotor blade, or a technology i.e. casting process. The value of LCA based environmental target setting was investigated for the case of a rotor blade design. LCA results revealed that the consumption of materials i.e. epoxy and fibreglass is responsible for more than 60% of the total impacts associated with the blade. LCA results highlighted that cutting down on materials such as Teflon and epoxy could be more effective compared to conventional targets for energy savings during manufacturing (Bonou et al., 2015).

4.1.2. Organizational level: sustainable innovation across the supply chain

The organizational level represents sustainable innovation in a value chain. Based on SWPs internal documentation, customer requests in regards to LCAs and other environmental information have increased between 2011 and 2014. Further, some customer requests have become more sophisticated with some customers inquiring about the total cost of ownership and the levelized cost of energy (Oliveirade, 2012). Thus life cycle thinking on a cost assessment level is an emerging external driver. The LCA results revealed that steel recycling at the end of life could offset 19% of climate change impacts due to the avoidance of primary steel production. Such information could be combined with an economic assessment of the end of life management of the wind power plants i.e. the savings from selling the metal scrap in the secondary steel market. In an interview in I-4 (Table 1) however, the head of product marketing indicates that such information is not a typical prerequisite in tenders, nor is strategic life cycle planning.

Similarly another example of sustainable innovation at the organizational level is that of alternative business models, such as the transition from the sale of an asset to that of a service, or product-service system (Cherrington, 2012; Mont, 2002). In relation to wind turbines, ownership of the generator could be retained by SWP who then sells the function of the product i.e. energy production through a leasing agreement rather than the sale of a tangible asset i.e. wind turbine. Doing so could improve the service the generator receives and extend its lifetime, while also securing ownership over the magnets that contain rare earths that are vulnerable to supply and cost volatilities (Hatch, 2012). In an interview in I-4 (Table 1) the head of product marketing acknowledged the strategic potential of a buy-back system but challenged its feasibility and its implications to the current business case.

4.1.3. Societal level: sustainable innovation to create shared value in society

The societal level represents sustainable innovation and socio-economic transitions across broader society, involving a number of other stakeholders outside the traditional value chain. Customer requests have not only grown, but have also matured in their scope of sustainability. The broadening of focus from an environmental to a societal one adds additional dimensions of impact assessment. Growing concerns about the wind power industry are related to its societal benefit i.e. social acceptance, local community involvement and local employment opportunities (Thabrew et al., 2009).

In such cases, methodologies such as Life Cycle Sustainability Assessment can be employed where LCA is coupled with Life Cycle Costing and Social LCA to support decisions that encompass all sustainability pillars in a life cycle perspective (Kloepffer, 2008). An

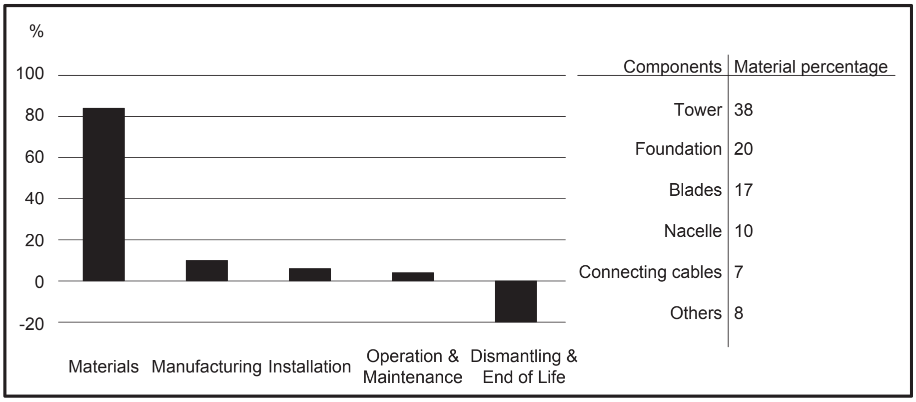

Fig. 3. Contribution of life cycle stages to climate change for an average wind power plant (20 SWT-2.3-108 turbines).

example from I-5 (Table 1) relates to a number of projects where LCA data was combined with economic and social criteria to help customers determine the positive benefits of wind power plants to society using different life cycle methodologies. The social cost of energy is another example where SWP has iterated. The company has determined that broadening the scope of electricity cost calculation is necessary in order to compare different energy technologies based on actual social burdens and benefits. The calculations indicate that the cost of wind power, and specifically offshore wind power, is 60€/MWh in comparison to traditional fossil based energy sources that range between 61 and 107€/MWh (Siemens, 2014b).

