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Doctoral Thesis

Anders Arvesen

Doctoral theses at NTNU, 2013:8

NTNU
Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
Faculty of Engineering Science & Technology
Department of Energy and Process Engineering

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Understanding the environmental implications of energy transitions

A case study for wind power

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Preface

They say the devil is in the details. A problem as intricate as climate change has many details and many devils. But this problem has another devil also – a big one, I believe – that sits not in any particular detail, but in the totality of the problem. That is, in the whole that all the details form when they combine and interconnect in subtle ways. What may be needed to bring the devil to light is generally a more holistic view of the problem and proposed solutions. It is my hope that this thesis can contribute to this end. The thesis includes three papers examining the environmental costs and benefits of wind power, and one paper evaluating indirect, countervailing effects of greenhouse gas-mitigating measures.

I wish to thank my supervisor, Edgar Hertwich, for his continued confidence in my abilities over several years and for providing me with the opportunity to pursue a doctoral degree. During the course of the work I have appreciated his solution-oriented view of difficult situations, his open-mindedness to my ideas and his supervision style which has helped me develop as an independent researcher. Another thank you goes wholeheartedly to my partner, Liv Ragnhild, for her support in times of stress and frustration and for giving me reasons to smile when I get home. I thank Liv Ragnhild and Kjartan for their comments on an early version of the Norwegian abstract for the thesis.

Now some technicalities: The thesis is submitted in partial fulfilment of the requirements for the degree of philosophiae doctor at the Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU). The work has been carried out at the Industrial Ecology Programme at NTNU and during a four-month visit at the Swiss Federal Institute of Technology Zurich. The research was funded by the Research Council of Norway (project number 186952). The work has been conducted over a four-year period (2008-2012), for which three year-equivalents of work have been allotted to the doctoral education and one year to teaching assistantship and other work. The doctoral education programme involved a research component and a course work component (one academic semester).

Contents

List of papers with authorship information

This thesis is based on the four papers listed below, which will be referred to by their roman numerals. One further paper [Arvesen, A., J. Liu, E.G. Hertwich. 2010. Energy cost of living and associated pollution for Beijing residents. *Journal of Industrial Ecology* 14(6): 890-901] was produced during the course of the scholarship period, but is not included as part of the thesis.

Paper I

Arvesen, A. and E. G. Hertwich. 2012. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. *Renewable and Sustainable Energy Reviews* 16(8): 5994-6006.

Arvesen performed data collection, analysis and writing. Hertwich supervised the study.

Paper II

Arvesen, A. and E. G. Hertwich. 2011. Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment. *Environmental Research Letters* 6(4): 045102.

Corrigendum:

Arvesen, A. and E. G. Hertwich. 2012. Corrigendum: Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment. *Environmental Research Letters* 7(3): 039501.

Arvesen performed data collection, analysis and writing. Hertwich supervised the work.

Paper III

Arvesen, A., C. Birkeland, and E. G. Hertwich. The importance of ships and spare parts in LCAs of offshore power. *Environmental Science and Technology*. Submitted for publication.

Birkeland performed and presented [Birkeland, C. 2011. Assessing the life cycle environmental impacts of offshore wind power generation and power transmission in the North Sea. MSc thesis, Norwegian University of Science and Technology, Trondheim, Norway] an initial assessment under supervision by Hertwich and Arvesen. Arvesen revised and extended the data collection in Birkeland (2011), performed new analysis and wrote the paper. Hertwich supervised the work.

Paper IV

Arvesen, A., R. M. Bright, and E. G. Hertwich. 2011. Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation. *Energy Policy* 39(11): 7448-7454.

Arvesen conceived of and designed the study and did the majority of the writing. Bright and Hertwich provided critical revision and contributed to the writing.

Abstract

A fundamental change in the ways in which we provide energy to run our economies, an energy transition, is needed to mitigate climate change. Wind power is an important part of future global energy supply in most energy scenarios. This thesis aims to contribute to a better understanding of the environmental implications of energy transitions, primarily by examining the case of wind power. This involves new investigations of both potential negative impacts of wind power and the positive role of the technology in emission reduction, as well as a critical review of past research. Three papers on wind power are presented: a comprehensive literature review of life cycle assessments (LCA) of wind power, a scenario-based LCA of large-scale adoption of wind power, and an LCA of an offshore wind farm. A hybrid LCA methodology is employed in the scenario-based LCA and LCA of an offshore wind farm. Another paper is presented which is not concerned with wind power in particular, but takes the form of an evaluation of limitations of climate change mitigation literature. It helps to achieve the aim stated above by bringing together knowledge of indirect effects of mitigation measures, and by elucidating how these effects may influence the viability of proposed mitigation strategies.

The literature review aims to take stock of insights from past research, with a particular view to identifying remaining challenges. A survey of results indicates 0.063 (±0.061) and 0.055 (±0.037) kWh energy used and 20 (±14) and 16 (±10) CO_2e emitted per kWh electricity for onshore and offshore cases. Evidence suggests strong positive effects of scale in the lower end of the turbine size spectrum, but is inconclusive for the megawatt range. LCAs tend to assume higher capacity factors than current real-world averages. Limitations of existing research are discussed; this includes poorly understood toxicity and resource depletion impacts, cut-off errors and seemingly inconsistent modelling of recycling benefits in analyses, lack of detailed considerations of installation and use phases, and lack of future-oriented assessments.

The scenario-based LCA is an initial attempt to integrate global energy scenario analysis and LCA in order to assess the economy-wide environmental costs and benefits of wind power. The study estimates aggregated global emissions caused by wind power toward 2050, following the

International Energy Agency's BLUE scenarios. It takes into account replacement at end-of-life and changing electricity mix in manufacturing, and distinguishes emissions occurring prior to, during and after the useful life of wind turbines. Results indicate emissions of 2.3 (3.5) gigatonnes CO_2e from wind power in 2007-50 in a scenario with 12% (22%) share of wind in electricity supply in 2050. A second key element of the analysis is that life cycle inventories for fossil fuel-based electricity are used to evaluate emissions savings from wind power; the evaluation is performed on the assumption that additional wind electricity, compared with a baseline, displaces fossil fuel electricity. Results suggest that emissions savings grossly exceed emissions caused by wind power, and thus confirm emission benefits of wind power. Uncertainty and limitations in scope of analysis need to be borne in mind when interpreting results.

The LCA of an offshore wind farm places special emphasis on marine vessel activities and supply of spare parts. The proposed Havsul I wind farm, Norway is used as a model. Total carbon footprint is estimated to 34 grams CO_2e per kWh. Results indicate greater contributions from vessels and spare parts than has previously been thought: Offshore activities during installation and use phases contribute 25-35% to totals for several impact categories (e.g., climate change, acidification) and 43% for photochemical oxidant formation. Supply of spare parts causes 7% of climate impacts and 13% of freshwater ecotoxicity.

Assembling evidence from different research fields, the discussion paper identifies important simplifying assumptions in current climate change mitigation assessments. An argument is presented that because simplifying assumptions represent a systematic neglect of indirect, countervailing effects of greenhouse gas-mitigating measures, they lead to overly optimistic assessments, which then become a basis for unrealistic technology optimism in climate policy.

For the thesis as a whole, the most significant contribution may be the contribution to moving beyond a single-minded concentration on static, unit-based assessments in wind power LCA research; another main contribution is the use of a hybrid LCA methodology to assess the environmental impacts of large-scale adoption of wind power and an offshore wind farm. By means of LCA studies of wind power and a wider evaluation study of indirect effects of climate change mitigation measures, the thesis illustrates the significance of taking a holistic view in evaluating the environmental implications of energy technologies and transitions.

Utvidet sammendrag [in Norwegian]

Klimaproblemet fordrer en radikal omlegging av den globale energiforsyningen. Vindenergi er fornybar og av mange regnet som en viktig del av løsningen. Med denne avhandlingen håper jeg å bidra til økt forståelse av hvilke konsekvenser store energiomlegginger kan ha for miljøet. Bidraget jeg tar sikte på å gi består primært i å utforske miljøfordeler og -ulemper ved vindkraft. Med «fordeler» tenker jeg her på den positive rollen vindkraft kan spille i reduksjon av utslipp; «ulemper» innbefatter negative miljøbelastninger gjennom hele livsløpet til vindkraftanlegg. Avhandlingen inneholder fire delstudier, presentert hver for seg i fire artikler. Tre av disse omhandler vindkraft: en sammenfattende framstilling av tidligere livsløpsvurderinger av vindkraft, en framtidsorientert livsløpsvurdering av global vindkraftutbygging og en livsløpsvurdering av en havvindpark. Den siste (fjerde) delstudien vurderer miljøaspekter ved store energiomlegginger generelt; den knytter sammen kunnskap om bivirkninger av klimatiltak med det mål for øyet å si noe om klimapolitiske følger av at bivirkninger i liten grad tas hensyn til i rådende modeller og tenkemåter.

Første delstudie

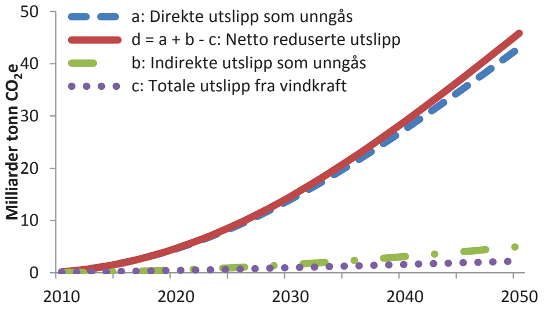
Den sammenfattende framstillingen kartlegger og sammenstiller omfang av, antagelser i og resultater fra tidligere studier, vurderer kvaliteten og relevansen av funn og gir anbefalinger for videre forskning. En kartlegging av resultater indikerer, for vindparker til henholdsvis lands og havs, at 0,063 (±0,061) og 0,055 (±0,037) kWh energi blir brukt og 20 (±14) og 16 (±10) CO_2e sluppet ut for hver kWh strøm levert. Effektstørrelse < 100 kW per turbin gir størst miljøbelastning per kWh; kartleggingen viser imidlertid ingen tydelig skalaeffekt for > 1 MW. Livsløpsvurderinger antar generelt høyere utnyttelsesgrad av installert effekt enn samlet utnyttelsesgrad for faktiske vindparker.

Potensielle mangler ved den eksisterende forskningen inkluderer: i) sannsynligvis betydelig undervurdering av miljøbelastninger i de fleste studier (fordi studiene ikke bruker hybride inventarregnskap); ii) tilsynelatende inkonsekvent modellering av materialgjenvinning i flere studier; iii) vurderinger av installasjons-, drifts- og vedlikeholdsfaser kan være overforenklete; iv) framtids-/endringsorienterte studier er sjeldne, men kan gi nye innsikter; og v) aspekter ved utslipp av miljøgifter og bruk av ikke-fornybare mineralressurser er i liten grad undersøkt og forstått.

Andre delstudie

Den framtidsorienterte livsløpsvurderingen tar initiativ til å løfte livsløpsanalyse fra mikro- til makronivå. Studien utforsker to hovedspørsmål: Hvor store utslipp vil en storstilt global utbygging av vindkraft medføre? Og hvordan kan livsløpsperspektivet virke inn på forventninger om kutt i utslipp på grunn av vindkraft? Analysen anvender hybride inventarregnskap og tar hensyn til framtidige endringer i strømsammensetning, mer effektiv vindutnyttelse og at utbygging i økende grad skjer til havs. Utskifting av komponenter etter endt levetid er inkludert.

Resultatene indikerer at 2,3-3,5 milliarder tonn CO_2e vil slippes ut som følge av bygging og drift av vindkraftanlegg sammenlagt i perioden 2007-2050, i scenarioer der vindkraft leverer 12-22 % av global elektrisitet i 2050. Reduserte utslipp er beregnet ut fra en antakelse om at *ekstra* vindkraft, sammenlignet med en referansebane, erstatter en årsspesifikk miks av kraft fra fossile brensler og gir utslippsreduksjon. Ifølge resultatene tilsvarer de totale klimagassutslippene forårsaket av vindkraft (lilla kurve i figur) 5 % av de direkte utslippene fra termiske kraftverk som blir erstattet (blå kurve) – dette gjelder altså utslipp som finner sted på selve kull-, gass- og oljekraftverkene. Videre er klimagassutslippene fra utvinningen og bearbeidingen av fossile brensler som erstattes (grønn kurve) større enn de totale utslippene fra vindkraft. De samme



Figur: Klimagassutslipp fra vindkraft og utslipp som unngås pga. vindkraft (kumulert) 2010-50 hovedkonklusjonene kan trekkes for NOx, gasser med forsurende effekt og gasser som fører til bakkenær ozon.

Resultatene bekrefter at det vil være miljøfordeler ved at vindkraft erstatter fossil kraft. Usikkerhet og analysens begrensete omfang må imidlertid tas i betraktning.

Tredje delstudie

Livsløpsvurderingen av havbasert vindkraft vier spesiell oppmerksomhet til bruken av marine fartøyer ved installasjon, drift og vedlikehold, og behov for å erstatte deler; dette fordi behandlingen av disse aspektene i tidligere forskning vurderes som mangelfull. Studien anvender hybrid inventaranalyse. Den planlagte havvindparken Havsul I i Møre og Romsdal brukes som modell.

Resultatene tilsier at for hver kWh som leveres vil 34 g CO_2e slippes ut; av denne mengden bidrar selve vindturbinene med 32 %, fundamentene 18 % og kabling 7 %. Analysen leder fram til større relative bidrag fra marine fartøyer og utskifting av deler enn hva som er funnet i tidligere studier: Operasjoner som foregår til havs forårsaker 25-35 % av den totale miljøbelastningen for flere av indikatorene (inkludert klimagassutslipp og gasser med forsurende effekt) og 43 % for kildene til bakkenær ozon. Produksjon av utskiftingsdeler forårsaker på sin side 13% av utslippene av miljøgifter til ferskvann. Mer forskning er nødvendig for å klarlegge hvilken betydning skip og erstatningsdeler har for miljøkonsekvensene av vindkraft. En sammenligning mellom vindkraft og gasskraft med karbonfangst og -lagring antyder at vindkraft er mer klimavennlig. Vindkraft ser på den annen side ut til å medføre mer utslipp av miljøgifter.

Fjerde delstudie

Delstudien samler kunnskap om indirekte virkninger av klimatiltak ved hjelp av et bredt litteratursøk – litteratursøket spenner over flere forskningsfelt, inkludert livsløpsvurderinger, energitilbakeslag og utslipp innbakt i internasjonal handel. Kunnskap om indirekte effekter av klimatiltak evalueres og brukes til å belyse svakheter i rådende teknologimodeller og studier av energiframtider, slik som klimavernscenarioene til Det internasjonale energibyrået (IEA). Ett eksempel på en slik svakhet er at modellene bare i begrenset grad fanger opp tilbakeslagseffekter:

Økt energieffektivitet fører typisk til redusert pris for en energitjeneste, og dermed økt etterspørsel etter tjenesten og/eller mer penger tilgjengelig for annet forbruk. Slik kan effektivitetsforbedringer indirekte stimulere til nytt forbruk og nye utslipp. Et annet eksempel er at modellene ikke fanger opp at energiomlegginger i seg selv medfører utslipp: Andre delstudie i denne avhandlingen kommer eksempelvis fram til anslagvis 2-3 milliarder tonn CO_2e på grunn av vindkraft i 2007-2050.

Studien påstår at modellberegninger leder til overoptimistiske beskrivelser fordi forenklinger i rådende teknologimodeller representerer en systematisk utelatelse av indirekte, gjerne skjulte effekter som *de facto* vanskeliggjør klimatiltak eller oppveier direkte gevinster av klimatiltak. Beskrivelsene gir grobunn for urealistisk teknologioptimisme i global klimapolitikk.

Vitenskapelig betydning

Det mest betydelige tilskuddet til forskningen som omhandler miljøkonsekvenser av energiteknologier er kanskje den framtidsorienterte livsløpsvurderingen av vindkraft presentert i den andre delstudien. Studien løfter, under gitte forutsetninger og forenklinger, livsløpsanalyse av vindkraft fra mikro- til makronivå, og inkluderer også en integrert livsløpsvurdering av forurensning som unngås. Etter min vurdering er dette originale bidrag til forskningslitteraturen som studerer miljøeffekter av vindkraft i livsløpsperspektiv, da tidligere arbeider nesten utelukkende studerer miljøbelastning forbundet med én enhet elektrisitet på mikronivå og i et statisk rammeverk. Ved å ta omfang av utbygging og enkelte endringer over tid (især strømsammensetning i produksjon) med i vurderingen, bidrar studien med nye innsikter om miljøfordeler og -ulemper ved vindkraft. Et annet vesentlig tilskudd er bruken av en hybrid metode for inventaranalyse til å studere miljøkonsekvenser av storstilt vindkraftutbygging (andre delstudie) og havbasert vindkraft (tredje delstudie). Tidligere studier anvender i overveiende grad ikke-hybride metoder.

Avhandlingen som et hele illustrerer, ved hjelp av livsløpsevalueringer av vindkraft og en diskusjonsartikkel som tydeliggjør relevansen av indirekte effekter av miljøtiltak, betydningen av helhetlige tilnærminger til miljø- og ressursproblemer.

1 Introduction

A fundamental change in the efficiency and composition of energy supply and demand is needed to address some of the greatest environmental and resource concerns of today, notably man-made climate change and security of energy supply. Some basic facts about what such a transition to a different energy supply will look like can be stated already: We know the transition must involve a gradual shift away from fossil fuels and towards renewable energy sources, and must deliver a drastic reduction in energy-related carbon dioxide emissions. What is too little understood, however, are the real-world environmental consequences of proposed energy transitions, taking into consideration the entire life cycles of technologies. To take an example: Despite that wind turbines need no other fuel than the wind – that is, a renewable energy flux that exists in ample quantities – to operate, fossil fuel-burning occurs in producing the steel that goes into the wind turbines, and in numerous other activities needed to manufacture, install and maintain the operation of wind power plants. Furthermore, harmful emissions occur that are not necessarily due to fossil fuel use; one example is releases of toxic substances in connection with mining. Keeping a life cycle perspective is pivotal in trying to understand the environmental costs and benefits of wind power, and in allowing for consistent comparisons between wind power and alternatives.

This thesis aims to contribute to a better understanding of the environmental implications of energy transitions. In order to achieve this aim, the thesis presents three papers exploring the environmental costs and benefits of wind power in a life cycle perspective. The three papers, referred to by the roman numerals I-III in this thesis, comprise an in-depth literature review of life cycle assessments of wind power (paper I), a scenario-based life cycle assessment of large-scale deployments of wind power (paper II), and an LCA of an offshore wind farm with a detailed investigation of the role of ships and spare parts (paper III). In addition, and as a secondary means to achieve the aim stated above, a fourth paper is presented which evaluates important limitations of contemporary climate change mitigation assessments (paper IV). This last paper helps to achieve the aim stated above by bringing together knowledge of indirect effects of mitigation measures, and by elucidating how these effects may influence the viability of proposed mitigation strategies.