4.2. Lessons learned from the ecodesign frameworks design iterations

Section 4.1 aimed to demonstrate the kind of discussions that quantitative approaches like LCA can intrigue and the kind of changes it can direct towards. However, ecodesign efforts in SWP to date have been primarily about developing tools and processes and engaging stakeholders rather than making actual product improvements. In I-2 of Table 1 functions other than environmental specialists reveal strong support for, and interest in, having more environmental information. Specialists from sales, communication, engineering and project management functions confirm the potential use of environmental information both externally and internally. The following are a number of lessons learned from the iterations. They include calling for assigned responsibility through eKPIs at project and functional levels; adaptive learning approaches to ecodesign based on continuous improvements; and additional capacity building amongst employees in life cycle thinking.

4.2.1. Assigned responsibility through key performance indicators

In I-3 of Table 1, the instruction with appended checklist and target setting guide underlines the project managers' responsibility in setting environmental targets and the environmental specialists' role as support function. Recent literature indicates a lack of sustainability integration in project management functions (Brones et al., 2014; Marcelino-Sádaba et al., 2015), which is one reason why requirements for project managers were established at SWP during I-3, rather than engineers who are traditionally identified as the key stakeholder function in ecodesign. Moving from the tactical to strategic level, literature also suggests the responsibility at the product portfolio management level (Brook, 2014).

Still, formalisation is not enough to ensure engagement in sustainability initiatives. A year after piloting the checklist and environmental target setting in I-3 of Table 1, 12 project managers provided feedback on their capacity building needs (Table 2). All 12 respondents indicated that eKPIs were relevant to product development projects and five believed that their position in the PLM was correct. However, only three respondents were aware of the checklist and eKPI requirements and only one thought the procedure was implemented and fully functioning. Four respondents believed there were obstacles preventing them from focussing on, or allocating time to, environment subjects altogether. Evidence suggests there is interest in ecodesign but further capacity building is needed for the environmental requirements in PLM. A number of suggestions for improving the current target setting process were made, including more target setting support from environmental specialists and design engineers.

Same is the picture on a strategic level. During I-4 of Table 1 the product portfolio manager expressed difficulties integrating environment, as there were no overarching portfolio strategies related to environmental improvements. This lack of engagement also relates to cross-functions operating with different intentions and overall goals throughout the PLM.

To address these challenges eKPIs are recognized as important elements in assigning responsibility at four different levels: portfolio; project, employee; and functional. Setting eKPIs would assign accountability and help to maintain commitment and continuity that now is ad hoc e.g. I-4 of Table 1 one project manager emphasized that environmental improvements were often inherently part of cost or quality targets but not explicitly labelled as such. Thus, eKPIs would be more effective if combined with existing measures i.e. also in I-4 of Table 1 another project manager stressed the need for ecodesign activities to be closely linked to employees' personal performance measurements and functional targets. Co-creating such eKPIs together with the employees that use them would further strengthen engagement. Petersson et al. (2013) indicate that ownership is a motivational factor for employees, particularly when they have contributed to developing indicators that suit their specific work situations.

4.2.2. An adaptive learning approach based on continuous improvements

The ecodesign framework's development has followed an iterative process of continuous improvement and cross-functional participation (ISO, 2002, 2011). It occurs in a phased approach that starts small and incrementally expands throughout the company with the overall aim to become rooted in the organizational culture, or routine way of developing products. Shelton (1995) suggests this gradual evolution helps to generate learning and minimize opposition from management and cross-functions. The

Table 2
Capacity building needs obtained through employee feedback one year after onset.

Responses to environmental checklist and target setting guide (I-3 of Table 1)	Number in support (12 total)
Environmental target setting is relevant to product development projects	12
Environment is placed in the correct PLM gates and milestones	5
Awareness of the checklist and environmental target setting requirements	3
Procedure is implemented and fully functional	1
Obstacles exist and prevent focus on, or allocation to, environment improvements	4

iterations presented in Table 1 between 2011 and 2014 show the adaptive learning which can be summarized below:

External drivers lead to internal momentum: Creating the ecodesign framework and using LCA were externally driven by requirements primarily from customers. In I-4 of Table 1, a design engineer admitted that unless there is a legislative or customer requirement, little attention is paid to product related impacts. However, after completing the EPDs in I-5 the environmental specialists have received internal requests to assist in target setting and to perform additional LCAs, indicating some degree of internal environmental momentum.

Combining top down and bottom up approaches: Shelton (1995) emphasizes the importance of corporate functions leading the initial stages of ecodesign implementation but cautions that it must be embedded in, owned by, and customized to, the different cross-functions. For this reason bottom up (I-2 and I-3 of Table 1) and top down (I-1, I-4 and I-5 of Table 1) approaches were used. Feedback identified the need for more management attention in the gate and milestone reviews, in addition to more training and capacity building. Design engineers in I-4 of Table 1 also expressed their need for more ecodesign knowledge and requested the involvement of other functions throughout PLM.

Need for simple but scientifically robust information: Concerns about complexity were raised in all iterations of Table 1, particularly with respect to tool use. Between I-1 and I-3 the number of environmental review points in PLM was significantly reduced and between I-3 and I-5 the checklist was simplified. In I-2 there was a lot of opposition to combining environmental with cost data e.g. the Eco Care Matrix (Wegener et al., 2009, 2011). However, the head of product marketing insisted that any environmental tool must be closely interlinked with existing PLM tools. Ecodesign tools and methodologies i.e. workshops, procedures, checklists, LCAs, etc. are used to assess and improve products. Their usefulness and success requires a balance between complicated and oversimplified elements. Ritzén (2001) advocates that tools facilitate learning and collaboration amongst users provided they are resource efficient and remain easy to comprehend and apply.

Different tools for different cross-functions: In SWP there are different business units that manufacture, assemble and service wind turbines. These have different contexts and will approach ecodesign differently both in terms of focus as well as in terms of tools e.g. process optimization is important in manufacturing while supplier collaboration is important in assembly. The iterations in Table 1 involved different ecodesign activities i.e. workshops, checklists, LCAs that resonate differently to the different functions, otherwise referred to as practice communities.

Different ecodesign possibilities for different product, technology and service types: Product maturity affects the degree of ecodesign possible; incremental ecodesign e.g. optimizations in mature products and radical ecodesign e.g. modifications in existing and new products with high growth potential (Shelton, 1995). A project manager in the manufacturing business unit indicated during I-3 of Table 1 that eKPIs are easier applied to product revisions rather than to new products due to lower uncertainties.

Engaging relevant stakeholders ensures feasibility: Ecodesign should target a number of cross-functions. It was suspected while piloting in I-3 and confirmed in I-4 of Table 1 that eKPIs in the Product Development Process was late in the PLM. A design engineer explained that if eKPIs were not specified in the requirement specification then resources would not be allocated for environmental improvements. He emphasized that engineers can offer environmental improvement ideas and possess interest, but have relatively low decision power in the PLM. Thus, I-4 and I-5 have begun targeting the product portfolio managers operating in the fuzzy front end alongside the project managers and design engineers. Johansson (2002) confirms that environmental issues must be included when establishing a company's technology strategy. The environmental product strategy is included in the second stage of the ecodesign framework (Fig. 2). Future ecodesign work at SWP must expand to involve other cross-functions including procurement and service specialists.

Engaging management at the right time is catalytic: Timely management involvement will also ensure support for resource allocation i.e. time, funding or training. In I-4 of Table 1 design engineers expressed concerns that they would be expected to do more within the same time and cost constraints of a project. In I-5 the resource availability for additional LCA studies remains unclear. Dewulf (2004) stresses the importance of management involvement since many decisions affecting ecodesign must be made at strategic levels. Improvement options most environmentally beneficial are those requiring a change of business strategy or technology, which can only be initiated by management.

Communication and stakeholder skills facilitate learning and thereby implementation: Environmental specialists should also be equipped with stakeholder management techniques to better communicate ecodesign, particularly LCA results. Most employees were highly interested in the LCA results during I-2 and I-5 of Table 1. However, there were a group of design engineers in I-4 who were introduced to LCA results that revealed high environmental impacts for the component they were responsible for. One of the engineers was highly disgruntled by the LCA results, claiming they were a “disgrace to their work”, while another was more impressed by the level of detail LCA provided regardless of the specific results. The authors agree that disagreement is often a good basis for discussion but LCA is not intended to assign blame. Environmental specialists should remain sensitive to stakeholder needs and perceptive to the way results are presented. Clear and objective communication of ecodesign progress e.g. by showcasing successful project improvements can increase motivation, facilitate buy-in and enhance cooperation from technical functions if done correctly (Johansson, 2002).

In support of continuous improvements, maturity models and improvement roadmaps (Pedersen, 2002; Pigosso et al., 2013) have been previously recommended to assist companies in systematically implementing ecodesign and could potentially help SWP in its continued efforts.

4.2.3. Further capacity building in life cycle thinking needed

Employee feedback showed a weak understanding of the different life cycle stages and perceived relevance to their functions.

Especially I-2 to I-4 of Table 1 reveal the difficulties employees have in understanding life cycle thinking (Fig. 4) and its relevance to product development. Some employees could relate to life cycle stages neighbouring their functional scope e.g. impacts associated with material extraction and transport for a procurement specialist. However, the greater the distance between the employees' function and a life cycle stage, the harder it was to perceive the dependencies. This is likely associated with a lack of related training in and a lack of visible environmental product strategy. However, all employees understood the relevance of life cycle thinking during manufacturing. Manufacturing was most tangible because employees had the ability to make product and process improvements. Also, environmental activities in SWP have traditionally been production-oriented e.g. cleaner production so employees have a better understanding of, and experience with, that life cycle stage.