The remainder of this introduction chapter is structured as follows: Section 1.1 introduces the challenge of achieving sustainability, while section 1.2 introduces wind power as a potentially important part of sustainable energy supply. In section 1.3 I argue that holistic environmental assessments are required to obtain a sound basis for developing energy strategies. Research aims and objectives of the current work are described in section 1.4.

1.1 The challenge of sustainability

Human activities are altering the planet Earth. We are transforming land (Haberl et al. 2007; Vitousek et al. 1997), changing the abundance and distribution of species (Butchart et al. 2010; MEA 2005), and interfering with biogeochemical cycles (Vitousek et al. 1997) to such an extent that some scientists speak of the 'Anthropocene' as a new geological era (Crutzen 2002; Zalasiewicz et al. 2010). It is now abundantly clear that human-induced global environmental change threatens to fundamentally change the climatic conditions to which the human civilization is adapted, and to deteriorate the ecological and physical basis on which all human activities rely. The consequences for human life, health and prosperity if problems go unabated are likely to be grave or – given the risk of encountering abrupt and unpredictable global environmental change – even catastrophic (Barnosky et al. 2012; Hansen et al. 2008; IPCC 2007a, 2007c; MEA 2005; Richardson et al. 2009; Rockström et al. 2009a; Rockström et al. 2009b; Steffen et al. 2005).

Perhaps chief among the environmental concerns is the concern about man-made climate change. Human activities are causing the build-up of carbon dioxide and other gases absorbing infrared radiation in the atmosphere, thus altering the planetary energy balance. The result is global warming: Reportedly, nine of the ten warmest years since the year 1880 have occurred after the year 2000 (Hansen et al. 2012), and a global temperature rise of 6 °C or more above pre-industrial level does not seem an unlikely scenario under a business-as-usual development (IEA 2011a). Potential impacts of global warming include an overall increase in human morbidity and mortality due to increased number of extreme weather events (e.g., heat waves, storms), an overall increase in the number of people exposed to water stress, reduced quantity and quality of food supply (due to, among other factors, loss of coastal wetlands and increase in areas affected by drought), and degradation of vulnerable ecosystems (Richardson et al. 2009; IPCC 2007c). Carbon dioxide emissions from the combustion of fossil fuels contribute about 60% of total global emissions of greenhouse gases (IEA 2011a; IPCC 2007b); mitigating energy-related carbon dioxide emissions is a prime motivation for shifting away from conventional fossil and towards low-carbon energy systems.

Another major concern is degradation of ecosystem services and loss of diversity of life on Earth. Humans are largely dependent on functioning ecosystems to exist and thrive, owing to the services ecosystems provide, such as food supply, water purification and climate regulation (MEA 2005). Of the 24 categories of ecosystem services examined in the Millennium Ecosystem Assessment, 15 are being degraded or used unsustainably (MEA 2005). The current species extinction rate is probably at least two orders of magnitude higher the natural background rate, and the future extinction rate (due to pressures occurring up to 2050) are expected to be at least one order of magnitude higher than current rate (MEA 2005). Butchart et al. (2010) find that most indicators of global biodiversity are in decline, the rates of decline are generally not decreasing, and pressures on biodiversity are increasing. Barnosky et al. (2011) warn that a new mass extinction event – the sixth in 540 million years – may be under way. Energy use is currently not a dominant driver for pressures on biodiversity – these pressures are more related to food supply and agriculture – but future increased utilization of biomass for energy purposes will interface with the biodiversity loss problem (MEA 2005; UNEP 2010a). Biodiversity loss is not addressed as an impact category in this thesis, but is relevant as part of the context – for discussions in paper IV in particular, and also because linkages exist between types of pressures or impacts that are addressed in the thesis and biodiversity loss (for example, climate change is anticipated to become a more important driver for biodiversity loss in the future).

Concerns about an array of other environmental problems exist as well (MEA 2005; UNEP 2010a; Steffen et al. 2005; Rockström et al. 2009b). Many of these concerns are related to releases to the environment of substances that cause toxic effects to humans or organisms; examples include emissions of smog-forming gases, heavy metals and persistent organic pollutants, and nuclear wastes. Other concerns arise from pollution (of nitrogen or phosphorus) that basically fertilizes natural ecosystems, generally with undesirable effects. If we include also availability of natural resources in the account, important concerns include depletion of abiotic resources (fossil fuels, metals) and biotic resources (in particular, fish and wood). Many of these problems are connected, in one way or the other, with energy use or energy technologies: Sometimes there is a direct and easy identifiable connection, such as between nuclear energy and nuclear waste, or between coal-fired power plants and emissions of mercury; other times the connections are more subtle or difficult to identify, such as when mining of steel that goes into a wind turbine entails leakages of heavy metals to ground water. Environmental impact categories that are (variably) addressed in the life cycle assessment studies of wind power presented in this thesis cover a fair share of the environmental concerns outlined here.

1.2 Energy solutions: the case of wind power

Over the past decades, wind power has established itself as a steadily growing and spreading source of electricity (figure 1; Kaldellis and Zafirakis 2011), recently surpassing bio to become the second most important source, next to hydro, of world renewable electricity (IEA 2011b). What is more, current expectations are that the growth in wind power markets seen so far is only a beginning and that in coming decades there will be a massive expansion, especially under scenarios involving significant reductions in greenhouse gas emissions: For example, EU member states' action plans project wind power capacity will increase from 40 GW in 2005 to 214 GW in 2020, providing 13% of EU combined electricity in 2020 (figure 2a; Beurskens et al. 2011). At the global level, a survey of results from climate change mitigation scenarios produced by energy-economic and integrated assessment models suggest a share of wind to total world electricity of 10% (5-24%) in 2030 and 13% (6-25%) in 2050, looking at the median values (interquartile ranges) of surveyed results for the most stringent mitigation scenarios (Krey and Clarke 2011) – the corresponding real number in 2007 was 0.9% (IEA 2010a).

Figure 2b shows the electricity production from wind in one long-term climate change mitigation scenario, the BLUE Map scenario of the International Energy Agency (IEA). In this scenario, which is the least-cost mitigation alternative in IEA (2010a), wind supplies 12% of world electricity in 2050. Another alternative in IEA's BLUE scenarios family, BLUE hi REN, includes more renewables and may be more representative if ambitious carbon capture and storage deployment pathways in BLUE Map are not achieved in practice. In BLUE hi REN, wind power provides 22% of world's electricity needs in 2050 (IEA 2010a) (not shown in figure 2).

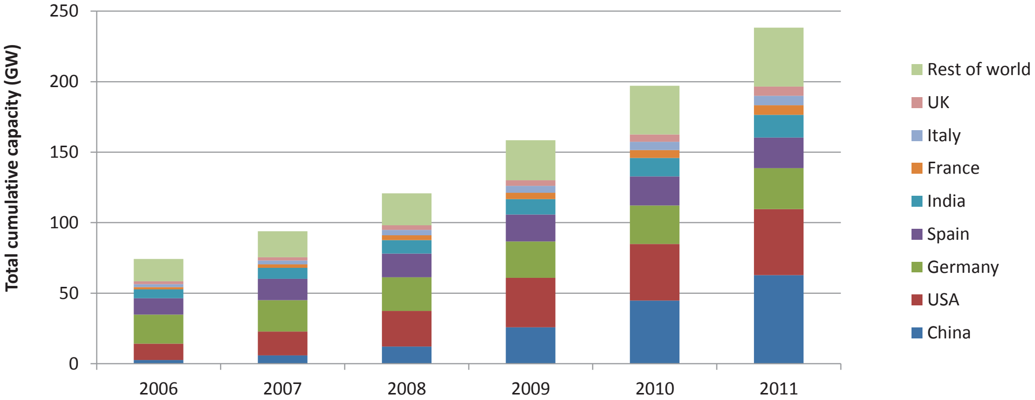
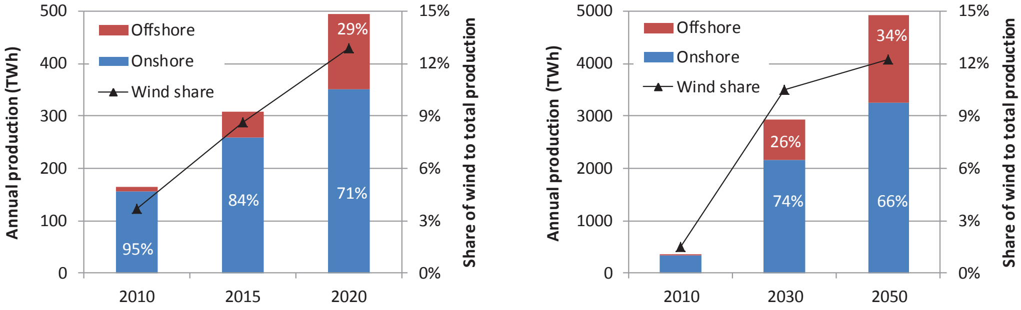


Figure 1. Global cumulative installed wind power capacity by region for the years 2006-2011.
Note: Based on data from GWEC (2007-2011, 2012). Figures for the year 2011 are provisional. Caution is needed in interpreting capacity figures for China, as about 25% (IEA 2011b) or 30% (Yang et al. 2012) of installed capacity by the end of 2010 and 28% by the end of 2011 (Qi 2012) was not connected to the grid.



(a) European Union member states action plans **(b) World, BLUE Map scenario**

Figure 2. Scenarios of electricity production from onshore and offshore wind power for (a) European Union member states (according to policy action plans; years 2010-2020) and (b) world (BLUE Map scenario; 2010-2050).
Note: European Union (a): figures represent the aggregate of projections published by individual member states in conjunction with the Renewable Energy Directive (Beurskens et al. 2011). World: figures for the years 2030 and 2050 are from the least-cost climate mitigation scenario (BLUE Map) in IEA (2010a). Numerical values in stacked columns (white font colour) give the relative shares of onshore and offshore production respectively.

Given a limited availability of suitable space on land and vast wind resources offshore (Wiser et al. 2011), in the future wind power development is expected to increasingly take place in ocean waters. This is illustrated by figure 2 by the examples of EU policy action plans (towards 2020) and IEA's global BLUE Map scenario (towards 2050). In the case of BLUE Map, one third of electricity supply from wind in 2050 comes from offshore installations (figure 2b).

1.3 A need for holistic assessments

To study something holistically means to study wholes rather than parts, or systems rather than system components. At the core of holistic thinking lies a recognition that parts are interconnected, and an idea that the whole is only explicable – or can be made more explicable – if firstly, all relevant parts are considered, and secondly, if interconnections between parts are properly identified and understood. Consider, for example, that numerous activities or operations (parts) are necessary to facilitate the delivery of a certain product, and that together these activities and operations may be viewed as comprising a product system (whole). The environmental implications of using a product cannot be fully understood without considering the product system as a whole, and fair comparisons between products cannot be made without consistent evaluations of the respective product systems. In another interpretation, a number of environmental impact indicators (parts) can together determine overall sustainability performance (whole) of a product. Environmental evaluations that do not take into consideration all types of environmental concerns are incomplete. Other interpretations can be made as well: The use and development of different technologies (parts) over time are intimately interconnected, forming clustered developments (whole), and behavioural factors and technological factors (parts) mix and contribute to determining the use of technologies (whole).

In the context of energy transitions and the environment, holistic assessments may be valuable by providing a fuller picture of environmental implications of proposed solutions, and in illuminating causality relations which might otherwise escape attention. In more concrete terms, holistic assessments are important for or can be put to use in: i) making fair and consistent comparisons between technologies; ii) developing system designs and strategies at technology or industry levels as well as on a macro (societal) level; and iii) identifying barriers to, or factors that are prerequisite for, wanted developments. One could say that, ultimately, the goal is to avoid problem shifting – which may occur, inter alia, from one part of a product system to another, from point in time to another, or from one environmental pressure to another – and instead: to realize true problem solving at a system-wide level.

As I see it, four factors underline the importance of taking a holistic approach to evaluating energy technologies and transitions, and may be summarized in four words: depth, breadth, severity and urgency. Depth points to that many of the problems are deep-rooted, in the sense that they are fundamentally linked with dominant technologies, long-lived infrastructures and human needs and lifestyles in modern societies (Grübler et al. 1999; Hertwich and Peters 2009; Lenzen et al. 2012; Moe 2010; Steinberger et al. 2012; UNEP 2010a; Unruh 2000, 2002), and as such cannot easily be solved by quick technological fixes. Breadth refers to the range of energy-related global environmental problems, severity to the potentially grave consequences on the lives and well-being of humans (section 1.1). Urgency is a reference to the failure to address important problems so far (notably, climate change and biodiversity loss), and the need to achieve real mitigation soon if the risk of large and unpredictable environmental change is to be kept at an acceptable low level (Barnosky et al. 2012; Meinshausen et al. 2009; Rockström et al. 2009a; UNEP 2010b).

Industrial ecology

Industrial ecology is one research field which takes a holistic view of environmental concerns. The term ‘industrial ecology’ was first used by Frosch and Gallopoulos (1989), envisioning future ‘industrial ecosystems’ that function in the same way as biological ecosystems: the waste of one industrial process (in biological ecosystems: organism) serves as raw material for another process (organism), and this principle is implemented universally so that useful materials (nutrients) circulate internally in the system, and exchanges with the external environment are minimized.

In my interpretation, industrial ecology is the study of the human appropriation and transformation of Earth’s resources, of the discharges to the environment resulting from such transformations, and of the effects on Earth’s life-supporting systems. Industrial ecology seeks system-wide solutions to environmental problems, recognizing that consumer activities, industrial activities, environmental pressures and environmental impacts are interconnected through complex causality chains. A central feature of industrial ecology is that aspects of environmental problems are approached from different disciplinary perspectives, using elements of engineering, natural and social sciences. Life cycle assessment is a central method in industrial ecology research and is introduced in chapter 2.

1.4 Research aims

In the preceding sections I have attempted to introduce part of the concerns about human-induced global environmental changes, chief among which in my eyes is the problem of man-made climate change. Further, I have briefly explained why an energy transition – that is, a fundamental change in the ways in which we provide energy to run our economies – is needed to mitigate climate change, and I have noted that wind power is an important part of future global energy supply in most energy scenarios. Finally, I have made the case that a holistic view of energy technologies and how those technologies relate to environmental change needs to be part of the basis on which energy strategies are developed. This brings me to the overall aim of this thesis, which is to contribute to a better understanding of the environmental implications of energy transitions by, primarily by examining the environmental impacts caused by wind power technology and large-scale deployments of wind power (papers I-III), and secondarily by means of a general evaluation of limitations of climate change mitigation literature (paper IV). Individually, the papers set out the following aims:

i) To take stock of insights from recent life cycle assessment studies of wind power, with a particular view to identifying potentials for improvement and specific needs for research, by means of an in-depth literature review (paper I; treated in section 3.1).

ii) To make an initial attempt to reconcile top-down integrated assessment scenario analysis and life cycle assessment in order to assess economy-wide environmental costs and benefits of wind power expansion (paper II; section 3.2).

iii) To assess the life cycle environmental impacts of an offshore wind farm, and to include in the assessment a detailed investigation of the importance of ships and spare parts (paper III; section 3.2).

iv) To evaluate important simplifying assumptions in climate change mitigation assessments in the literature, and present part of the case that assessments are the basis of unfounded technology optimism in world climate policy (paper IV; chapter 4).

An explanation is warranted on the use of the term 'case studies for wind power' to describe papers I-III. Merriam-Webster's (2008) dictionary defines a case study as:

> an intensive analysis of an individual unit (as a person or community) stressing developmental factors in relation to environment

When describing papers I-III as case studies, I think of wind power technology or wind power system as the individual unit defining a case study – I do not mean to refer to individual projects or applications. Indeed, wind power is one technology (one case) in the set of proposed technological solutions to the problem of man-made climate change.

1.5 Structure of thesis

In the remainder of the thesis, I first present background theory of LCA in terms of conceptual basis and prevailing methodological approaches (chapter 2). Next in chapter 3, I give summaries and discussions of each of papers I-III. These papers share a common topic, the life cycle environmental impacts of wind power, but approach the topic differently. Paper IV takes the form of a wider evaluation and argument that unrealistic technology optimism exists in assessments that support world climate policy; a précis of the main points of the argument is provided in chapter 4. Presentations in chapters 3 and 4 draw on material presented in the papers, but also give new substance in terms of elaborations of selected issues, and new discussions. The final discussion presented in chapter 5 includes an evaluation of the research contribution of the thesis as a whole, and a discussion of the environmental credentials of wind power in light of the current work. Chapter 5 also serves the function of concluding the thesis. Papers I-IV, together with supplementary notes and information, are included in the appendices.

2 LCA: conceptual basis and methods

Life cycle assessment (LCA) may be defined as the quantification of environmental pressures instigated by the delivery of or demand for a product or service, and the assessment of this product or service based on the quantified environmental pressures. For the criteria assessment in LCA to be meaningful and credible, LCA analysts must strive to achieve extensive coverage of activities arising from or necessitated by the product or service throughout its lifetime, from raw material acquisition through to waste handling. Together these activities make up a *product system*.

LCA usually comprises two quantitative stages. In the *inventory analysis* stage*,* the practitioner makes a systematic mapping of relevant activities and the environmental loads directly generated in these activities (with reference to the matrix representation introduced later in section 2.1, construct A, y and F). Also part of the inventory analysis is the calculation of environmental pressures attributable to the product or service under study (section 2.1: calculate e). In the *impact assessment*, inventory analysis results at the level of environmental pressures are converted into environmental impact category indicators (calculate d). As is typical of assessment work, LCA should also include a proper definition of the goal and scope and critical interpretation of results. A broad review of LCA methods and practices is provided in Finnveden et al. (2009); other useful background literature includes Hauschild (2005), ISO (2006), Pennington et al. (2004), Rebitzer et al. (2004), and Suh and Huppes (2005).

In the following sections, I first introduce the basic mathematical framework for LCA using matrix representation of product system (section 2.1). Next, in section 2.2 I give a brief description of prevailing techniques for life cycle inventory quantification.

2.1 Mathematical framework

I here limit the presentation to the case where all interrelationships between activities in the product system, as well as between activity levels and environmental loads and impacts, are assumed to be linear – this is a typical assumption in LCA (Pennington et al. 2004; Rebitzer et al. 2004). Under the assumption of linearity, the product system may be represented by a set of matrices and analysed through matrix operations. I here use the matrix notation of input-output analysis (Miller and Blair 1985; UN 1999) to describe the LCA model mathematically, following Strømman and colleagues (Strømman et al. 2006; Strømman et al. 2009).