Although manufacturing has a low impact compared to other life cycle stages, it provides a fertile ground for communicating concepts. Competence training is necessary to increase the awareness and understanding of cross-functions from a life cycle thinking perspective. Bras (1997) and Johansson (2002) also suggest effective forms of capacity building which include, training of the product development functions, support from environmental specialists and examples of good environmental business cases.

5. Ecodesign framework for driving sustainable wind turbine innovations

The purpose of this article was to propose a life cycle based ecodesign framework in the context of SWP and demonstrate how it can be used as a driver for sustainable innovations in components, product systems, technologies and business models.

In Section 2 the authors described how an ecodesign framework was developed using an iterative, action research design approach which relied on the participation of cross-functional employees. Stakeholder involvement was an inherent part of the framework's development through the use of participatory methods and tools in order to elicit input from the employees at different hierarchical levels. The authors and employees worked collaboratively to propose a new course of action towards more environmentally oriented product development practices.

The participatory nature enabled an open and responsive approach to the various employee inputs. The framework was developed based on ISO/TR 14062:2002 and 14006:2011. Five iterations occurred over a four year time frame and methods such as workshops, pilots, interviews and LCA were applied. To date, it continues to be adjusted and implemented based on cross-functional employee feedback.

In Section 3 the authors presented the ecodesign framework and indicated how it was aligned with the company's formal product development processes. The framework was adjusted to SWP's existing PLM process in order to facilitate user adoption since employees were accustomed to working with formalized processes, milestones and gate reviews.

In Section 4 the authors exemplified applications of ecodesign using the framework in combination with LCA. When combined with LCA, the framework can identify potential environmental improvements and contribute to coherent and transparent environmental target setting. This is because LCA serves as the quantitative backbone of ecodesign and assists in the uptake of life cycle thinking. Three select cases demonstrated how both LCA and life cycle thinking can support sustainable innovation broadening the focus from a technological level to organizational and societal levels. The examples showed that LCA enables the company to perform environmental target setting that is scientifically robust and make efficiency and transparency improvements. The information provided by LCA gives a novel view of the company's processes and products, thus identifying risks and opportunities that may otherwise not have been acknowledged.

Further, lessons learned obtained during the design iterations were presented and indicate:

- The importance of official procedures and assigned responsibility: the ecodesign framework correlates with gate and milestones throughout the PLM and requires one eKPI per project. Further responsibility could be assigned via portfolio, employee and functional specific eKPIs.
- The need for adaptive learning approaches based on continuous improvements: the iterations allowed for progressive advancements and continuous improvements in the development of an ecodesign framework. Other important points related to a combination of approaches from bottom up to top down, a simplified approach balanced with quantitative methods, variables in approach and tool selection depending on cross-functions and project scope, importance of employee and management participation, and the positive effects of communication and stakeholder management skills on learning.
- The need for capacity building in life cycle thinking: this lesson is a pre-requisite to the previous and should be an integrated element in the framework.

Although the lessons learned may appear self-evident many companies continue to struggle in rooting sustainability in their design practices. Given this fact, the lessons learned can be a reminder that beyond normative views e.g. how things should be; there is often another reality i.e. how things are. This research demonstrates the value of life cycle thinking in an applied setting and shows how ecodesign can initiate constructive dialogues with multiple stakeholders and build sustainability momentum. The process and learnings may provide useful information for managers and researchers seeking to introduce environmental considerations into product development, and companies on a more general level. Earlier ecodesign discourse did not focus on embedding the life cycle tools and concepts within business processes but rather on