In an LCA model, interrelationships between activities that make up a product system can be expressed mathematically by

$$x = Ax + y \tag{1}$$

where y is a column vector representing the demand that is imposed on the system (e.g., to deliver one unit of electricity from wind power), and x a column vector giving the total activity levels induced by the demand (e.g., total combustion of coal in coal-fired power stations that occur as a consequence of the demand for one unit of wind electricity). The direct requirements matrix A holds information on relations between activities. In A, the element in row i and column j represents the direct requirement for activity i needed for every unit of activity j; for example, direct requirement for electricity (i) in steel manufacturing (j). There are no principal restrictions on mixing of physical and monetary units in A (Weisz and Duchin 2006).

Further, let F be a matrix of environmental load intensities (e.g., carbon dioxide directly emitted by a coal-fired power plant) and C a matrix of characterization factors (e.g., global warming potential of carbon dioxide). Solving equation (1) with respect to x and left multiplying with C and F yields a column vector d of total impact indicator values:

$$d = Ce = CFx = CF(I - A)^{-1} y \tag{2}$$

e is a column vector containing life cycle inventory analysis results in terms of environmental pressures (loads). I is the identity matrix.

2.2 Methods for life cycle inventory

This section is divided into three subsections. The first two subsections treat the two prevailing approaches to life cycle inventory (LCI) analysis of product systems, process-based LCI and input-output-based LCI. Both approaches have a fairly long history of application in resource and environmental assessments: the emergence of process-based LCA may be traced back to energy analyses of industrial systems in the 1970s (e.g., Boustead and Hancock 1979), and input-output analysis began to be used at around the same time to study the energy required to supply goods and services (e.g., Bullard and Herendeen 1975). The combination of the two techniques in a hybrid approach is dealt with in the last subsection.

Process-based LCI

Process-based LCI models are constructed using a bottom-up type of thinking, and generally define and describe activities in physical terms – in this context, ‘activities’ in the direct requirements matrix A may be thought of as *processes*. As is characteristic of bottom-up modelling approaches, process-LCI facilitates the use of data that are specific to the individual operations that are modelled; hence it has the potential to support detailed analyses and achieve high levels of specificity. The one big disadvantage, on the other hand, is that process-LCI models are generally very incomplete representations of real product systems (Lenzen and Dey 2000; Majeau-Bettez et al. 2011; Strømman et al. 2006; Suh and Huppes 2005); essentially, this issue occurs because there is a natural limit to how many individual operations that can be taken into account in a bottom-up approach. Literature that attempts to quantify the cumulative importance of missing elements in process-LCIs is inconclusive, but tends to find that process-based approaches fail to account for 30% or more of total inventories (Majeau-Bettez et al. 2011). Research suggests that typical process-LCAs of renewable power generation underestimate impacts with 50% or more (Crawford 2009; Wiedmann et al. 2011; Zhai and Williams 2010).

Input-output-based LCI

Input-output (IO) based LCI models are top-down representations of economies, holding information on transactions between economic sectors and, variably, pollution and resource use that occur in the sectors (Miller and Blair 1985; UN 1999). IO-based models operate at the level of economic sectors; ‘activities’ in the direct requirements matrix A may be thought of as *sectoral activities*. While the sector resolution is generally too coarse for making product-level assessments, input-output modelling has found extensive application in studying how different types of final demand can be linked with pollution or resource use at a macro level (e.g., Hertwich and Peters 2009, Lenzen et al. 2012; literature reviews are available in Hertwich 2011 and Wiedmann 2009). Another application is in hybrid LCI modelling, which is dealt with next.

Hybrid LCI

Hybrid LCI models aim to combine process-LCI and IO-based LCI in such a way that the advantages of both approaches – that is, the high precision level of process-LCI and the extensive coverage of product systems facilitated by IO-based LCI – is exploited. In order to achieve this, process-LCI should be used to model important activities, and IO-based LCI to model activities that would otherwise be omitted. Different techniques have been proposed or used in the literature to fuse together process-based and IO-based perspectives in a way that leads to compatible interaction, such as *tiered* (Strømman et al. 2009), *input-output-based* (Suh et al. 2004), *integrated* (Suh et al. 2004), *waste input-output* (Nakamura and Kondo 2002; Kondo and Nakamura 2004) and *path exchange* (Lenzen and Crawford 2009; Treloar 1997) hybrid analysis.

Differences among hybrid LCI techniques is outside the scope of this presentation, but it may be noted that the unit-based analyses performed in papers II and III fall into the category of tiered hybrid analysis. In essence, this means that process-based and IO-based models are linked by adding IO-based inventory elements to selected processes in the process-based model (A^{nf} in equation 3). The decomposition of the direct requirements matrix A into sub-matrices in equation (3) reveals the structure of the tiered hybrid LCA model employed in this work (Strømman et al. 2006).

$$A = \begin{bmatrix} A^{ff} & 0 & 0 \\ A^{pf} & A^{pp} & 0 \\ A^{nf} & 0 & A^{nn} \end{bmatrix} \qquad (3)$$

Index *f* denotes ‘foreground’; A^{ff} represents linkages between processes that are specific for the present work. Index *p* denotes ‘process-LCA database’; A^{pp} represents linkages between generic processes defined in an LCA database. Index *n* denotes ‘input-output’; A^{nn} represents linkages between economic sectors described in an IO-based model. Accounts of methods used in papers II and III are provided in the actual papers and supplementary information.

3 Environmental implications of wind power deployment

Here I present papers I-III, all of which are concerned with the life cycle environmental impacts of wind power. The papers are dealt with in turn in sections 3.1-3.3.

3.1 Paper I: Literature review

Rationale

The literature abounds with LCAs of wind power. It is known that results differ appreciably across studies, and the reasons for the variability are often difficult to disentangle (Kubiszewski et al. 2010; Raadal et al. 2011; Wiser et al. 2011). The large availability of studies combined with large and often unexplained variability in results pose a challenge for those who seek to orientate themselves in the literature, and may ultimately limit the real or perceived value of the research. In such circumstances the need for literature reviews is particularly apparent.

Previous literature reviews (Lenzen and Munksgaard 2002; Kubiszewski et al. 2010; Raadal et al. 2011; Wiser et al. 2011) present comprehensive surveys of energy and greenhouse gas emissions estimates, but also have limitations. Firstly, there are gaps to be filled by considering results for other impact categories, capacity factor and lifetime assumptions, contribution analysis, turbine size and method for life cycle inventory, and secondly recent review papers only to a limited degree discuss future research directions. Finally, owing to strong developments in wind power technology as well as LCA methods and databases, a seminal review paper by Lenzen and Munksgaard (2002) may be partially out-dated.

Table 1. Summary of scope, methods and assumptions, and results of LCA studies surveyed in paper I. (This table is an expanded version of table 1 in the paper.)

Notes: References: Arvesen et al. (2012); Lenzen and Schaeffer (2012); Kabir et al. (2012); Guezuraga et al. (2012); Arvesen and Hertwich (2011) (corrigendum: Arvesen and Hertwich 2012a); Chen et al. (2011); Vestas (2011); Wagner et al. (2011); Wiedmann et al. (2011); Zhong et al. (2011); Gonçalves da Silva (2010); Vattenfall (2010); Crawford (2009); Fleck and Huot (2009); Fthenakis and Kim (2009); Martínez et al. (2009b), Martínez et al. (2009a) (related: Martínez et al. 2010); Rule et al. (2009); Tremeac and Meunier (2009); Weinzettel et al. (2009); Ardente et al. (2008); Lee and Tzeng (2008); NEEDS (2008); Pehnt et al. (2008); Ecoinvent (2007) (related: Burger and Bauer 2007, Jungbluth et al. 2005); Celik et al. (2007); Pehnt (2006); Rankine (2006); Vestas (2006a, 2006b); White (2006); Hondo (2005); Khan et al. (2005); Elsam (2004); Lenzen and Wachsmann (2004); Chataignere and Le Boulch (2003); Properzi and Herk-Hansen (2003); Kemmoku et al. (2002); Pacca and Horvath (2002); Voorspools et al. (2000); Schleisner (2000). Site: Ons = Onshore; Off = Offshore. Size: Wind turbine capacity (kW). LT = Lifetime (years): ‘¤’ means longer lifetimes for some components. CF = Capacity factor (%). RC = Recycling credits: ‘x’ means system is credited; ‘(x)’ means system is credited, but results without credits are also presented. Geo. = Geographical scope: Eur = Europe; Asi = Asia; NA = North America; Oth = Other/unspecified. Met. = Method: Pro = Process-LCA; Hyb = Hybrid LCA; IOA = Input-output analysis. Results: Energy intensity (kWh/kWh); GHG = greenhouse gases (g CO_2e/kWh); CO_2 = Carbon dioxide (g CO_2/kWh); ‘*’ indicates average of multiple results. For studies of extended systems (e.g., w/storage), results include wind system only. Impact categories: C = CO_2; CC = Climate change; E = Cumulative energy; R = Mineral resources, abiotic depletion; A = Acidification; O = Stratospheric ozone depletion; HT = Human toxicity; P = Particulate matter, dust; ET = Ecotoxicity; PO = Photochemical oxidation (smog); N = Nutrient enrichment, eutrophication; W = Waste; L = Land use, land transformation; h = human health endpoint; e = natural environment endpoint; r = natural resources endpoint; s = single-score endpoint; α = additional emissions, non-toxic; τ = additional emissions, toxic (‘additional’: not included in accounted impact categories). Characters are underlined if results are in generic units (e.g., ‘points’).

First author		Methods and assumptions							Selected results			Impact categories	Temporal scope, other notes
	Year	Site	Size	LT	CF	RC	Geo.	Met.	Energy	GHG	CO_2		
Arvesen	2012	Off	5000	25	32.0		Eur	Hyb		34.5	31.3	CC R A HT P ET PO N	Not included in survey
Lenzen	2012						Oth					C	2009-2010
Kabir	2012	Ons	5	25	23.0		NA	Pro	0.118	42.7		CC E A PO	
Kabir	2012	Ons	20	25	22.0		NA	Pro	0.062	25.1		CC E A PO	
Kabir	2012	Ons	100	25	24.0		NA	Pro	0.037	17.8		CC E A PO	
Guezuraga	2012	Ons	2000	20	34.1	x	Eur	Pro	0.033	9.7		CC E	Conventional generator
Guezuraga	2012	Ons	2000	20	20.8	x	Eur	Pro	0.032	8.8		CC E	Direct-drive, no gearbox
Arvesen	2011	Ons	2500	20	23.4		Oth	Hyb		22.5	19.9	C CC A PO N	2007-2050
Arvesen	2011	Off	2500	25	37.5		Oth	Hyb		21.2	18.2	C CC A PO N	2007-2050
Chen	2011	Ons	1250	20	24.9	x	Asi	IOA	0.047	7.6		CC E	
Vestas	2011	Ons	3000	20		x	Eur	Pro	0.025	7.0	5.8	CC E R A P ET PO N W	
Wagner	2011	Off	5000	20	44.5		Eur	Pro	0.137	32.0		CC E A HT PO N	Alpha Ventus wind farm
Wiedmann	2011	Off	2000	20	30.0		Eur	Hyb		33.4*	29.2*	C CC	Two hybrid techniques
Zhong	2011	Ons	600	20		(x)	Eur	Pro				CC E R A O HT ET L	End-of-life scenarios
Gonç. da Silva	2010						Oth	-				E	20 years
Vattenfall	2010	Mix	Mix	20	28.7		Eur	Pro		15.0	13.0	C CC A O P PO N W τ	Wind farm portfolio
Crawford	2009	Ons	850	20	33.9		Oth	Hyb	0.048	35.0		CC E	
Crawford	2009	Ons	3000	20	33.3		Oth	Hyb	0.043	31.6		CC E	
Fleck	2009	Ons	0.4	20	16.9		NA	Pro		45.7		CC	Residential off-grid use
Fthenakis	2009	Ons		30			Eur	Pro				L	
Martínez	2009	Ons	2000	20	22.8	(x)	Eur	Pro	0.025*	6.6*		CC E R A O HT ET PO N L s	
Rule	2009	Ons	1650		45.0	x	Oth	Pro	0.020		3.0	C E	100 years
Tremeac	2009	Ons	0.25	20	20.0	(x)	Eur	Pro	0.333	46.4		CC E h e r	
Tremeac	2009	Ons	4500	20	30.0	(x)	Eur	Pro	0.083	15.8		CC E h e r	Concrete tower
Weinzettel	2009	Off	5000	20	53.0	(x)	Eur	Pro	0.054	11.5		CC E R A HT ET PO N	Floating offshore

Table 1, cont.

Ardente	2008	Ons	660	20	19.0		Eur	Pro	0.052		14.2	C CC E A O P PO N W τ	
Lee	2008	Ons	Mix	20	30.2		Asi	Pro	0.014		3.6	C E	Wind farm portfolio
NEEDS	2008	Off	2000	20¤	46.2		Eur	Pro		8.1	7.6	C P L α τ	GHG calculated here
Pehnt	2008	Off	5000				Eur	Pro		22.0		C	2005-2020, consequential
Ecoinvent	2007	Ons	30	20	8.0		Eur	Pro	0.193	55.6	51.6	C CC E R A O HT P ET PO N W L h e r s	
Ecoinvent	2007	Ons	150	20	9.5		Eur	Pro	0.117	32.3	29.6		
Ecoinvent	2007	Ons	600	20	14.0		Eur	Pro	0.065	18.2	16.7		
Ecoinvent	2007	Ons	800	20	20.0		Eur	Pro	0.042	11.7	10.7		
Ecoinvent	2007	Off	2000	20	30.0		Eur	Pro	0.049	14.7	13.6		
Celik	2007	Ons	8-22	25			Eur	Pro				C CC E	Micro wind system w/battery
Pehnt	2006	Ons	1500				Eur	Pro	0.033	11.0	10.2	C CC E A P N α τ	
Pehnt	2006	Off	2500				Eur	Pro	0.031	9.0	8.9	C CC E A P N α τ	
Rankin	2006	Ons	1.5	20	19.0	(x)	Eur	Pro	0.139		53.2*	C E	Rooftop wind turbine
Vestas	2006	Ons	3000	20	30.0	x	Eur	Pro	0.027		4.6	C CC E A O HT ET PO N W	
Vestas	2006	Off	3000	20¤	54.2	x	Eur	Pro	0.028		5.2	C CC E A O HT ET PO N W	
Vestas	2006	Ons	1650	20	40.8	x	Eur	Pro	0.030	7.1	6.6	C CC E A O HT ET PO N W	
White	2006	Ons	342.5	25	25.6		NA	Pro	0.042		13.8	C E	
White	2006	Ons	600	20	19.9		NA	Pro	0.091		34.4	C E	
White	2006	Ons	750	30	28.6		NA	Pro	0.036		17.9	C E	
Hondo	2005	Ons	300	30	20.0		Asi	Pro		29.5		CC	
Hondo	2005	Ons	400	30	20.0		Asi	Pro		20.3		CC	
Khan	2005	Ons	500	20			NA	Pro	0.025	20.9		CC E	Wind-fuel cell integrated
Elsam	2004	Ons	2000	20	32.2	x	Eur	Pro	0.032	7.0	6.8	C CC E A O HT N W α	
Elsam	2004	Off	2000	20¤	46.2	x	Eur	Pro	0.038	7.8	7.6	C CC E A O HT N W α	
Lenzen	2004	Ons	550				Oth	Hyb	0.070*		19.8*	C E	Geograph. location scenarios
Wagner	2004	Ons	500	20	24.7		Eur	Pro	0.020			E	
Wagner	2004	Ons	1500	20	24.7		Eur	Pro	0.020			E	
Chataignere	2003	Ons	600	20	28.5		Eur	Pro		7.5	7.2	C α	
Chataignere	2003	Ons	1500	20	28.5		Eur	Pro		12.2	11.7	C α	Deep foundation
Chataignere	2003	Ons	1500	20	28.5		Eur	Pro		12.6	12.1	C α	Shallow foundation
Chataignere	2003	Off	2500	20	45.7		Eur	Pro		9.8	9.6	C α	Tubular + Monopile
Chataignere	2003	Off	2500	20	45.7		Eur	Pro		8.3	8.0	C α	Lattice + Tripod
Chataignere	2003	Ons	4500	20	45.7		Eur	Pro		8.9	8.4	C α	Concrete tower
Properzi	2003	Off	2000	20¤			Eur	Pro				CC A HT ET PO W	Nysted/Rødsand wind farm
Kemmoku	2002	Ons	250	15			Asi	Pro	0.025		7.9	C E	Wind-PV-diesel integrated
Pacca	2002	Ons	600	20	23.6		NA	IOA		7.3		CC	
Voorspools	2000	Ons	500	20	25.1		Eur	Pro	0.033		9.7	C E α s	
Voorspools	2000	Off	500	20	28.5		Eur	Pro	0.049		16.5	C E α s	
Schleisner	2000	Ons	600	20	22.8		Eur	Pro	0.065	18.1		CC E	
Schleisner	2000	Ons	600	20	22.8		Eur	IOA	0.074	16.0		CC E	

Aims and objectives

The principal aim of the study can be formulated as to take stock of insights from recent LCA studies of wind power, with a particular view to identifying potentials for improvement and specific needs for research. With this aim in mind, the following objectives are outlined in the paper:

i) To synthesize and critically review current state of knowledge about the life cycle environmental impacts of wind power, taking a broader view of environmental impacts than in past review papers.
ii) To analyse and discuss aspects of data, methods and results that are not sufficiently considered in past LCA reviews, including capacity factor assumptions, modelling of recycling benefits, contribution analysis and method for life cycle inventory quantification.
iii) To identify remaining challenges and suggest directions that future research may take in order to advance knowledge.

Method

A total of 44 studies are surveyed for the purpose of review, and 34 of these are selected for quantitative analysis. The set of studies surveyed is largely comprised of work published in academic journals, but also includes a (non-exhaustive) selection of grey literature. The studies surveyed are shown in table 1 with information on methods and assumptions, selected results, impact category coverage and temporal scope. Paper III, which is presented later in section 3.2, is included in table 1 as well, even though it is not part of the literature database used in paper I.

Results

I here distinguish two broad categories of findings: results of literature survey, and critical evaluation of present knowledge and research needs. The first category, results of literature survey, includes the following elements and findings:

i) LCA studies generally assume lifetimes of 20 years, but sometimes longer for offshore. On average, studies assume capacity factor values of 31% for MW-sized wind turbines onshore and 43% offshore.

ii) Energy and climate change stand out as the most studied impact categories. The survey of results indicates 0.063 (±0.061) and 0.055 (±0.037) kWh energy used and 20 (±14) and 16 (±10) CO_2e emitted per kWh of electricity for onshore and offshore cases. For all impact categories, results vary considerably across studies.

iii) The wind turbine is generally a dominant contributor to emissions for onshore systems; for offshore systems, emissions caused by the foundation may be comparable to that of the wind turbine. If the avoided burden method is employed, the end-of-life stage may yield significant emissions reductions.

iv) Evidence support the notion of strong positive effects of scale in the lower end of the turbine size spectrum, but is inconclusive for the megawatt range.

v) Wind power LCA research typically assesses impacts associated with one (small) reference unit in a static framework, but a handful of studies with broadened scopes are identified.

vi) Studies predominantly employ process-LCA methodologies. If on the other hand hybrid LCA is used, impact indicator results are generally significantly higher.

The paper concludes that the current body of LCAs "provides a fairly good overall understanding of fossil energy use and associated pollution", but also identifies several remaining challenges. A recap of selected issues is given below.

i) Toxicity impacts and aspects of mineral resource depletion are poorly understood.

ii) Applications of the avoided burden method generally either use inappropriate methodologies or the use of an appropriate methodology cannot be verified because studies fail to report key assumptions.

iii) There appears to be a general tendency of wind power LCAs to assume higher capacity factors than current, real fleet-wide averages[1].

iv) Due to the use of process-LCA methods, the majority of studies are likely to suffer from significant cut-off errors.

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[1] A supplementary note on capacity factor values is in appendix A.3.

v) Certain assumptions are generally not referenced and/or their validity is yet to be verified. This includes assumptions that support modelling of replacement of parts and, for offshore wind farms, operations that take place in ocean waters. It also includes assumptions that generic materials in LCA databases are representative for the actual materials that go into the systems.

vi) As a rule, current LCA literature falls short of examining network integration of variable wind power, temporal aspects and the absolute magnitude of emissions[2].

Uncertainty and limitations

As is noted in the paper, the observations included in the survey do not comprise a random sample: the observations were not selected in a formal, randomized manner, some observations are known to be not independent, and the survey involves some subjective choices (notably, concerning how multiple observations from single studies are accounted). These factors may have influenced results to some extent. Another limitation is that while a survey is performed for impact indicator values in terms of energy, greenhouse gas emissions and nine individual pollutants, results from impact assessments by other categories (acidification, eutrophication, etc.) are not surveyed – the reason for this that different characterization methods and units of measurement among studies hamper proper comparisons. Finally, I note that a proper meta-analysis could provide additional and more robust insights[3]; with very few exceptions however, extant research does not provide accounts of data, assumptions and results at the level of detail required for meta-analyses – this conclusion is also drawn by Price and Kendall (2012).

Potential impact of study

I believe the review may be useful in providing an overview of what has been done in the field of wind power LCA research, in conveying insights that emerge from this research and shedding light on some of the reasons why results differ across studies, and in pointing to remaining challenges that future research may address. The paper makes an original contribution owing to:

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[2] See also later discussions in section 3.2 and third subsection in section 5.3.

[3] The term meta-analysis was coined by Glass (1976) and described as “the analysis of analyses”. While paper I presents some limited analysis of assumptions and results, it does not provide any detailed analysis of analyses.

i) new surveys and simplified analyses, for example of results by several impact categories, relative contributions from components and life cycle stages, and effects of wind turbine size and method for life cycle inventory;
ii) critical appraisal of scope of analysis (e.g., impact category coverage, micro- and static-minded assessments), data and assumptions (e.g., uncertainty surrounding emissions embodied in materials, seemingly unverified basis for modelling installation and use phases) and methods (e.g., seemingly inconsistent use of avoided burden method, system boundary issues in process-LCA).

Owing to these attributes, I anticipate the study may assist those who seek to distil key insights from and understand limitations of the voluminous wind power LCA literature. Furthermore, the work can hopefully provide inputs to future analysts as they seek and decide on new research directions. Three concrete implications that can be drawn from the paper are that future research should avoid inconsistent modelling of recycling benefits, should attempt further to move beyond static, unit-based assessments, and should employ hybrid LCA methods.

3.2 Paper II: System-wide emission costs and benefits

Rationale

Among the existing methods for sustainability assessments of power generation technologies, large-scale integrated assessment models investigate energy transitions at the economy-wide level (IEA 2010a; Krey and Clarke 2011), but do not consider environmental effects caused by the act of building power plants – in general they lack a life cycle perspective. Conversely, as is noted in section 3.1 and paper I, conventional, unit-based LCAs do not address aspects of scale and time. Thus, while scenario analyses and conventional LCAs generate useful insights, individually they are also missing important elements; combining the two perspectives could provide additional insights and help create a more solid basis for evaluating energy strategies. A similar point is made by Sathaye et al. (2011):

> By extending scenario analyses to include lifecycle emissions and the energy requirements to construct, operate and decommission the different technologies explicitly, integrated models could provide useful information about the future mix of energy systems together with its associated lifecycle emissions and the total environmental burden. (p. 729)

Aims and objectives

The study aims to make an initial attempt to integrate scenario analysis and LCA in order to assess the economy-wide environmental costs and benefits of wind power expansion. To achieve this aim the following primary objectives must be met:

i) To quantify and assess global environmental impacts due to the act of building, operating and dismantling wind power plants toward 2050, following energy scenarios achieving a substantial degree of climate change mitigation.
ii) To include in the analysis an integrated LCA modelling of emission reductions thanks to wind power expansion.

In addition, secondary objectives that help to achieve the aim are:

iii) To develop life cycle inventories, using a hybrid LCA approach, for hypothetical onshore and offshore wind farms meant to represent average conditions.
iv) To adjust, year by year, the electricity mix used in the LCA scenario model.

Method

The unit-based analysis falls into the category of tiered hybrid analysis (section 2.2). The scenario analysis, which follows two of the International Energy Agency's BLUE climate change mitigation scenarios (IEA 2010a), includes additional elements: The quantification of aggregated life cycle inventory results consists, in essence, of scaling inventories for generic onshore and offshore wind farms to match future capacity requirements. The scenario analysis includes replacement of components at their end-of-life, and distinguishes emissions occurring prior to, during and after the useful life of the wind turbines. A year-by-year global mix of electricity sources, which change with time according to the BLUE scenarios, is assumed. A second key element of the scenario analysis is the quantification of emissions savings from wind power, which is performed on the assumption that additional wind electricity, compared with a baseline, displaces the current-year mix of electricity from fossil fuel power stations.

Results[4]

According to the results, cumulative emissions of 2.3 Gt CO_2e may be ascribed to wind power development in 2007-2050 in a scenario where 12% of world electricity comes from wind in 2050. The figure for a 22% contribution from wind in 2050 is 3.5 Gt. As a result of increased capacity factor and cleaner electricity mix, the greenhouse gas emission intensity is reduced from around 22 g CO_2e/kWh in 2007 to 14 g CO_2e/kWh in 2050; thus, decarbonizing electricity supply is not sufficient to make wind power close to CO_2-free – an elimination of other pollution sources than fossil fuel-fired power stations is required as well. The sensitivity analysis demonstrates that changing the assumed lifetimes changes emissions estimates significantly.

Moving on to the evaluation of the positive role of wind power in emission reduction, the following are true for all impact categories: i) Direct (in-plant) emissions of replaced fossil-fuel power plants grossly exceed the total emissions of wind power (broken blue and dotted purple lines in figure 4 in the paper); and ii) indirect (fuel-chain) emissions of replaced fossil-fuel power plants also exceed the total emissions of wind power (broken green and dotted purple lines).

Uncertainty and limitations

The modelling of technological changes is limited, both when it comes to manufacturing and other activities in the background economy (which changes only in terms of the electricity mix) and design of wind energy systems (which changes only through increased load factors and a shift towards offshore development). Future research may replace simplifying assumptions about technological change with more sophisticated reasoning in order to reduce uncertainty and offer additional insights.

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[4] Due to an error in the model used to compute results for the originally published paper, a corrigendum was published with corrected results. Figures given in this thesis are the corrected results.

Another important limitation is that network integration is not considered. In reality, large-scale adoption of wind power will not take place in isolation of background energy supply and distribution systems, but will require upgrades in electricity infrastructure, may need to be supplemented by additional energy storage, and may lead to a less optimal operation of thermal and hydro power plants[5]. As environmental implications of such effects may not be trivial, I can see that one possible critique of the paper is that it does not fully live up to the promise of "estimat[ing] aggregated emissions caused by global wind power development" (introduction in the paper). At the same time, I would argue that in any LCA at some point you need to draw your system boundary and say *ceteris paribus* – all else being equal. This is in principle true for this scaled-up LCA as it is true for a unit-based LCA, although, admittedly, the high penetration of wind power is made more explicit in the former case.

Based on subsequent work (paper III), emissions arising from production of spare parts and, for the offshore wind farm, operations by ships are probably underestimated in paper II. Limitations also arise from weaknesses in the materials and methods for the input-output inventory modelling. Firstly, the breakdown of costs by individual processes is subject to considerable uncertainty. Secondly, the manner in which the problem of double counting is dealt with is not optimal: Instead of subtracting monetary equivalents of physical flows (Strømman et al. 2009), entries in the input-output system that include flows covered in the process-based system are zeroed out. The former approach is preferable to the latter, but requires additional and perhaps higher-quality data. Thirdly, the input-output data set covers eight air pollutants; this limited set allows meaningful impact characterizations for four impact categories only.

In general, moving from a static, unit-based study to a futures study introduces new sources of uncertainty and increases the overall uncertainty of results formidably.

Potential impact of study

As I have previously argued, static, unit-based LCAs are, while useful, inadequate for evaluating future energy transitions; therefore, it is of importance that the field moves beyond a purely unit-based focus. The present paper may be viewed as an early research attempt in this

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[5] See also note on grid expansion and network integration of renewables in third subsection of section 5.3.

direction. The primary research contributions lie in the original modelling approach and analysis used to assess the environmental implications of wind power development, and in the new insights provided on the environmental costs and benefits of wind power expansion.

Previous attempts to compare the environmental performance of wind power vis-à-vis fossil fuel-based power – such attempts occur in original LCA research publications (e.g., Wagner et al. 2011) as well as in broader evaluations or literature reviews (e.g., Jacobson 2009, Kaldellis and Zafirakis 2011, Raadal et al. 2011, Sathaye et al. 2011) – have juxtaposed emissions per unit of electricity for different technologies. Such inquires typically offer the observation that the life cycle emissions of wind power are comparatively very small or negligible. In comparison, the current assessment incorporates additional elements: i) the time lag between emission costs (which occur in large part during the production of plant stage) and emission benefits (which are distributed over the useful life); ii) the absolute magnitude of wind power expansion; and iii) hybridized inventories, which lead to more complete system descriptions than in most previous work. Moreover, the assessment is performed on the assumption that only additional wind power substitutes fossil power. Despite that all of these elements pull in the direction of a less positive evaluation for wind power, the present study concludes that emission costs appear low in comparison with emission benefits. In this respect, the study may be viewed as confirming the emission benefits of wind power. At the same time, the connection with a planetary boundary of 680 gigatonnes CO_2 in 2010-2049 (see discussion section in the paper) suggests that emissions caused by wind power are too large to be neglected.

3.3 Paper III: The importance of ships and spare parts

Rationale

The motivation for investigating the environmental impacts of offshore wind power is twofold. Firstly, the relative importance of offshore projects in wind power development is expected to increase in the future (section 1.2). Secondly, there are weaknesses and gaps in current knowledge about the environmental effects of offshore wind farms, and more research is needed to clarify potential differences between onshore and offshore wind power generation (section 3.1 and paper I). Here I wish to highlight two issues:

i) Existing LCAs do not consider sea-based activities for installation or maintenance of offshore wind farms in any detail, or they lack transparency in the reporting of assumptions for modelling such activities (for a fuller account and references, see the literature review in the paper). The legitimacy of such practices may be questioned, as installation and maintenance contribute significantly to the overall costs of offshore wind energy projects (Blanco 2009; EWEA 2009a), and pollution from ships is a significant and growing concern in the general case (Eyring et al. 2005; IMO 2009).

ii) Existing LCAs do not justify or provide references for assumptions supporting the modelling of production of replacement parts. A comparison of replacement rates typically assumed in LCAs with corresponding data or assumptions in other sources (Echavarria et al. 2008; Rademakers and Braam 2002) suggests that LCAs tend to assume too low replacement rates (section 1.1 in the paper and section 2 in the supporting information for the paper).

In addition, most published LCAs of offshore wind power employ process-LCA methodologies known to suffer from systematic underestimation of impacts, and few studies address impact categories other than energy use and greenhouse gas emissions (section 3.1 and paper I).

Aims and objectives

The aim of the paper is to address the identified weaknesses and gaps in knowledge in order to advance understanding of the environmental impacts of offshore wind power in general, and the role of ships and spare parts in LCAs of offshore wind power in particular. More specifically, the main objectives are:

i) To quantify and assess the life cycle environmental impacts of a Scandinavian offshore wind farm by a range of impact categories and using a hybrid LCA methodology.

ii) To include in the model representations of marine vessel activities at a higher level of detail and with greater transparency than in previous studies, and to evaluate the importance of such activities in LCAs of offshore wind power.

iii) To make an initial attempt to reconcile assumptions about replacement rates in LCAs with operational experiences, and to evaluate the role of replacement production in LCAs of wind power.

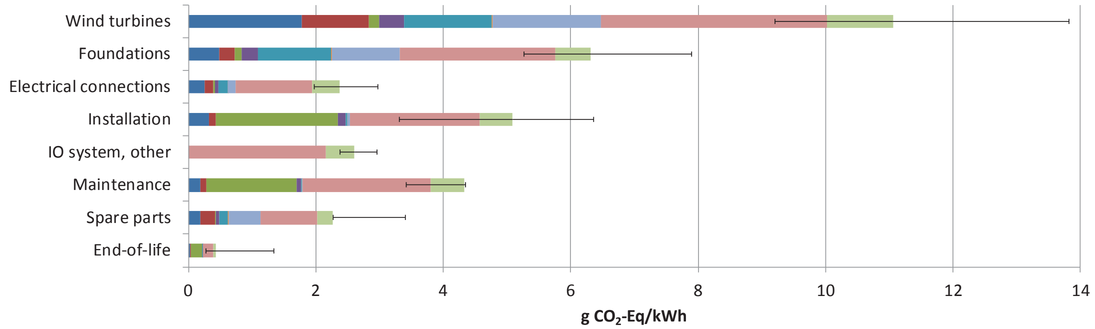
Method

A tiered hybrid method for life cycle inventory is employed (section 2.2). The proposed Havsul I wind farm in Norway is used as a model. The LCA model incorporates a detailed representation of offshore operations connected with the installation, operations and maintenance, and decommissioning of the wind farm. ReCiPe is chosen as method for impact assessment (Hegger and Hischier 2010; ReCiPe 2009) and is applied for twelve impact categories.

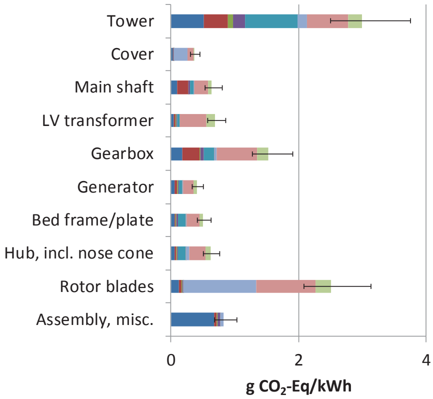
Results

According to the results, every kWh of electricity delivered will bring about greenhouse gas emissions of 34 g CO_2e; this falls in the upper range of values given in the existing literature (paper I). As is evident from figure 3, installation and maintenance activities are responsible for significant shares of the total carbon footprint (15% and 13%). Production of replacement parts is typically responsible for 5-10% of total impact potentials and 13% at the most (freshwater ecotoxicity). These findings may not be wholly consistent with the notion that “emissions from the manufacturing stage dominate overall lifecycle [greenhouse gas] emissions” (Wiser et al. 2011) (p. 571), and contradicts the perception that greenhouse gas emissions from the use phase are “almost negligible” (Raadal et al. 2011) or “negligible” (IEA Wind 2002). Moreover, direct emissions of nitrogen oxides, sulphur dioxide and particulates from ships cause considerable impact potentials in the categories of marine eutrophication, particulate matter formation, photochemical oxidant formation and terrestrial acidification (figure 1 in the paper).

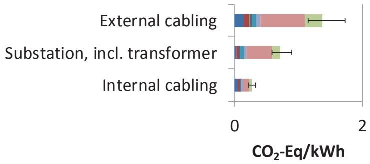
A comparison of offshore wind power and natural gas power with carbon capture and storage (Singh et al. 2011) indicates that offshore wind power exhibit several times lower greenhouse gas emissions, but offshore wind power appears as the less environmentally friendly option by human toxicity, freshwater ecotoxicity and freshwater eutrophication impact categories (discussion section in the paper and figure S3 in the supporting information of the paper).



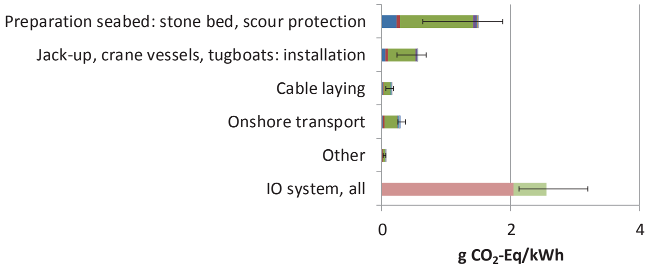
(a) Main components and phases (all emissions covered)



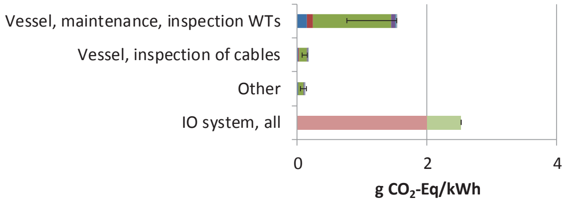
(b) Wind turbines



(d) Electrical connections



(c) Installation



(e) Maintenance

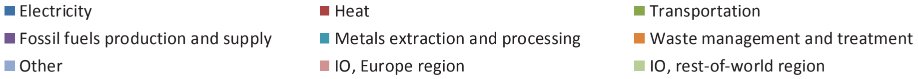


Figure 3. Climate change impact indicator results for offshore wind farm by eight main components and nine stressor sources (a), and breakdowns into sub-categories for selected main components (b-e).