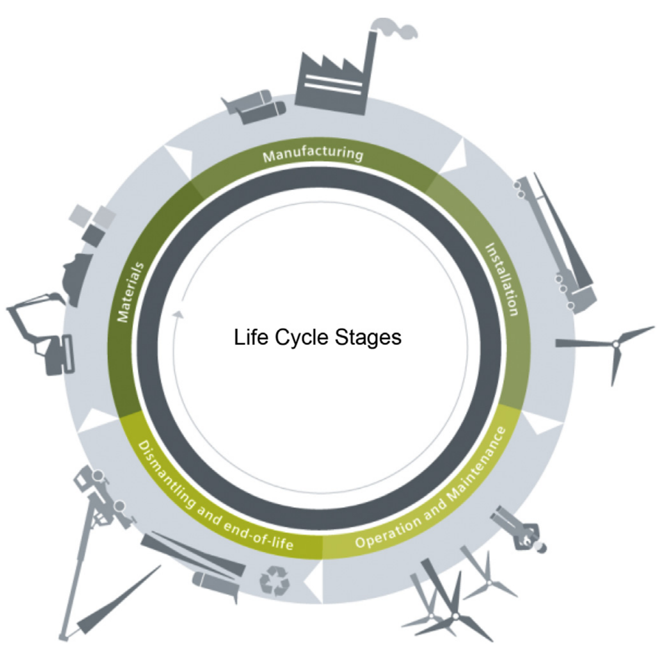

Fig. 4. Conceptual model of life cycle thinking used to determine how it applies to the daily work of internal cross-functions (Siemens, 2014a).

pilot projects and ad hoc approaches, often neglecting the work needed for process integration and behavioural change (Ammenberg and Sundin, 2005; Brezet and Rocha, 2001; Charter, 2001).

The intention of this paper was to shift the focus from the single ecodesign applications to an integrated approach based on continuous iterations and learning amongst the different functional communities. Such an approach requires further research into cross boundary practice and system integration so methods, data and tools can be combined for various levels of environmental decision-making.

Acknowledgements

This research has been carried out as two industrial Ph.D. projects in the Wind Power and Renewables division and the Corporate Technology department of Siemens AG. Funding was provided by Innovation Fund Denmark. The opportunity and support is gratefully acknowledged, particularly from Tine H. Jørgensen. The authors are further thankful for the honesty and openness of those interviewed and for their lively discussions.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.02.093.

References

Alves, C., Ferrão, P.M.C., Silva, A.J., Reis, L.G., Freitas, M., Rodrigues, L.B., Alves, D.E., 2010. Ecodesign of automotive components making use of natural jute fiber composites. J. Clean. Prod. 18, 313–327. http://dx.doi.org/10.1016/j.jclepro.2009.10.022.

Ammenberg, J., Sundin, E., 2005. Products in environmental management systems: drivers, barriers and experiences. J. Clean. Prod. 13, 405–415. http://dx.doi.org/10.1016/j.jclepro.2003.12.005.

Angelakoglou, K., Botsaris, P.N., Gaidajis, G., 2014. Issues regarding wind turbines positioning: a benchmark study with the application of the life cycle assessment approach. Sustain. Energy Technol. Assessments 5, 7–18. http://dx.doi.org/10.1016/j.seta.2013.10.006.

Bano, M., Zowghi, D., 2015. A systematic review on the relationship between user involvement and system success. Inf. Softw. Technol. 58, 148–169. http://dx.doi.org/10.1016/j.infsof.2014.06.011.

Barquet, A.P.B.C.A., Pigosso, D., Rozenfeld, H., 2013. Systematic approach to formulate PSS development project proposals in the fuzzy front end. In: Meier, H. (Ed.), Proceedings of the 5th CIRP International Conference on Industrial Product-Service Systems. Springer International Publishing, Bochum, pp. 121–131. http://dx.doi.org/10.1007/978-3-642-30820-8.

Birch, A., Hon, K.K.B., Short, T., 2012. Structure and output mechanisms in design for environment (DfE) tools. J. Clean. Prod. 35, 50–58. http://dx.doi.org/10.1016/j.jclepro.2012.05.029.

Blessing, L.T.M., 2009. DRM, a Design Research Methodology. Springer.

Bonou, A., Olsen, S.I., Hauschild, M.Z., 2015. Introducing life cycle thinking in product development – a case from Siemens wind power. CIRP Ann. Manuf. Technol. 64, 45–48. http://dx.doi.org/10.1016/j.cirp.2015.04.053.

Bras, B., 1997. Incorporating environmental issues in product design and realization. Ind. Environ. 20, 7–13.

Brezet, H., van Hemel, C., 1997. Ecodesign: a Promising Approach to Sustainable Production and Consumption. UNEP and TU Delft, Paris, France.

Brezet, H., Rocha, C., 2001. Towards a model for product-oriented environmental management systems. In: Tischner, U., Charter, M. (Eds.), Sustainable Solutions: Developing Products and Services for the Future. Greenleaf Pub, pp. 243–262.

Brones, F., de Carvalho, M.M., de Senzi Zancul, E., 2014. Ecodesign in project management: a missing link for the integration of sustainability in product development? J. Clean. Prod. 80, 106–118. http://dx.doi.org/10.1016/j.jclepro.2014.05.088.

Brook, J.W., 2014. Integrating sustainability into innovation project portfolio management – a strategic perspective. J. Eng. Technol. Manag. 34, 46–62.

BTM, 2013. World Market Update 2013.