Note: Stacked bars represent reference scenario results. Negative error bars give total values in Optimistic scenario and positive error bars in Pessimistic scenario. Panel (b) shows a breakdown of contribution from wind turbines (32% of total emissions); similarly, (c) shows a breakdown of installation (15%), (d) of electrical connections (7%), and (e) of maintenance (13%). For installation and maintenance, disaggregated results are not available for emissions elicited in the IO subsystem; hence the IO system contribution is represented by a single bar in panels (c, e). The stressor source categories stacked horizontally within each bar are the same as in figure 1 in the paper.

Uncertainty and limitations

Uncertainty is an inherent feature of many aspects of LCA, manifesting itself both at the inventory analysis and impact assessment stages (Finnveden et al. 2009; Lloyd and Ries 2007). The paper explores uncertainty by considering multiple scenarios reflecting different assumptions and through qualitative discussions, but does not attempt to quantify all uncertainty (e.g., through Monte Carlo analysis).

The estimated emissions from offshore activities are subject to considerable uncertainty. Firstly, uncertainty stems from a lack of certain knowledge about which activities that are needed and what are the associated work times; in this regard, the analysis relies in large part on assumptions made in Ramboll (2009) based on a survey of current practices. In reality, strategies for installing and maintaining offshore wind farms differ depending on project-specific conditions (e.g., distance from shore, foundation concept), and the individual developer or contractor. Secondly, significant uncertainty exists in the assumed operating mode data determining fuel consumption rates. There is also large uncertainty surrounding the rates at which parts require replacement, as little empirical evidence on exchange rates is publicly available (Echavarria et al. 2008; Faulstich et al. 2011; Ribrant and Bertling 2007). Further research is needed to test the robustness of the results for installation and maintenance. From the perspective of the LCA analyst, access to better and more comprehensive information on real-world work times and operating modes of marine vessels, and replacement rates for individual components, would be beneficial.

The weaknesses in materials and methods used for the input-output inventory modelling noted in section 3.2 for paper II apply here as well, but are to some degree alleviated by the use of an improved environmentally extended input-output database in this work. The improved database has a higher level of disaggregation and covers more – albeit still a limited number of – stressor types. Due to the limited set of stressors, the assessment becomes, de facto, a process-based LCA for some of the impact categories.

The general lack of spatial specificity – both in connection with stressor *source* characteristics (e.g., pollution emitted from sea vessels versus onshore sources) and *receiving environment* sensitivity (e.g., ecosystems relatively more susceptible to acidification effects versus ecosystems less susceptible) – is a recognized limitation of prevailing impact assessment methods (Finnveden et al. 2009; Hauschild 2005; Pennington et al. 2004). The current analysis uses generic characterization factors from ReCiPe (Hegger and Hischier 2010; ReCiPe 2009); however, with Norway-specific characterization factors for terrestrial acidification, for example, results for this impact category may have looked different (Posch et al. 2008; Seppälä et al. 2006), and I am not certain that the utilized characterization factors are really applicable to activities offshore.

Owing to the very large number of chemicals involved and complex effect chains (Hauschild 2005; Pettersen and Hertwich 2008; Rosenbaum et al. 2008), characterization models are probably less developed – and thus uncertainty is higher – for toxicological impacts than for most other impact categories. Analogously, mineral resource depletion impacts also involve a very large number of minerals and complex effect chains. There is no agreed upon method to measure mineral resource depletion in LCA; competing methods approach the problem from different angles and may lead to different results (De Schryver and Goedkoop 2008; Steen 2006). Complicating factors include current diversifying trends in non-fuel minerals use (Graedel and Erdmann 2012), the need to consider future availability and usability of secondary materials (Graedel et al. 2011; Müller et al. 2006; Pauliuk et al. 2012), the trend of declining metal ore grades (Mudd 2010; Norgate and Jahanshahi 2010; Prior et al. 2012), and linkages that occur because minerals are mined together or used together in, for example, metal alloys (Graedel 2011; Yellishetty et al. 2011). With these factors in mind, indicators of mineral resource depletion seem somewhat arbitrary and may be unable to properly gauge the problem of mineral resource depletion.

Potential impact of study

The main contribution of the paper lies in the original investigation of environmental effects of installation and use phases of offshore wind power, and the new insights generated by this investigation. Previous LCAs give only cursory consideration to operations required by sea-based activities and to the need to replace parts and – implicitly or explicitly – suggest that these elements of the product system of wind power are unimportant or negligible when it comes to total environmental impacts. By providing new analysis and discussion on aspects of installation and use phase, the paper addresses a significant weakness in existing knowledge. The results indicate greater contributions from offshore activities and supply of replacement parts to total impacts than has previously been thought. Furthermore, it is conceivable that the relative importance of offshore operations increases in the future as developments increasingly take place in deeper and more distant waters. This indicates a need for future LCA research on offshore wind power to give more consideration to installation and use phases. The issue of production of spare parts is not exclusive to the offshore case, but is also relevant for assessments of onshore wind farms.

In addition, the research fills a gap in the literature by studying a range of impact categories, and by presenting results that illuminate differences among impact categories with respect to which components lead to environmental pressures and in which types of activities pressures occur. To the extent that cut-off errors are avoided, the use of a hybrid LCA methodology arguably gives the results more credibility compared to most previous assessments of offshore wind farms.

In a broader context, the study can perhaps provide a useful perspective for undertaking environmental assessments of activities in coastal and marine areas – activity levels in such areas are generally increasing due to a number of uses, including offshore wind power and other ocean energies, subsea power transmission, maritime transport, oil and gas extraction, commercial and recreational fisheries, aquaculture and port development. Incorporating detailed representations of installation and use phases in environmental assessments may be important for some of these other technologies also, similarly as for wind power.

4 Paper IV: Evaluation of limitations in mitigation assessments

Rationale

An underlying premise of world energy and climate policy is that technology can solve energy-related global environmental problems, even under scenarios of continued strong growth in economies and populations. Consequently, the climate policy arena is devoid of attempts to seriously confront resource intensive lifestyles, population growth and fundamental economic structures. Suggested portfolios of solutions (e.g., IEA 2010a, 2010b, IPCC 2007b, Jacobson and Delucchi 2011, McKinsey 2009, Pacala and Socolow 2004) are commonly perceived to demonstrate the feasibility of solving the problem of climate change, but rests on many simplifications. The nature of the climate change problem is such that we cannot afford fundamental biases in the knowledge base that support policy: Either the technology optimism permeating current policies can withstand objective scrutiny, or it must be replaced by a more nuanced view.

Aims and objectives

The prime aim of the paper is to evaluate important simplifying assumptions in policy-supporting climate change mitigation assessment literature, and present part of the case that assessments are the basis of unfounded technology optimism in world climate policy. In order to achieve this aim, the paper brings together evidence from different fields of literature, for instance life cycle assessment, energy rebound, and carbon lock-in literature.

Results

The paper presents six arguments that, arguably, are underappreciated in the climate policy arena. The overarching theme of the arguments is that incomplete coverage of side effects of mitigation measures, and neglect of many interlinkages between physical and social sub-systems, lead to overly optimistic assessments. A brief summary of the arguments is provided below.

- A transition to low-carbon energy supply will in itself cause emissions of greenhouse gases. Current knowledge about the absolute magnitude of these emissions is poor, but total emissions are probably too large to be neglected (section 3.1 in the paper).
- The real ability of energy efficiency measures to deliver emissions reductions is generally overrated. There are two reasons for this. Firstly, as market failures and non-market failure factors hinder energy efficiency investments in practice, full technical potentials are not utilized easily. Secondly, successful strategies to implement energy efficiency measures may to some degree rebound on society: Through higher-order effects, efficiency may stimulate more energy consumption (section 3.2 in the paper).
- Implementing carbon capture and storage (CCS) on a large scale means preserving forces that add to a lock-in of fossil fuel-based energy systems, while not implementing CCS on a large-scale implies a probably significant increase in overall mitigation costs. In other words: Proposed least-cost pathways (that is, pathways where large-scale development of renewable energy run in tandem with large-scale modifications and extensions of fossil energy systems) may have large problems with lock-in barriers in the long-term, while dedicated renewable energy pathways are more costly in conventional terms – in either case, realizing mitigation at such low overall costs as indicated by least-cost scenarios may prove difficult in practice (section 3.3 in the paper).
- Examples of absolute decoupling of global environmental impacts or resource use from economic growth are rare; to my understanding, past experiences provide little support for the notion that greenhouse gas emissions, total material extraction and biodiversity loss can be reduced as income grows (section 3.4 in the paper; see also UNEP 2011).
- Linkages between environmental pressures and impacts are likely to complicate mitigation (section 3.5 in the paper).
- It is conceivable that the future may hold surprises in terms of unanticipated growth in demand for energy. Firstly, entirely new categories of demand may emerge that are not

foreseen by energy analysts today[6]. Secondly, more energy may be needed to extract, process and transport natural resources (water, minerals) in an ever more resource-constrained world (section 3.6 in the paper).

Uncertainty and limitations

One fundamental limitation of the paper is that while it brings together evidence from different research fields and points to gaps in knowledge, and makes a preliminary evaluation of potential implications, it does not present new research findings or evidence, and thus does not contribute to filling knowledge gaps about the environmental implications of energy transitions as such. In more concrete terms, the paper is limited by the exclusive focus on energy; the important role of agriculture as a driver for global environmental problems, including climate change, biodiversity loss and water use (MEA 2005; UNEP 2010a), is not treated. The conflict between crop-based bioenergy development on the one hand and food production and biodiversity on the other hand is not explicitly considered either, but is nevertheless an important concern (Creutzig et al. 2012; UNEP 2009; van der Voet and Graedel 2010). According to Creutzig et al. (2012), current large-scale integrated assessment models underexplore the issue of indirect land use change due to biofuels.

The intermittent nature of renewable energy is not noted in the paper as a fundamental barrier to a transition towards a renewable energy future, primarily because I for my part am unsure about the degree to which it may be solved by managed demand responses, energy storage, diversified production and other measures. The academic literature seems to be divided on this question (compare, for example, Trainer 2010 and Delucchi and Jacobson 2011). Williams et al. (2012) couple climate change mitigation scenarios with a security-constrained electricity market dispatch algorithm, and find that renewables can supply a maximum of 74% of California’s electricity in 2050 if grid operability is to be maintained, even under optimistic assumptions such as perfect power generation forecasting, radical innovations in storage technologies and a major shift in demand curves.

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[6] For example: Global air transport is presumably included in current large-scale assessment models, but would analysts of the 1930s include aviation in global energy scenarios? Correspondingly, do energy scenarios of today include space tourism as a demand category? – if not, do they miss out on some of the potential growth?

Potential impact of study

While the idea that innovations in technology – coming face-to-face with long-term growth in populations or economies – will fall short of creating truly sustainable societies is not new (e.g., Daly 2005, Ehrlich and Holden 1971, Hardin 1968, Jackson 2009, Malthus [1798] 2001, Meadows et al. 1972, Speth 2008), the paper presents an original contribution by bringing together evidence from different research fields in a way that has not been done before. I believe the paper may be seen as valuable because it pinpoints important gaps in knowledge, and connects dots that have not been connected in such a way before. The paper strives to be concrete on what exactly is amiss in the technology optimism that permeates current policies. Finally, it is my hope that the paper may contribute to raising awareness on the issue that simplifying assumptions systematically lead to biased assessments – and here a distinction must be made between biased assessments and uncertainty in assessments: bias is an inclination to go in one direction.

5 Final discussion and conclusions

In previous chapters I have presented four papers. Papers I-III are concerned with the life cycle environmental impacts of wind power, and may, in the larger setting of "understanding the environmental implications of energy transitions" indicated by the main title of this thesis, be regarded as case studies for wind power. The last paper, paper IV, is more broad in scope, treating also other issues than life cycle environmental impacts, and not focusing on wind power in particular. The need for and pursuit of a better and more complete understanding of the environmental implications of energy transitions is a unifying theme for all the papers.

In previous chapters 3 and 4 I have already discussed the research contribution of the papers individually. Next in section 5.1, I discuss the contribution of the thesis as a whole, before revisiting the environmental performance of wind power in section 5.2. Suggestions for further work are provided in section 5.3. Sections 5.1-5.3 also serve the function of concluding the thesis.

5.1 Research contribution

Here I discuss the research contribution of the thesis as a whole. The discussion is meant to supplement, not to give an extensive summary of, discussions presented previously in chapters 3 and 4 on the individual contribution of the papers.

Moving beyond static, unit-based LCAs

For the thesis as a whole, the most significant contribution may be the initial attempt to move beyond static, unit-based LCAs of wind power. Given the almost single-minded concentration in existing wind power LCA literature on assessing impacts associated with one (small) reference unit in a static framework, I believe the analysis presented in paper II may be regarded as novel, and as an early research attempt in the direction of reconciling LCAs and macro-level energy scenarios. I can see a conceptual element to paper II's contribution in that the paper demonstrates one (simplified) approach which may be taken to perform macro-level LCAs of emerging energy technologies, and illustrates some dynamics at play in the emergence of an energy technology (the absolute scale of the expansion, the need for replacement systems at end-of-life, effects of cleaner electricity mix in manufacturing). I can also see an empirical element to the contribution in that paper II quantifies and assesses emissions caused and avoided by large-scale adoption of wind power, thus providing new quantitative insights into the environmental costs and benefits of wind power deployment.

At the same time, paper II is clearly limited by simplifying assumptions made for the scenario analysis; the paper does not present any detailed modelling of technological change. Challenges connected with incorporating technological change in similar analyses could be a point of departure for future research (see also discussions in section 3.2 and in the paper). Moreover, wind power is but one proposed technological solution to the problem of man-made climate change; in the future, wider and more comprehensive studies may address whole portfolios of technologies.

Related to the research contribution of paper I noted above are the discussions of the need for LCA research to address aspects of scale and time presented in papers I and IV. Both papers point to limitations of static, unit-based assessments. Paper I identifies a limited number of existing future-oriented wind power LCAs, and calls for future research to focus more attention on consequential effects, temporal aspects and the absolute magnitude of impacts. Paper IV discusses the importance of real-world life cycle impacts of energy transitions and contextualizes the issue in such a way that the need for research on this topic is highlighted. Owing to these attributes of papers I and IV, the papers can perhaps help to motivate and instigate a broadened focus of attention – one which encompasses both conventional and future-oriented approaches – in future (wind) energy LCA research.

Using a hybrid LCA methodology

Another main contribution of the thesis is the use of a hybrid LCA methodology to assess the environmental impacts of large-scale adoption of wind power (paper II) and an offshore wind farm (paper III). As is discussed in section 3.1 and paper I, existing LCA studies of wind power predominantly employ process-LCA methodologies, but the use of a hybrid LCA methodology facilitates more complete system coverage. While cut-off errors due to the use of process-LCA may not be equally problematic for all applications of LCA[7], they are potentially highly problematic when impact indicator values are meant to accurately reflect real-world environmental damages, or when results are used for comparing technologies that serve the same functions but have differently structured product systems (Majeau-Bettez et al. 2011). Limitations arise from weaknesses in the materials and methods used for the input-output inventory modelling in the current work, however, as is discussed in sections 3.2 and 3.3.

Illustrate the significance of taking a holistic view

By means of LCA studies of wind power and a wider evaluation study of indirect effects of climate change mitigation measures, the thesis illustrates the significance of taking a holistic view in evaluating the environmental implications of energy technologies and transitions. The significance of holistic views is made clear, I believe, by several perspectives and findings presented in the current work; most notable are perhaps the preliminary findings that the carbon footprint of large-scale adoption of wind power is, in the aggregate, probably too large to be neglected, but at the same time emissions stemming from wind power appear low when contrasted with emission savings that occur if wind power displaces fossil fuel-based power. In the results presented in paper II, even the *indirect* emissions of displaced fossil fuel power exceed the total emissions of wind power, which perhaps more than anything else is illustrative of how polluting conventional fossil fuel-based electricity really is in a life cycle perspective.

A central tenet of holistic environmental assessments is to seek to identify – or conversely: rule out – potential cases of problem shifting from one impact category to another (section 1.3). Papers I and III identify increased toxicity and mineral resource depletion impacts as two potential cases of problem shifting if wind power is deployed instead of fossil fuel power.

Another element which may help to illustrate the significance of holistic assessments is the identification of indirect, countervailing effects of greenhouse gas-mitigating measures in paper IV; also important is the framing of the discussion of indirect effects in the paper, which, at

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[7] It may be relatively less problematic for comparative LCAs of products with similar product systems (Majeau-Bettez et al. 2011).

least by intention, makes clear the need for research to evaluate mitigation in a broad, system-wide perspective.

Other remarks

In contrast with nearly all previous wind power LCAs (paper I; Price and Kendall 2012), complete accounts of inventory data are provided for the current work (see also supporting information for the papers) in order to ensure transparency and allow for informed comparisons across studies, and to assure better reproducibility of results. I believe this may be seen as a positive attribute of the current work. Making process-level input data available may be one key to alleviating confusion due to unexplained variability in results from wind power LCA studies, and enhancing the real and/or perceived usefulness of LCA research.

Some further limitations of the current work may be noted here that have not been noted previously. On a general level, the wind power LCAs presented in papers II and III do not incorporate detailed technology descriptions; for example, the wind turbine model used in paper III includes nine components made up of five generic materials, whereas a real-world wind turbine reportedly contains up to eight thousand parts (EWEA 2007). Besides introducing uncertainty, the rather cursory technology representations make the LCAs not suitable for detailed product design considerations. Essentially, this problem stems from a disconnect between the LCA analysts and industry; standing in academia, access to more detailed data from the industry would be beneficial.

As for the merit of the present work in describing the environmental credentials of wind power, it needs to be emphasized that the types of environmental impacts explored do not exhaust all environmental concerns associated with wind power, which include also bird and bat collision fatalities, impact on local climate, habitat change and negative impacts on visual amenity (Wiser et al. 2011). The omission of such impact categories from the current assessment and papers I-III does not imply that they are considered to be unimportant, but is rather a result of firstly, a need to limit the scope of the work, and secondly, difficulties in assessing such impacts quantitatively (difficulties arise from the case-specific and sometimes subjective nature of the impacts, and lack of coverage in prevailing impact assessment methods used in LCA).

5.2 Environmental performance of wind power

So, is wind power environmentally benign? My short answer would be: It depends. In attempting to extend the answer, or at least provide some basis for making a longer, partial answer, below I revisit and discuss further some of the lessons learned from the current work, before presenting a note on displacement of fossil fuels. Fossil fuel displacement is given special attention here because I see it as a crucial aspect in evaluating the net environmental benefits of wind power, and because the degree to which wind displaces fossil fuels is a central assumption in the evaluation of emission reductions in paper II.

A revisit of some lessons learned

As we have seen, results from unit-based LCAs suggest that the greenhouse gas emissions of wind power are very low in comparison with that of fossil fuel-based electricity (papers I and III). Studies employing hybrid LCA methodologies, such as papers II and III, generally show significantly higher emissions than conventional assessments, but emissions of fossil fuel power are much higher still. Furthermore, and as I have previously argued in section 3.2, the evaluation of net emission benefits of wind power expansion presented in paper II incorporates additional elements that are not considered in unit-based evaluations, and besides assumes that only additional wind power substitutes fossil fuel power. These factors all pull in the direction of a less positive evaluation for wind power. Nevertheless, the figures for net emission benefits in paper II put wind power in a favourable light, and thus – notwithstanding the considerable uncertainty and limitations in scope of analysis – I see them as a confirming the emission benefits of wind power, for climate change and the three other impact categories addressed in the paper.

Potentially, if mitigation strategies in themselves cause substantial emissions, society may find itself in a bit of a catch-22 situation where measures that by intention reduce emissions in reality lead to more emissions, again leading to a requirement of more (and maybe even less effective) measures, and so on. Findings presented in this thesis do not support the notion that large-scale deployments of wind power will be responsible for creating such a negative, reinforcing spiral. At the same time, there is reason to be concerned that cumulative greenhouse gas emissions instigated by massive expansions of wind power markets in the future may not be insignificant –

and this is more about the scale of typically foreseen expansions than the emission intensity of wind electricity, which by relative measures may appear low.

A further element which may be noted is that it is the reliance on fossil fuels today which is the reason why wind power is not CO_2-free, and thus one could argue that fossil fuel-related emissions are not inherent characteristics of wind power systems as such (Pehnt 2006; Hillman and Sandén 2008). Fossil fuel-burning in thermal power plants – exactly the plants that wind parks are meant to replace – causes 20-29% of the unit-based impacts in paper II. Using fossil energy systems of today for the purpose of developing energy systems for tomorrow cannot be avoided entirely; what we should be concerned about is the degree to which such use takes place, and in a broad context, to seek designs and strategies that maximize net environmental benefits.

There may be a need to manage trade-offs between climate change mitigation delivered by wind power on the one hand and increased toxicity and/or mineral resource depletion impacts induced by wind power on the other hand (papers I and III; see also Uncertainty and limitations subsection in section 3.3). Besides the very tentative conclusions that can be drawn about toxic and mineral resource depletion impacts of wind power based on papers I and III, in a long-term perspective I see some further potential grounds for concern. This includes generally declining metal ore grades (Mudd 2010; Norgate and Jahanshahi 2010; Prior et al. 2012), the possibility that geopolitical factors and regional differences in resource endowments affect real resource availability in the future (Erdmann and Graedel 2011; Habert et al. 2010; Yellishetty et al. 2010), and the possibility that public resistance due to local environmental impacts (water use, toxic releases from mining activities or waste deposits, land transformation) hinder future resource exploitation in practice (Prior et al. (2012); see also UNEP 2010a).

Concerning displacement of fossil power

The perspective taken in paper II that only additional wind electricity displaces fossil fuel electricity differs from conventional thinking about benefits of wind power, which takes for granted, often implicitly, a one-to-one correspondence between wind electricity supplied and fossil fuel electricity saved: LCA studies (e.g., Chen et al. 2011, Jacobson 2009, Tremeac and Meunier 2009), the wind industry (e.g., EWEA 2009c) and the Intergovernmental Panel on Climate Change (Wiser et al. 2011) either explicitly use the difference in life cycle emissions of wind and fossil fuel electricity as a measure of the net emission savings of wind power, or give the impression that the difference can be used as a measure of such savings[8]. Wiser et al. (2011) (p. 570) claim, for example, to show that the life cycle emissions of wind power and emission penalties due to variability "are modest compared to the net [greenhouse gas emission] reduction benefits of wind energy", where the implicit assumption is a one-to-one displacement with fossil fuel electricity – many other similar statements are made in Wiser et al. (2011) as well.

Analysts may assume that one unit of wind power delivered implies one saved unit of fossil fuel power if this helps to illustrate a point or provide an insight. At the same time, I see the one-to-one displacement perspective as potentially problematic for two principal reasons:

i) The assumption that one unit of wind power always displaces one unit of fossil fuel power implies that all growth in electricity, or new electricity demands, is supplied by fossil fuel-fired power plants, while wind power plants supply none of the growth in demand (wind power cannot support growth in demand, because the assumption is that it displaces fossil fuel power). This seems not realistic. Historically, renewable energy markets have grown even in absence of climate mitigation policies, and baseline scenarios for the future suggest that renewable energy markets will grow significantly (IEA 2010a; Krey and Clarke 2011), again in absence of strong mitigation policies.

ii) It is an artificial premise that wind power competes solely with conventional fossil fuel power. It is conceivable that if wind power is not employed to satisfy demand, other renewable or low-carbon technologies would contribute to filling the gap or there would be more energy conservation investment, especially under scenarios with high carbon prices.

Owing to these two principal reasons, I see the perspective that each unit of wind power displaces one unit of fossil fuel power as unrealistic at a macro level – it does not accurately reflect any real-world relationship. I would describe the crux of the matter as follows: A fraction of wind farms may indeed displace fossil fuel power stations and analysts may assume, *a priori* or based on some evidence, that electricity from a specific wind farm displaces fossil fuel electricity. Further, comparisons of life cycle emissions of wind power with that of conventional

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[8] Similar references to 'conventional thinking' and one-to-one displacement as an underlying premise of reports by the Intergovernmental Panel on Climate Change are made by York (2012).

forms of power generation do indicate a significant mitigation potential of wind power. All the same, a one-to-one displacement ratio is not a meaningful assumption at a macro level, because in practice a portion of electricity from wind will support new demands (point i above) or replace other non-fossil electricity (ii above), and not displace fossil fuel electricity.

It may also be noted here that a regression analysis of energy data for 132 countries from 1960 to 2009 suggests that in the past it has taken 11-13 units of non-fossil electricity to displace one unit of fossil fuel electricity (York 2012). Nuclear and hydro power have been more effective in displacing fossil fuel power than other renewable power generation, the analysis suggests (York 2012). The results are identified as statistically significant in York (2012), but still there may be issues associated with data inconsistencies and lack of detailed control variables in the analysis. And of course, a picture that emerges from historical records may change in the future. Nonetheless, I think it is important to recognize that wind power employment may not automatically reduce fossil energy use, and, again, the perspective that every unit of wind electricity displaces one unit of fossil electricity is unrealistic at a macro level.

Returning to the question presented at the outset of this chapter – is wind power environmentally benign? – a slightly longer answer than “it depends” could be: It depends on many factors, but above all it depends on the extent to which wind power actually replaces fossil fuel-based power. Policies that are effective in phasing out fossil fuels are prerequisite for good environmental performance for wind power.

Not a full picture

As was noted in section 5.1, the types of environmental impact categories considered in this work are only part of the full picture: Environmental concerns about bird and bat collisions, modifications to ecosystems (may be positive or negative) and negative impacts on visual amenity are subjects of significant public interest and relevant for decision-making processes that concern wind power (Wiser et al. 2011), but are not addressed in the current work. All of these impact types are inherently site-specific. Availability of global wind resources (de Castro et al. 2011; Jacobson and Archer 2012; Wiser et al. 2011) is not treated in this work either; according to Wiser et al. (2011) however, it is unlikely that limitations in technical potentials will in itself restrict global deployment of wind power.

5.3 Further work

Recommendations for future research in the area of LCA of wind power are provided in section 3.1 and paper I, and the points of these discussions will not be extensively reiterated here. Here I will limit the discussion to three topics, the reconciliation of global energy scenario analysis and LCA (first subsection) material implications of large-scale wind power deployment (second subsection) and electricity network-related issues (third subsection).

Integrating global energy scenario analysis and LCA

In section 5.1 I named the initial attempt to move beyond static, unit-based LCAs of wind power (cf. paper II) as perhaps the most significant research contribution of the current work. However, as was also noted in section 5.1, wind power is but one proposed technology to mitigate energy-related greenhouse gas emissions. In the future, wider and more comprehensive studies may address system-wide environmental costs and benefits of the large-scale adoption of whole portfolios of technologies. Such studies may be valuable in at least three respects. Firstly, they can potentially contribute to a more solid basis for evaluating the real effectiveness of proposed climate change mitigation strategies (by means of comparisons of economy-wide environmental burdens and benefits). Secondly, and related to the previous point, quantifications of total environmental impacts caused by of a whole set of mitigation options may facilitate a much more interesting connection with planetary boundaries than that offered by paper II based on an analysis of wind power only (cf. discussion section in paper II; see also section 3.1 in paper IV). Thirdly, scenario-based and macro-oriented assessments spanning an array of mitigation alternatives may shed new light on comparative advantages and disadvantages of individual options (because dynamic aspects that may differentiate technologies are incorporated in the assessments), potentially providing a better basis for performance benchmarking than that offered by comparisons of unit-based impact potentials as typically found in existing literature (e.g., Sathaye et al. 2011, Varun et al. 2009, Wagner et al. 2011). The last point warrants that technologies are analysed and assessed in a consistent framework.

As is briefly discussed in section 3.2 and paper II, large-scale integrated assessment models (IEA 2010a; Krey and Clarke 2011) and life cycle assessment models have some complimentary characteristics: strengths of the former may supply lacks of latter, and vice versa. What the integrated assessment models are lacking is the ability to capture causality relations that occur in, to use the terminology of LCA, product systems – one such relation is that steel is needed to manufacture a wind turbine. What conventional LCA models are lacking are notions of scale and time. For example – to keep to the example of steel-making and wind turbines – changes in the share of recycled content, efficiency gains, fuel switching and deployment of carbon capture and storage in the iron and steel sector are taken into consideration in the International Energy Agency's energy scenarios (IEA 2009, 2010a), but the effects of such changes are not studied in LCAs of wind power.

The full integration of a large-scale integrated assessment model and LCA model represents a substantial methodological challenge and may be approached from different analytical angles. A detailed discussion of this lies outside the province of this thesis, but two elements that may be relevant to consider are noted here, as follows. The first element is that, if the goal is to quantify future aggregated impacts of technology deployments, large-scale integrated assessment models and conventional LCA models may not fill out each other's lack completely. This is because in general both types of models lack, to my understanding, detailed representations of future technological design changes. Technological change is included in integrated assessment models (e.g., IEA 2010a, 2011a) through changes in basic parameters such as cost and efficiency, but design configurations are typically not considered in detail (Martinsen 2010). Hence, in addition to combining the perspectives of integrated assessment models and LCA models, one may need to incorporate the perspective of technology foresight and evolution studies as well (e.g., for wind power, Cohen et al. 2008, NEEDS 2008). Existing research attempts to study future technological design developments in a life cycle framework includes Singh et al. (2012) for fossil-fuel power with carbon capture and storage and Viebahn et al. (2011) for concentrated solar power.

The second element is that caution needs to be exercised so that integrated models (i.e., models integrating global energy scenario analysis and life cycle analysis) do not double-count emissions that arise from building and operating power plants. While the engineering-economic models behind, for example, (IEA 2010a, 2011a) do not explicitly take into account that as wind power markets grow, more steel is needed for wind turbine manufacturing, they do incorporate overall growth in steel demand, and wind turbine supply chains are part of this picture. An integrated global energy scenario model and LCA model thus may need to be able to properly identify the wind turbine supply chain component of overall steel demand growth in order to avoid miscounting. For the same reason, while at a cursory glance the emissions caused by wind power in paper II may be seen as representing a type of 'negative stabilization wedge'[9] that will undo part of the anticipated emission reduction, this interpretation is not necessarily valid. Again, this is because wind turbine supply chain growth is, at least to some degree, already part of the baseline trend below which the stabilization wedges are conceptualized.

Material implications and consequent environmental impacts

Here I briefly introduce one further planned research article (Arvesen and Hertwich 2012c) on environmental implications of large-scale adoption of wind power. This work has been initiated, but it was not feasible to generate extensive results or produce a paper manuscript in publishable form in time to be included in this thesis.

Two broad categories of concern form the rationale underpinning the planned study (Arvesen and Hertwich 2012c). Firstly, in the general case use of materials is an important driver for environmental and resource pressures, including pollution, waste deposition, extraction of mineral resources and land transformation (UNEP 2010a). Total human use of materials has grown exponentially over the past one hundred years, while the composition has changed towards more use of non-renewable materials (Fischer-Kowalski et al. 2011; Krausmann et al. 2009). In the case of wind power systems, requirements for steel, copper, concrete and other materials give rise to environmental and resource pressures – the degree to which this occurs under different circumstances is an active area of research (e.g., Kleijn et al. 2011, paper II).

The second category of concern is that availability issues may threaten the viability of proposed energy transitions. In recent years there has been a growing research interest in the vulnerability of global energy strategies to disruptions in the supply chains of key materials (Erdmann and Graedel 2011; Graedel 2011); for evaluations of wind energy, particular interest is devoted in the literature to the supply of the rare earth elements (e.g., Alonso et al. 2012, DOE 2010, Du and Graedel 2011, Jacobson and Delucchi 2011, Kleijn and van der Voet 2010).

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[9] cf. the stabilization wedge analogy of Pacala and Socolow (2004).

The planned study intends to present a scenario-based analysis of material inflows (materials that go into physical components of wind power systems) and outflows (wastes) associated with large-scale adoption of wind power, following BLUE scenarios of the International Energy Agency, as in paper II. In addition, the study intends to assess environmental impacts induced by the material requirements using ReCiPe (2009) impact assessment method, including breakdowns of impacts by material types. The analysis should incorporate several basic wind power technology configurations (e.g., conventional generator or rare earth permanent magnet generator, concrete or steel foundation), and should at a minimum cover the materials aluminium, concrete, composites, copper, iron and steel, and rare earth elements. Potential problems with mineral resource availability are intended to be evaluated.

Grid expansion and network integration of renewables

In the general literature, costs of integrating variable renewables are calculated region by region (IEA 2010b; Wiser et al. 2011), and as far as I know case studies are available for European countries and US states only (e.g., Pehnt et al. 2008, Valentino et al. 2012)[10]. The additional costs associated with accommodating variable renewables in the electric system can be grouped into the categories listed below (IEA 2010b; Wiser et al. 2011).

i) Increased balancing costs: These relate to matching electricity supply with demand over seconds to days, which becomes more demanding with higher shares of intermittent supply. Hence, renewable deployment may lead to more sub-optimal operation of thermal power plants. The relative change in emissions from fossil power plants with increasing wind penetration may be different for different air pollutants (Katzenstein and Apt 2009; Valentino et al. 2012).

ii) Increased capacity adequacy costs: The contribution of a wind power plant to (peak-load) capacity adequacy is typically smaller than for conventional power generation technologies in the system. Simulations of European and North American power systems indicate that wind power’s contribution to overall system capacity adequacy amounts to 5-40% of the installed nominal wind power capacity (Holttinen et al. 2011).

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[10] That 25-30% of installed wind power capacity in China is not connected to the grid (IEA 2011b; Yang et al. 2012; Qi 2012) is suggestive of significant challenges connected with network integration in China, however.

iii) Costs of power transmission: These arise from the need to transfer electric power from the wind farms to the load centres. In contrast to many power generation technologies, infrastructure for electricity transmission (and distribution) has received attention in the peer-reviewed LCA literature, though recent publications have started to fill this gap (e.g., Bumby et al. 2010, Jorge et al. 2012a, Jorge et al. 2012b).

While not addressed in any systematic or comprehensive manner, the issue of network integration of intermittent renewables is touched upon several times in this thesis: For example, the neglect of emission penalties due to network integration in the analysis in paper II is noted as one major limitation of the paper (section 3.2). Paper I encourages future research in the direction of integrating life cycle inventory analysis and network integration considerations for wind power, and notes that this would be congruent with the prevalent view that LCA should strive to provide holistic assessments. Besides, environmental impacts associated with power transmission and distribution is an interesting topic of investigation in itself, and one that is probably underexplored in existing LCA literature (Jorge et al. 2012a) – substantial investments in electricity networks will be needed in the future to replace or refurbish old components and accommodate higher demands, irrespective of increasing shares of intermittent supply (IEA 2011a).

It is my hope that I may contribute to a future planned LCA study (Nes et al. 2012) of a subsea power grid in the North Sea facilitating the integration of offshore wind farms and interconnecting Northern European countries. Expansion of North Sea electricity grid has received significant interest in several spheres in recent years (academia, industry organisations, policy; e.g., EWEA 2009b, Greenpeace 2008, Veum et al. 2011). Subsea power transmission in Northern Seas is identified as one of four "priority corridors for the transport of electricity" in EU energy and climate policy (Carvalho 2012). I see the research topic of LCA of a North Sea power grid as being complimentary to the environmental assessment of an offshore wind farm presented in paper III.

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Appendix A: Paper I and associated content

Paper I

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A.1 Paper I

Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs

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ABSTRACT

We critically review present knowledge of the life cycle environmental impacts of wind power. We find that the current body of life cycle assessments (LCA) of wind power provides a fairly good overall understanding of fossil energy use and associated pollution; our survey of results that appear in existing literature give mean values (± standard deviation) of, e.g., 0.060 (±0.058) kWh energy used and 19 (±13) g CO_2e emitted per kWh electricity, suggesting good environmental performance vis-à-vis fossil-based power. Total emissions of onshore and offshore wind farms are comparable. The bulk of emissions generally occur in the production of components; onshore, the wind turbine dominates, while offshore, the substructure becomes relatively more important. Strong positive effects of scale are present in the lower end of the turbine size spectrum, but there is no clear evidence for such effects for MW-sized units. We identify weaknesses and gaps in knowledge that future research may address. This includes poorly understood impacts in categories of toxicity and resource depletion, lack of empirical basis for assumptions about replacement of parts, and apparent lack of detailed considerations of offshore operations for wind farms in ocean waters. We argue that applications of the avoided burden method to model recycling benefits generally lack transparency and may be inconsistent. Assumed capacity factor values are generally higher than current mean realized values. Finally, we discuss the need for LCA research to move beyond unit-based assessments in order to address temporal aspects and the scale of impacts.