Byggeth, S., Hochschorner, E., 2006. Handling trade-offs in Ecodesign tools for sustainable product development and procurement. J. Clean. Prod 14, 1420–1430. http://dx.doi.org/10.1016/j.jclepro.2005.03.024.

Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc. Natl. Acad. Sci. U. S. A. 104, 18866–18870. http://dx.doi.org/10.1073/pnas.0702737104.

Charter, M., 2001. Integrated product policy and eco-product development. In: Tischner, U., Charter, M. (Eds.), Sustainable Solutions: Developing Products and Services for the Future, pp. 98–116.

Cherrington, R., 2012. Producer responsibility: defining the incentive for recycling composite wind turbine blades in Europe. Energy Policy 47.

Chevalier, J.M., 2013. Participatory Action Research: Theory and Methods for Engaged Inquiry. Routledge.

Cooper, R.G., 1990. Stage-gate systems: a new tool for managing new products. Bus. Horiz. 33, 44–54. http://dx.doi.org/10.1016/0007-6813(90)90040-I.

Dewulf, W., 2004. Integrating eco-design into business environments – a multi-level approach. Prod. Eng. Eco-design, Technol. Green Energy 55–76.

Dombrowski, U., Schmidt, S., Schmidtchen, K., 2014. Analysis and integration of design for X approaches in lean design as basis for a lifecycle optimized product design. Procedia CIRP 15, 385–390. http://dx.doi.org/10.1016/j.procir.2014.06.023.

Domingo, L., Buckingham, M., Dekoninck, E., Cornwell, H., 2015. The importance of understanding the business context when planning eco-design activities. J. Ind. Prod. Eng. 32, 3–11. http://dx.doi.org/10.1080/21681015.2014.1000398.

Eco-innovation Observatory, 2013. Europe in Transition: Paving the Way to a Green Economy through Eco-innovation. Annual Report 2012.

Ehrenfeld, J., Lenox, M., 1997. Implementing Design for Environment: a Primer. Digital Equipment Corporation, Maynard, Massachusetts.

European Commission, 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources. OJ L 140/16.

European Commission, 2009b. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-related Products. OJ L 285/10.

European Commission Joint Research Centre Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle Assessment - Detailed Guidance, first ed. Publications Office of the European Union, Luxembourg.

Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renew. Sustain. Energy Rev. 13, 1082–1088. http://dx.doi.org/10.1016/j.rser.2008.03.008.

EWEA, 2014. Wind Energy Scenarios for 2020.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2004. The ecoinvent database: overview and methodological framework (7 pp). Int. J. Life Cycle Assess. 10, 3–9. http://dx.doi.org/10.1065/lca2004.10.181.1.

Gassmann, O., Schweitzer, F., 2014. Managing the unmanageable: the fuzzy front end of innovation. In: Gassmann, O., Schweitzer, F. (Eds.), Management of the Fuzzy Front End of Innovation. Springer International Publishing. http://dx.doi.org/10.1007/978-3-319-01056-4.

Guezuraga, B., Zauner, R., Pölz, W., 2012. Life cycle assessment of two different 2 MW class wind turbines. Renew. Energy 37, 37–44. http://dx.doi.org/10.1016/j.renene.2011.05.008.

GWEC, 2014. Global Wind Report Annual Market Update 2014.

Haapala, K.R., Prempreeda, P., 2014. Comparative life cycle assessment of 2.0 MW wind turbines. Int. J. Sustain. Manuf. 3, 170. http://dx.doi.org/10.1504/IJSM.2014.062496.

Hatch, G.P., 2012. Dynamics in the global market for rare earths. Elements 8, 341–346. http://dx.doi.org/10.2113/gselements.8.5.341.

Hauschild, M.Z., Jeswiet, J., Alting, L., 2004. Design for environment — do we get the focus right? CIRP Ann. Manuf. Technol. 53, 1–4. http://dx.doi.org/10.1016/S0007-8506(07)60631-3.

Ho, T.H., 2005. Modeling the Psychology of Consumer and Firm Behavior with Behavioral Economics.

Huang, G., Mak, K., 1998. Re-engineering the product development process with "design for X." Proc. Inst. Mech. Eng. 212, 259–268. http://dx.doi.org/10.1243/0954405981515671.

IEA, 2013. Technology Roadmap – Wind Energy. Paris.

IPCC, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Genebra, Suíça. Cambridge University Press, Cambridge, United Kingdom.

ISO, 2011. ISO 14006:2011 Environmental Management Systems – Guidelines for Incorporating Ecodesign.

ISO, 2002. ISO/TR 14062:2002 Environmental Management – Integrating Environmental Aspects into Product Design and Development.