Keywords: LCA, carbon footprint, sustainability assessment, wind energy, electricity

1 Introduction

Electric power generation by wind turbines is commonly regarded as a key technology in addressing some of the greatest environmental and resource concerns of today, namely man-made climate change and other negative effects of air pollution, and security of energy supply. Among other factors, strong growth in today's markets and prospects of exploiting vast resource potentials at offshore sites contribute to the anticipation that wind power will play a significant role in achieving a shift away from fossil-based power generation towards renewables in coming decades [1, 2]. Wind power likewise features prominently in the current body of climate change mitigation scenarios produced by large-scale integrated assessment models [3, 4]. Even though wind power is driven by a renewably energy flux (that is, the kinetic energy in air streams), in a life cycle perspective there are non-renewable resource demands and harmful emissions associated with it. These environmental and resource pressures can be quantified and assessed by the method of life cycle assessment (LCA).

Surveying LCA studies published from the year 2000 on, this paper synthesizes and critically reviews current state of knowledge about the life cycle environmental impacts of wind power. The work was carried out with the goal of contributing to a wider, comparative study of the environmental and resource impacts of low-carbon energy technologies by the International Resource Panel for the United Nations Environment Programme.

Several literature reviews of wind power LCAs are already available. Lenzen and Munksgaard [5] survey 72 energy and CO_2 analyses of wind power systems published between 1977 and 2001. Kubiszewski and colleagues [6] and Raadal and colleagues [7] extend the work of Lenzen and Munksgaard [5], adding additional analyses, focusing on energy demand and greenhouse gas (GHG) emissions, respectively. In another review in the IPCC Special Report on Renewable Energy Sources and Climate Change [1, 8], 126 estimates from 49 studies are surveyed. The present LCA review aims to supplement the previous assessments, providing new surveys and analyses of results as well as qualitative discussions. In particular, we attempt to make the following original contributions: i) taking a broader view of environmental impacts, focusing not only on cumulative energy demand and GHG emissions [5-7], but on a wider set of impact categories assessed in the LCA literature; ii) discussing important aspects that are not sufficiently treated in previous LCA reviews, including capacity factor assumptions, modeling of recycling benefits, techniques for calculating life cycle inventories (process-LCA or hybrid LCA), and static versus future-oriented LCA; iii) critically assessing the scope and quality of existing studies, identifying areas that are well understood as well as important knowledge gaps; and iv) proposing directions that future research may take in order to gain a more complete and solid understanding of the environmental implications of wind power.

The following section briefly introduces the conceptual basis of LCA and the two prevailing methodological approaches to life cycle inventory analysis. Next, Section 3 describes the construction of the literature database which forms the basis of the survey and review. Results of the literature survey are presented in two sections: Scope, assumptions and methodologies of existing LCA research on wind power are dealt with in Section 4, while Section 5 presents stressor and impact indicator results. A critical evaluation of present knowledge and research needs is given in Section 6. Finally, Section 7 provides concrete recommendations for future research.

2 LCA: conceptual basis and calculation techniques

LCA is a method to explore how the delivery of or demand for a specific product or service (e.g., the delivery of one unit of electricity from wind) initiates processes that may cause environmental impacts. Through a systematic mapping of operations and associated environmental pressures along a product's life cycle, LCA strives to give a complete picture of the environmental burdens caused by one product [9].

Two approaches to quantifying life cycle inventories are in use. In conventional LCA methodology, henceforth referred to as process-LCA, a bottom-up approach is taken to define and describe operations in physical terms. This approach makes possible the use of data that are specific for the operations under consideration, meaning that results can potentially be generated at high levels of detail and accuracy. On the downside, there is a need to apply cut-off criteria to exclude operations that are not expected to make significant contributions. It is known, however, that added together the excluded contributions are significant [10, 11]. The second approach, environmentally extended input-output analysis (EEIOA), is a top-down technique in which inventories are quantified using monetary data at the level of economic sectors. As EEIOA does not require cut-offs to be made, it does not have the same problem with truncation as process-LCA. However, EEIOA operates at a high aggregation level; the sector resolution in EEIOA is generally too coarse for making LCAs of specific products. Hybrid methods – where process-LCA is used to model important operations, and EEIOA is used to model operations that would otherwise be omitted – can potentially exploit advantages of both approaches, but is more challenging to employ [10-12]. Also, depending on the method of hybridization and quality of data [12], most hybrid models may offer limited support for following material flows through product systems.

LCA results may be presented as inventories of individual stressors, or as environmental impact category indicators at 'midpoint' or 'endpoint' levels of aggregation. Midpoint indicators allow for environmental effects of several individual stressors to be assimilated into a single impact category. Endpoint indicators measure impact potentials by endpoints in the effect chain; human health, ecosystem health and natural resources are typically regarded as three such endpoints, but sometimes even one single indicator of environmental damage is used [13, 14].

3 Literature survey

In surveying published LCA research, priority was given to cover publications in peer-reviewed journals, and for the most part, studies were identified through searches in common scientific databases. However, when found appropriate other types of publications (e.g., environmental reports by manufacturers, documentation of LCA databases) that have been known to the authors were included as well. The LCA survey presented here differ from that of past reviews in that studies published prior to 2000 are excluded. The primary reason for this is the strong developments in wind power technologies, LCA methodologies and databases, and background economy characteristics in previous decades. Furthermore, the set of studies reviewed was judged to be large enough to provide interesting insights.

Table 2. Overview of assumptions, methods and scope of reviewed LCA studies. Site: Ons = Onshore; Off = Offshore. Size: S = Small (< 100 kW); M = Medium (100 kW-1 MW); L = Large (> 1 MW). Lifetime: '*' means longer lifetimes for some components. Credits: 'x' means system is credited with indicator values that are perceived to be avoided through recycling at end-of-life; '(x)' means system is credited, but results without credits are also presented. Temporal scope: A blank means static assessment under assumptions of present technologies; non-blank entries indicate future-oriented assessments. Method: Pro = Process-LCA; Hyb = Hybrid LCA; IOA = Analysis that relies fully or in large part on input-output multipliers. Impact categories: C = CO_2 emissions; CC = Climate change; E = Cumulative energy demand; R = Resource requirements, abiotic depletion; A = Acidification; O = Stratospheric ozone depletion; HT = Human toxicity; P = Particulate matter formation, dust; ET = Ecotoxicity; PO = Photochemical oxidation (smog); N = Nutrient enrichment, eutrophication; W = Solid waste generation; L = Land use, land transformation; h = human health endpoint; e = natural environment endpoint; r = natural resources endpoint; s = single score endpoint; α = non-toxic emissions that provide additional information; τ = toxic emissions that provide additional information ('additional' with regards to the impact categories that are accounted in this table column). Characters are underlined if results are presented in generic units only (e.g., 'points').

Citation	Site	Size	Lifetime (years)	Credits	Geographical scope	Temporal scope	Method	Impact categories
[15]	-	-	-		Global	2009-2100	-	C
[16]	Ons	S M	25	x	Canada		Pro	CC E A PO
[17]	Ons	L	20		Germany Denmark China		Pro	CC E
[18, 19]	Ons Off	L	20 (Ons) 25 (Off)		Europe/Global	2007-2050	Hyb	C CC A PO N
[20]	Ons	L	20	x	China		IOA	CC E
[21]	Ons	L	20	x	Denmark		Pro	CC E R A P ET PO N W
[22]	Off	L	20		Germany		Pro	CC E A HT PO N
[23]	Off	L	20		UK		Hyb	C CC
[24]	Ons	M	20	(x)	Europe		Pro	CC E R A O HT ET L
[25]	-	-	20		Brazil	20 years	-	E
[26]	Mix	L	20		Northern-Europe		Pro	C CC A O P PO N W τ
[27]	Ons	M L	20		Australia		Hyb	CC E
[28]	Ons	S	20		Canada		Pro	CC
[29]	Ons	-	30		Denmark		Pro	L
[30-32]	Ons	L	20	(x)	Spain		Pro	CC E R A O HT ET PO N L s
[33]	Ons	L	-	x	New Zealand	100 years	Pro	C E
[34]	Ons	S L	20	(x)	France		Pro	CC E h e r
[35]	Off	L	20	(x)	Norway		Pro	CC E R A HT ET PO N
[36]	Ons	M	20		Italy		Pro	C CC E A O P PO N W τ
[37]	Ons	-	20		Taiwan		Pro	C E
[38]	Off	L	20^*		Denmark	2005-2050	Pro	C P L α τ
[39]	Off	L	-		Germany	2005-2020	Pro	C
[40-42]	Ons Off	S M L	20		Switzerland/Europe		Pro	C CC E R A O HT P ET PO N W L h e r s
[43]	Ons	S	25		Turkey		Pro	C CC E
[44]	Ons Off	L	-		Germany	2010	Pro	C CC E A P N α τ
[45]	Ons	S	20	(x)	UK		Pro	C E
[46]	Ons Off	L	20 (Ons) 20^* (Off)	x	Denmark		Pro	C CC E A O HT ET PO N W
[47]	Ons	L	20	x	Denmark		Pro	C CC E A O HT ET PO N W
[48]	Ons	M	20-30		US		Pro	C E
[49]	Ons	M	30		Japan		Pro	CC
[50]	Ons	M	20		Canada		Pro	CC E
[51]	Ons Off	L	20 (Ons) 20^* (Off)	x	Denmark		Pro	C CC E A O HT N W α
[52]	Ons	M	-		Germany Brazil		Hyb	C E
[53]	Ons	M L	20		Germany		Pro	E
[54]	Ons Off	M L	20		Europe		Pro	C α
[55]	Off	L	20^*		Denmark		Pro	CC A HT ET PO W
[56]	Ons	M	15		Japan		Pro	C E
[57]	Ons	M	20		US	40 years	IOA	CC
[58]	Ons Off	M	20		Denmark		Pro	C E α s
[59]	Ons	M	20		Belgium		Pro IOA	CC E

An overview of the reviewed LCA studies on wind power systems is given in Table 1. Of the 44 reviewed studies (Table 1), 34 were selected for quantitative analysis. In general, the following guidelines were followed in constructing the set of observations used for quantitative analysis: i) Only original LCA research was included. ii) Studies of integrated wind power generation and energy storage systems were excluded in the cases where the contribution from the actual wind power system could not be extracted from the inventories presented. iii) For studies presenting a number of results that apply to different systems (e.g., onshore and offshore wind farms, differently sized turbines), all reported results were included. iv) For studies presenting a number of results for one specific system, but with differing methods or assumptions (e.g., different capacity factors, different approaches to modeling benefits of recycling), the default (reference) scenario was surveyed if such a scenario was defined. Conversely, if a default scenario was not defined, an average of reported values was surveyed. Table S1 in the supplementary information provides the raw data for the quantitative analysis in terms of system characteristics, and emission and impact indicator results.

Finally, we note that the set of observations included in the quantitative analysis is not a random sample. The identification of studies did not follow a formal, randomized procedure, and the studies that were identified are sometimes not independent, as they utilize common sets of assumptions or data. Also, the survey involved some subjective choices (e.g., regarding how multiple observations from single studies should be inventoried) that may to some extent have influenced quantitative analysis results.

4 Scope, assumptions and methodologies

The LCA literature covers the whole spectrum of available wind turbine sizes, from hundreds of watts sized units [28, 34] to multi-MW turbines in onshore and offshore locations. As is evident from Table 1, analyses of wind farms operating on land form a vast majority, and there is a predominance of analyses with Europe countries as their reference locations. A fair number of analyses (13) of ocean-based systems were also identified. With exceptions, LCAs of offshore wind power study bottom-fixed wind turbines in relatively shallow waters. Two studies analyze, respectively, a hypothetical wind farm comprised by floating units [35] and an operational wind farm at a water depth of 30 m [22].

Manufacturing of the actual wind turbines is the only life cycle stage that is common to all analyses. In addition, all assessments based on wind turbines with capacities of hundreds of kilowatts and more include the manufacturing of foundations, and the majority model electrical connections (internal cables within wind farm, external cabling and sometimes transformer stations) needed to connect a wind farm to an existing grid. Most studies also take into consideration – though variably –the operation and maintenance of the system, as well as transportation activities. A number of assessments [28, 39, 43, 50, 56] address integrated systems where wind energy converters are supplemented with other power generation technologies and/or technologies for energy storage.

The manner in which the end-of-life phase is modeled varies. Some studies make assumptions to model transport and disposal of waste, others omit this part. End-of-life is unique among the life cycle phases in that it may reduce emissions and resource use: Negative contributions occur when analysts deduct indicator values that are perceived to be avoided when, after the operating lifetime, system components are recycled or incinerated to produce valuable outputs. In this way, the system is credited for returning usable resources (e.g., recyclable steel) to the technosphere – in the LCA literature this is referred to as substitution by system expansion or avoided burden method [13]. LCA studies that employ the avoided burden method are in minority, but nevertheless represent a significant share (Table 1) Decommissioning of a wind farm after the service lifetime is typically modeled as identical to installation.

LCAs of wind power generally assume lifetimes of 20 years, for onshore and offshore wind farms alike (Table 1). Fig. 1 displays capacity factor assumptions by region as a function of power rating. Three overall trends may be observed from Fig. 1, in overall terms consistent with general knowledge and expectations [60, 61]: i) performance in terms of capacity factor increases with wind turbine nominal capacity; ii) offshore wind farms exhibit greater energy capture than onshore farms; and iii) for a given power rating, sites in North America tend to show higher capacity factors than European sites. Across all regions, the assumed capacity factor mean value (± standard deviation) is 18% (±5.4%) for onshore wind turbines with nameplate capacity below 100 kW, 22% (±5.1%) for onshore with capacity 100 kW - 1 MW, 31% (±7.5%) for onshore with capacity > 1 MW, and 43% (±8.4%) for offshore (Table S2 in the supplementary information).

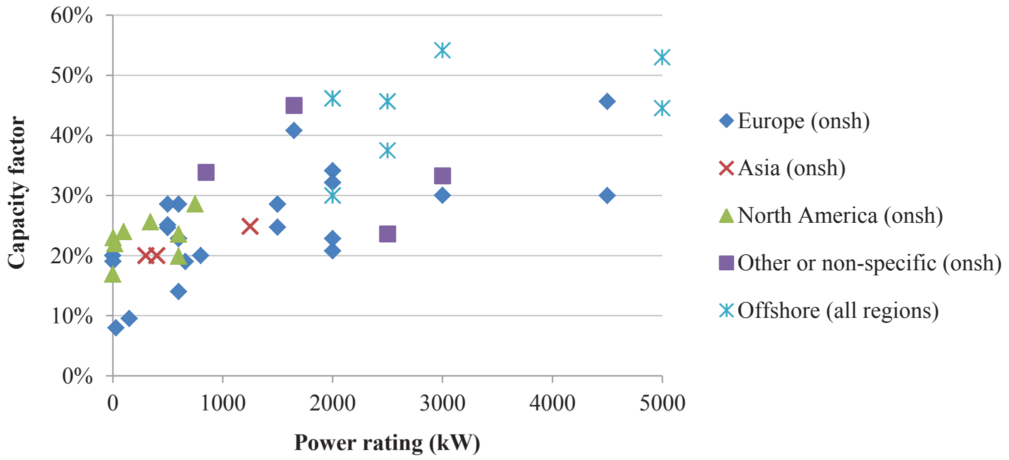

Fig. 1. Capacity factor by location as a function of power rating.

Energy demand and GHG emissions have historically been the main focus of attention for LCA research on wind power [5], and still dominate the impact assessments in recent literature (Table 1; also, compare the sample sizes of energy, GHG and CO_2 versus other air pollutants in Fig. 2). Estimates of climate change indicator values are often comprised of contributions from CO_2, CH_4 and N_2O, but in some cases (e.g., [23, 41]) fluorinated GHGs (SF_6, HFC, PFC) are also taken into account. Of the studies cited in Table 1, more than half include impact categories other than energy and GHGs. In general, environmental stressors of high coverage are air pollutants associated with production and combustion of fossil energy carriers: CO_2, CH_4, CO, NH_3, NMVOC, N_2O, NOx, particulates and SO_2. Such a set of pollutants facilitates meaningful impact assessments in the categories climate change, acidification, eutrophication and photochemical oxidation (smog). In comparison to fossil fuel-related air emissions, other kinds of pollution have received little attention; only 10 studies cited in Table 1 quantify characterized toxicity indicator results. Apart from fossil energy carriers, resource requirements and non-renewable resource depletion are scarcely addressed in detail. A handful of studies [21, 24, 31, 35] address non-renewable resource depletion; others [26, 46] display life cycle inventories for individual mineral resources without applying any impact assessment. One publication [29] was identified that examines in some detail direct and indirect land use of power generation technologies, including wind. Some studies quantify life cycle water use, but water use is generally not highlighted or discussed in detail. Fthenakis and Kim [62] review previous studies and evaluate life cycle use of water in electricity supply by different technologies.

As is evident from Table 1, process-LCA studies dominate the wind power LCA literature, and few studies employ hybrid LCA methodologies. As a final point regarding methodology, we note that different kinds of future-oriented LCAs of wind energy have started to emerge in the literature, but are yet to gain widespread employment (cf. ‘temporal scope’ column in Table 1). Methodological approaches and results of future-oriented LCAs are discussed in Section 5.3.

5 Stressor and impact indicator results

Fig. 2 presents literature survey results with respect to total emissions and impact indicator values, and the numbers of estimates and studies that were surveyed; numerical results in tabulated form are provided in the supplementary information. For onshore and offshore wind power respectively, the mean energy intensity value is 0.063 (±0.061 standard deviation on either side of the mean) and 0.055 (±0.037) kWh/kWh; mean GHG emissions are 20 (±14) and 16 (±9.6) g CO_2e/kWh; and mean CO_2 emissions 16 (±14) and 12 (±7.3) g/kWh. These relatively large standard deviations, and the broad ranges that can be observed for all categories displayed in Fig. 2, illustrate that results vary considerably. For example, reported energy intensity values across all wind power system categories form an interval of 0.014-0.333 kWh/kWh. If analyses of wind turbines with nameplate capacity less than 100 kW are excluded, however, the interval narrows to 0.014-0.137 kWh/kWh – this exemplifies a general pattern that the by far highest emissions and indicator values are observed for small wind turbine sizes (< 100 kW). Offshore wind power systems show comparable or slightly higher emissions than onshore systems comprised of large wind turbines (Fig. 2), despite the systematically higher wind capacity factors assumed for offshore systems (Fig. 1). This is due to the higher resource requirements of wind power systems located offshore. Another observation that can be made from Fig. 2 is a tendency for estimates to concentrate in the lower part of the observed intervals (note from Fig. 2, for example, that the mean values lie systematically above median values).