Johansson, G., 2002. Success factors for integration of ecodesign in product development. Environ. Manag. Health 13, 98–107. http://dx.doi.org/10.1108/09566160210417868.

Karlsson, R., Luttropp, C., 2006. EcoDesign: what's happening? An overview of the subject area of EcoDesign and of the papers in this special issue. J. Clean. Prod. 14, 1291–1298. http://dx.doi.org/10.1016/j.jclepro.2005.11.010.

Kemmis, S., McTaggart, R., Nixon, R., 2014. The Action Research Planner: Doing Critical Participatory Action Research. Springer International Publishing.

Kloepffer, W., 2008. Life cycle sustainability assessment of products. Int. J. Life Cycle Assess. 13, 89–95. http://dx.doi.org/10.1065/lca2008.02.376.

Lewin, K., 1947. Frontiers in group dynamics: II. Channels of group life; social planning and action research. Hum. Relat. 1, 143–153. http://dx.doi.org/10.1177/001872674700100201.

Lewin, K., 1946. Action research and minority problems. J. Soc. Issues 2, 34–46. http://dx.doi.org/10.1111/j.1540-4560.1946.tb02295.x.
Lindahl, M., 2006. Engineering designers' experience of design for environment methods and tools – requirement definitions from an interview study. J. Clean. Prod. 14, 487–496. http://dx.doi.org/10.1016/j.jclepro.2005.02.003.
Luyet, V., Schlaepfer, R., Parlange, M.B., Buttler, A., 2012. A framework to implement Stakeholder participation in environmental projects. J. Environ. Manag. 111, 213–219. http://dx.doi.org/10.1016/j.jenvman.2012.06.026.
Marcelino-Sádaba, S., González-Jaen, L.F., Pérez-Ezcurdia, A., 2015. Using project management as a way to sustainability. From a comprehensive review to a framework definition. J. Clean. Prod. 99, 1–16. http://dx.doi.org/10.1016/j.jclepro.2015.03.020.
Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., Blanco, J., 2009. Life cycle assessment of a multi-megawatt wind turbine. Renew. Energy 34, 667–673. http://dx.doi.org/10.1016/j.renene.2008.05.020.
Mont, O., 2002. Clarifying the concept of product–service system. J. Clean. Prod. 10, 237–245. http://dx.doi.org/10.1016/S0959-6526(01)00039-7.
Mulder, A., 2008. Do economic instruments matter? Wind turbine investments in the EU(15). Energy Econ. 30, 2980–2991. http://dx.doi.org/10.1016/j.eneco.2008.02.005.
Muñoz, I., Rieradevall, J., Domènech, X., Gazulla, C., 2005. Using LCA to assess eco-design in the automotive sector: case study of a polyolefinic door panel (12 pp). Int. J. Life Cycle Assess. 11, 323–334. http://dx.doi.org/10.1065/lca2005.05.207.
NBS, 2012. Innovating for Sustainability: a Guide for Executives.
Oliveira, W.S., 2012. Cost-effectiveness analysis for wind energy projects. Int. J. Energy Sci. 2.
Pedersen, C., 2002. Environmental, health, safety and social life cycle management of moulded-fibre packaging for consumer electronics. In: EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing. Tokyo, pp. 779–785.
Petersson, L., Lennart, S., Bellgran, M., 2013. Green KPI'S as drivers for environmental improvements on shop floor level – a case study at ABB. In: The 6th International Conference on Life Cycle Management in Gothenburg 2013. Gothenburg.
Pigosso, D.C.A., Rozenfeld, H., McAloone, T.C., 2013. Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. J. Clean. Prod. 59, 160–173. http://dx.doi.org/10.1016/j.jclepro.2013.06.040.
Premalatha, M., Abbasi, T., Abbasi, S.A., 2014. Wind energy: increasing deployment, rising environmental concerns. Renew. Sustain. Energy Rev. 31, 270–288. http://dx.doi.org/10.1016/j.rser.2013.11.019.
Reckwitz, A., 2002. Toward a theory of social practices: a development in culturalist theorizing. Eur. J. Soc. Theory 5.
Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431. http://dx.doi.org/10.1016/j.biocon.2008.07.014.
Remmen, A., Munster, M., 2003. An Introduction to Life-cycle Thinking and Management. Copenhagen.
REN21, 2015. RENEWABLES 2015 GLOBAL STATUS REPORT, Paris.
Ritzén, S., 2001. Actions for integrating environmental aspects into product development. J. Sustain. Prod. Des. 1, 91–102. http://dx.doi.org/10.1023/A:1014446421205.
Sarmah, B., Islam, J.U., Rahman, Z., 2015. Sustainability, social responsibility and value co-creation: a case study based approach. Procedia – Soc. Behav. Sci. 189, 314–319. http://dx.doi.org/10.1016/j.sbspro.2015.03.227.
Scerri, A., James, P., 2010. Accounting for sustainability: combining qualitative and quantitative research in developing "indicators" of sustainability. Int. J. Soc. Res. Methodol. 13, 41–53. http://dx.doi.org/10.1080/13645570902864145.
Shelton, R.D., 1995. Organizing for successful DFE: lessons from winners and losers. In: Proceedings of the 1995 IEEE International Symposium on Electronics and the Environment ISEE (Cat. No.95CH35718). IEEE, pp. 1–4. http://dx.doi.org/10.1109/ISEE.1995.514938.
Siemens, AG., 2014a. Environmental Performance- Assessing the Environmental Impact of Siemens Wind Turbines [WWW Document]. URL. http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/epd.htm (accessed 06.01.15.).
Siemens, AG., 2014b. Redefining the Cost Debate – the Concept of Society's Cost of Electricity [WWW Document]. URL. http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/SCOE.htm.
Simonsen, J., 2012. Routledge International Handbook of Participatory Design. Routledge.
Stark, J., 2011. Product Lifecycle Management: 21st Century Paradigm for Product Realisation. Springer.
Susman, G.I., Evered, R.D., 1978. An assessment of the scientific merits of action research. Adm. Sci. Q. 23, 582–603. http://dx.doi.org/10.2307/2392581.
Thabrew, L., Wiek, A., Ries, R., 2009. Environmental decision making in multi-stakeholder contexts: applicability of life cycle thinking in development planning and implementation. J. Clean. Prod. 17, 67–76. http://dx.doi.org/10.1016/j.jclepro.2008.03.008.
Tischner, U., Schmincke, E., Rubik, F., Prösler, M., 2000. How to do EcoDesign. Ein Handbuch für die ökologische und ökonomische Gestaltung. Verlag form, Frankfurt am Main.
TPWind Advisory Council, 2006. Wind Energy: a Vision for Europe in 2030.
UNDP, 2015. Sustainable Development Goals [WWW Document]. URL. http://www.undp.org/content/undp/en/home/librarypage/corporate/sustainable-development-goals-booklet.html.
UNEP, 2010. Assessing the Environmental Impacts of Consumption and Production – Priority Products and Materials [WWW Document]. URL. http://www.unep.org/resourcepanel-old/Publications/PriorityProducts/tabid/56053/Default.aspx.
UNEP/SETAC, 2007. Life Cycle Management: a Business Guide to Sustainability [WWW Document]. URL. http://www.unep.fr/shared/publications/pdf/DTIx0889xPA-LifeCycleManagement.pdf.
UNEP/SETAC, 2009a. Life Cycle Management: How Business Uses it to Decrease Footprint, Create Opportunities and Make Value Chains More Sustainable [WWW Document]. URL. http://www.unep.fr/shared/publications/pdf/DTIx1208xPA-LifeCycleApproach-Howbusinessusesit.pdf.
UNEP/SETAC Life Cycle Initiative, 2009b. Guidelines for Social Life Cycle Assessment of Products. United Nations Environmental Programme. URL http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf.
Vezzoli, C., Ceschin, F., Diehl, J.C., Kohtala, C., 2015. New design challenges to widely implement "sustainable product-service systems." J. Clean. Prod. 97, 1–12. http://dx.doi.org/10.1016/j.jclepro.2015.02.061.
Wegener, D., Finkbeiner, M., Geiger, D., Olsen, S.I., Walachowicz, F., Universität, T., Tub, B., Sut, S., 2009. Comprehensive approach to energy and environment in the eco care program for design, engineering and operation of Siemens industry solutions. RISO Int. Energy Conf. 45–52.
Wegener, D., Finkbeiner, M., Holst, J., Olsen, S.I., Walachowicz, F., 2011. Improving energy efficiency in industrial solutions – walk the talk. In: Proc. Risø Int. Energy Conf. 2011, pp. 187–196.
Weidema, B.P., Thrane, M., Christensen, P., Schmidt, J., Løkke, S., 2008. Carbon footprint. J. Ind. Ecol. 12, 3–6. http://dx.doi.org/10.1111/j.1530-9290.2008.00005.x.
Wenger, E., 2000. Communities of practice and social learning systems. Organization 7, 225–246. http://dx.doi.org/10.1177/135050840072002.
Wiser, R., Yang, Z., Hand, M., Hohmeyer, O., Eld, D.I., Jensen, P.H., Nikolaev, V., O'Malley, M., Sinden, G., Zervos, A., 2011. Wind energy. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stecho, C. (Eds.), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, in. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy 35, 2683–2691. http://dx.doi.org/10.1016/j.enpol.2006.12.001.