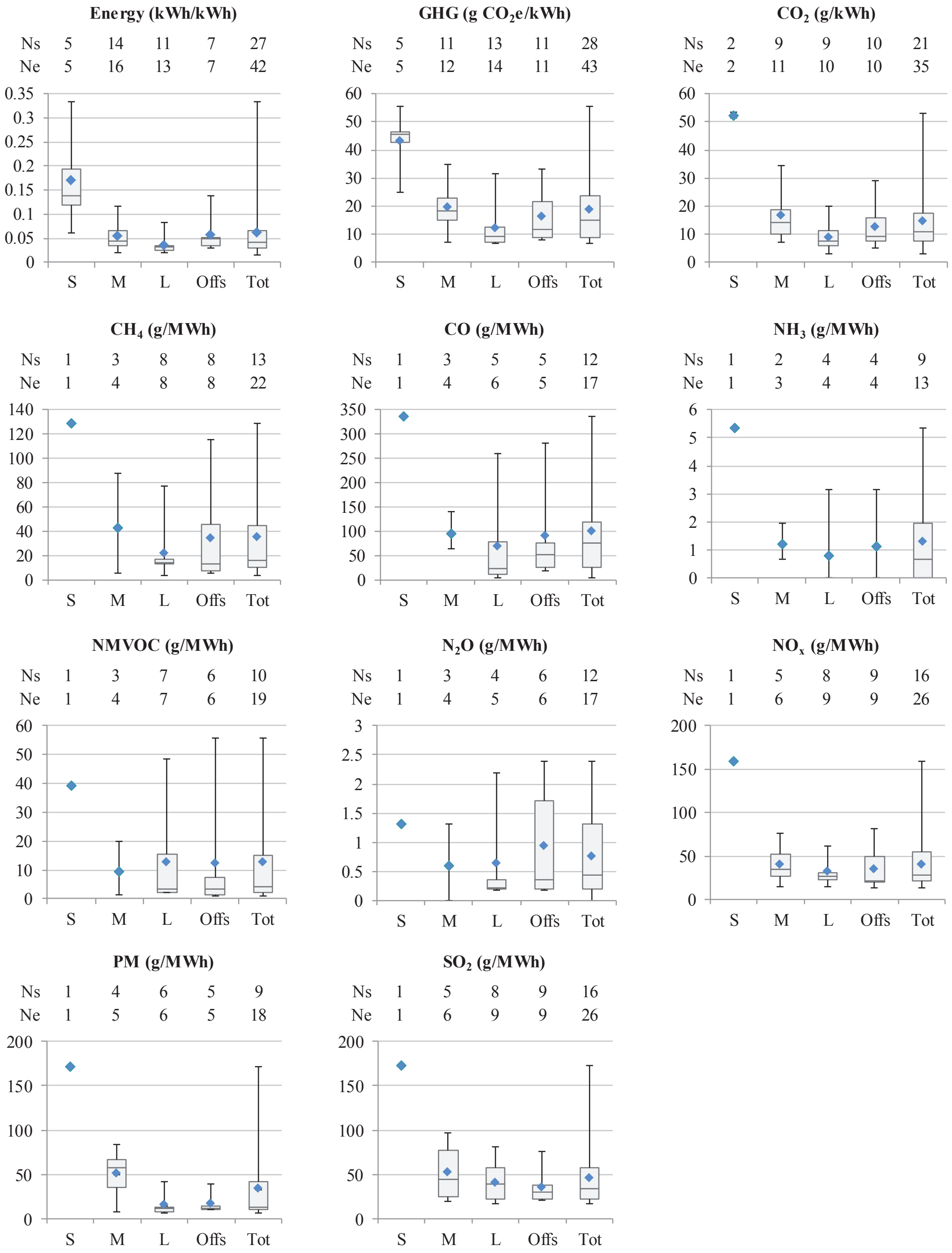

Fig. 2. Stressor and impact indicator results by 5 wind power system categories and 11 impact categories. Box: range from first to third quartile; Horizontal bar within box: median value; Diamond: mean value; Upper and lower fences (whiskers): maximum and minimum values. 'S' means small wind turbine (< 100 kW) at onshore site; 'M' means medium wind turbine (100 kW - 1 MW) at onshore site; 'L' means large wind turbine (> 1 MW) at onshore site; 'Offs' means offshore wind power (any wind turbine size); 'Tot' denotes total sample. Ns = Number of studies; Ne = Number of estimates. Ne > Ns if more than one estimate was surveyed from one study. In some cases total sample size slightly exceeds the sum of the sub-sample sizes; this is because estimates for wind farm portfolios were not assigned a system type, but were included in the total sample. If Ne < 5, interquartile ranges (boxes) are not shown; If Ne = 1, the one value is shown as a diamond. Energy indicator value refers to the ratio between life cycle energy demand and electricity generated over the lifetime. GHG = Greenhouse gases; CO_2 = Carbon dioxide; CH_4 = Methane; CO = Carbon monoxide; NH_3 = Ammonia; NMVOC = Non-methane volatile organic compounds; N_2O = Nitrous oxide; NO_x = Mono-nitrogen oxides; SO_2 = Sulfur oxides.

Releases of individual toxic substances in the life cycle of wind power systems are in some cases reported, but to synthesize these findings is difficult due to differences in what chemicals are reported and a lack of transparency on calculation methods and assumptions. Table 2 compares human toxicity and freshwater and terrestrial eco-toxicity indicator results from five studies. Marine aquatic eco-toxicity is not included due to weaknesses in current impact assessment methods [63], and because two of the cited studies [22, 35] do not address this impact category. One of the publications [21] cited in Table 2 report results that are up to three orders of magnitude smaller than those from the other studies. The reason for this discrepancy is unknown, but could possibly be a consequence of different impact characterization methods.

Table 2. Overview toxicity indicator results by three impact categories, as quantified by five studies. HT = Human toxicity. FET = Freshwater eco-toxicity. TET = Terrestrial eco-toxicity. DCBe = 1,4-dichlorobenzene equivalents.

Citation	**Wind turbine size, site**	**Stated impact characterization method**	**Results (g 1,4-DCBe/kWh)**		
			HT	FET	TET
[21]	1.85 MW, onshore	USETox (2008)	0.83	0.03	0.03
[22]	5 MW, offshore	-	69	-	-
[31]	2 MW, onshore	CML (2000)	16	2.8	0.16
[35]	5 MW, offshore	CML (2000)	83	12	0.23
[41]	800 kW, onshore	CML (2001)	54	10	0.16
[41]	2 MW, offshore	CML (2001)	53	10	0.18

5.1 Contribution analysis

Looking at the relative contribution from different life cycle stages to total energy use and climate change indicator result, manufacturing of components dominates, and is sometimes of the order 90% of total impact indicator values (Fig. 3; see also discussion in previous LCA reviews [5, 7]). Fig. 3 compares breakdowns of energy use and GHG emissions by components and life cycle stages. It should be noted that ambiguity exists in the categories shown in Fig. 3; for example, some studies separate transportation as an individual category, while other studies subsume transportation activities within other categories. Nevertheless, it is clear from Fig. 3 that for onshore wind power systems, the wind turbine is the most important single component with regards to energy use and GHG emissions, followed by the substructure (i.e., the foundation). The tower may hold a share of 30-70% of total wind turbine indicator values. For offshore wind farms, the substructure becomes relatively more important.

Generally, emissions associated with transportation are found to be negligible or of minor importance, though they sometimes are relatively more important for NMVOC and NOx emissions. The results of [34] (not included in Fig. 3) stand out with large relative contributions from transportation (34% of GHG emissions are due to transportation) – this could possibly be related to the choice of concrete as tower material in [34], as opposed to (lighter) tubular steel towers modeled in most other studies. Emissions of heavy metals in manufacturing processes is the primary cause of toxicity indicator results [21, 22, 35].

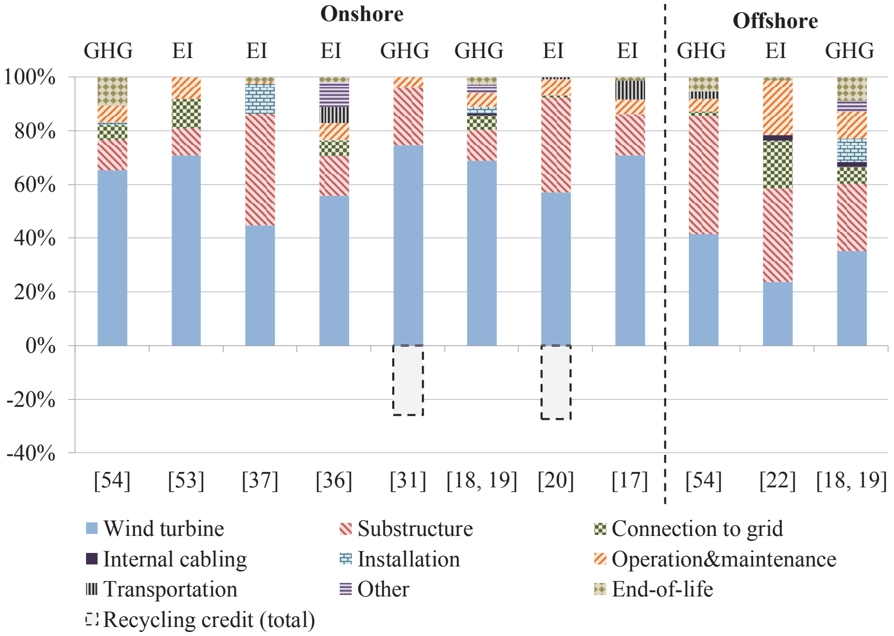

Fig. 3. Breakdown of energy intensity (EI) or greenhouse gas emission intensity (GHG) by main components or life cycle stages according to 8 onshore and 3 offshore estimates. In some cases interpretation of results and/or reading off charts in the cited publications was necessary. Shown positive indicator shares from [20, 31] do not include recycling credits.

If the avoided burden method is applied, the end-of-life phase typically yields considerable emissions reductions: Recycling credits approximately halve the energy or GHG emissions embodied in the wind turbine and lower total indicator values by 26-27% in [20, 31] (Fig. 3). In another study, recycling credits lead to around 20% (4.5 MW wind turbine) and 40% (250 W) reductions in GHG emissions [34]. In total, the end-of-life phase contributes -19% to GHG emissions in [35].

5.2 Effects of wind turbine size and method for life cycle inventory

Previous reviews of wind power LCA studies maintain economies of scale in the life cycle environmental impacts of wind power systems. Lenzen and Munksgaard [5] report that a 1 MW wind turbine appears to require only one third of the life cycle energy per unit output needed for a 1 kW sized unit. Kubiszewski and colleagues [6] and Raadal and colleagues [7] show evidence of energy use and GHG emissions decreasing with growing wind turbine size, but in the former case it remains unanswered to what extent the trend continues when moving into the MW size spectrum, and in both cases it appears that the practice of surveying old and, arguably, outdated analyses (going all the way back to the late 70s) on a par with recent analyses obscures the picture. Moving on to the results of the present survey, Fig. 4 depicts GHG emissions with increasing wind turbine nameplate capacity. The figure confirms the presence of strong economies of scale for power ratings up to 1 MW or so, but a downward trend is not readily discernible for larger turbine sizes.

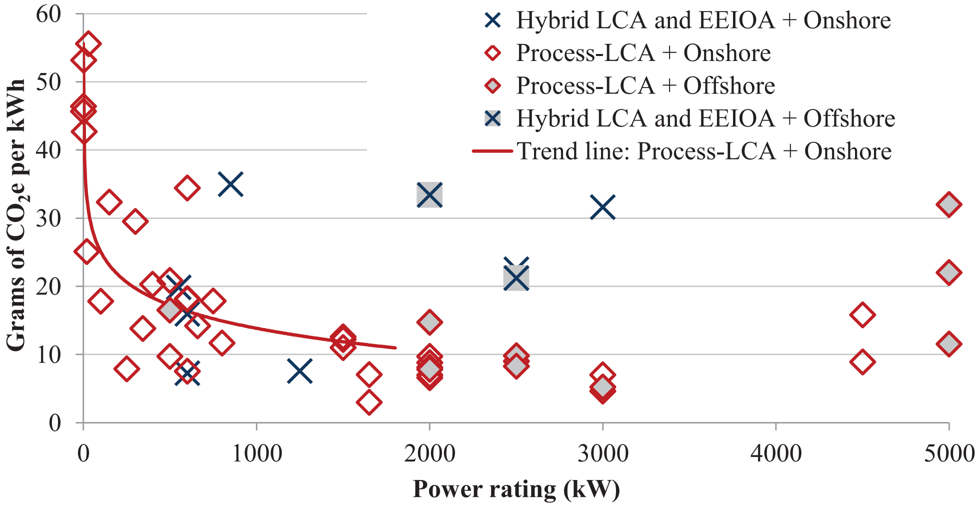

Fig. 4. Total GHG or CO_2 emissions as a function of wind turbine power rating by 4 combinations of methods (hybrid LCA and EEIOA versus process-LCA) and sites (onshore versus offshore). When available, total GHG emissions estimates were included in the figure. If GHG emissions estimates were not available, CO_2 emissions estimates were included. For estimates for offshore wind farms, markers are filled with grey. The trend line represents the sample characterized by a process-LCA method and onshore site, and power rating ≤ 1800 kW. Trend line equation: $y = -4.9\ln(x) + 47.7$. $R^2 = 0.72$.

Theory and empirical evidence from the broader LCA literature foretell that hybrid LCA and EEIO-based assessments give systematically higher impacts (cf. Section 2), and Fig. 4 gives some confirmation of this. Total contributions from economic input-output sectors amount to 23-26 g CO_2e/kWh (74% of totals) in Crawford [27], 19 g CO_2e/kWh (57% of totals) in Wiedmann et al. [23] and 10-13 g CO_2e/kWh (45-61% of totals) in Arvesen and Hertwich [18, 19]. The size of the sample representing hybrid LCA in Fig. 4 is too small to admit a robust assessment comparing results of hybrid LCA and process-LCA, however.

5.3 Future-oriented assessments

In a forward-looking study for Germany, Pehnt et al. [39] couple life cycle inventories with a stochastic electricity market model to study the life cycle CO_2 emissions of wind power, grid expansion, energy storage by means of compression of air, and balancing requirements, in an integrated framework. Results for the year 2020 show only negligible emissions from storage and grid upgrades, but a relatively large emission penalty of 18-70 g CO_2/kWh arising from the balancing of variable wind electricity by fossil-fueled power stations. A global scenario-based assessment is presented by Arvesen and Hertwich [18, 19], who estimate 3.5 Gt CO_2e emitted due to the act of building and operating wind power plants in the time period 2007-2050 to supply 22% of worldwide electricity in 2050. The same study includes an integrated life cycle modeling of cumulative avoided emissions; results suggest emissions avoided by wind power grossly exceed emissions caused by wind power. Lenzen and Schaeffer [15] analyze caused and avoided climate change impacts of eight energy technologies towards 2100, the primary objective being to illustrate differences between emissions and temperature-based indicators for climate change mitigation potential (the authors argue that indicators of avoided temperature are more relevant for decision-making than avoided emissions). In yet another study, Gonçalves da Silva [25] proposes a mathematical framework for simulating the time dynamics in net and gross energy balances of renewable energy technology deployments; computational results are favorable for wind power. Finally, the report on offshore wind technology in the NEEDS project [38] makes assumptions on design changes and economies of scale in wind electricity technologies to establish life cycle inventories for future offshore wind power systems. For all scenario assessments cited above, there are important simplifying assumptions and thus careful interpretations of results are required – indeed, this point is also emphasized by the authors of the original publications.

6 Current state of knowledge and research needs: a discussion

6.1 Capacity factor and lifetime assumptions

The strong influence of assumed capacity factors and lifetimes on results is obvious, as emissions per unit of electricity (in units of grams of CO_2 per kWh, or similar) scale in inverse proportion with the amount of electricity generated over the lifetime – this is analogous to calculations of generation costs (in units of Euro per kWh, or similar).

With respect to capacity factor, one interesting comparison to make is that of assumptions made in LCAs (Fig. 1) versus real-world experiences. The average realized capacity factor in EU15 in 2003-2007 is reported at 20.8%, with country-level averages ranging from a low 18.3% (Germany) to a high 26.1% (UK) [60]; these real-world performances are significantly lower than the overall picture emerging from the assumed values shown in Fig. 1 for onshore wind turbines in the range of 1 MW and above, but relatively more consistent with assumptions for smaller turbine sizes. As regards capacity factors in the US, there are conflicting reports of real-world average values of around 26% [60] and 30% [61], while average capacity factors for China are reported at 16-17% in [64] and 23% in [65]. Data points representing North America and Asia in Fig. 1 are mostly in the lower end of the turbine size spectrum, however, not providing a good basis for comparison. Turning to the offshore case, LCA studies often assume capacity factors above 40% and even 50% (Fig. 1), which also appears somewhat optimistic in comparison with currently available measurements data: One study [66] concludes from a survey that "a typical offshore installation has an utilization time of 3000 hours or more" (i.e., capacity factor 34% or more); while, based on experiences from early Danish and Dutch wind farms, [67] generally expects a 35% capacity factor value for UK offshore wind farms, but finds that the real average value for UK round 1 offshore wind farms is 29.5%. Finally, we note that [66] proposes a constant 37.5% average capacity factor for offshore wind power to be used in scenario analysis towards 2050, while more optimistic scenarios are derived in [18] from IEA data [4], leading to an average offshore load 43% in 2050.

Based on the above information, there appears to be a general tendency of wind power LCAs to assume higher capacity factors than current averages from real-world experiences. At the same time, it needs to be emphasized that many LCAs make assumptions that are specific to one technology or wind farm site and as such not intended to be representative for overall trends.

Unlike capacity factor, real-world empirical evidence on the lifetimes of modern wind turbines is lacking; assumptions on lifetimes thus need to be guided by wind turbine specialists' evaluations and design lifetimes set by manufacturers. While LCAs typically assume lifetimes of 20 years for onshore and offshore systems alike (Table 1), Blanco [68] find that current economic assessments of wind power generally set lifetimes to 20 years onshore and 25-30 years offshore. On this basis, it appears that assumptions regarding lifetimes in the LCA literature are less favorable for offshore wind power, compared with equivalent assumptions underlying economic assessments.

6.2 Impact category coverage

The current survey shows that life cycle energy demand and GHG emissions of wind power are extensively covered in the extant literature. Also, there is a fairly large set of quantifications on air pollutants typically connected with the burning of fossil fuels (e.g., NOx, SO2) and associated impact categories (acidification, eutrophication, photochemical oxidant formation, and to a lesser extent, particulate matter). In our view, given the material intensive nature of wind power compared to fossil alternatives [69], and that toxic releases to the environment are known to originate from materials manufacturing [21, 22, 35], the most serious gap in knowledge is the insufficient understanding of toxic emissions generated in the life cycle of wind power systems. From the viewpoint of the LCA practitioner, assessing toxic effects may be difficult because: i) emissions data on toxic substances is missing or is incomplete, and ii) current impact assessment methods for toxicity produce contradictory results and hence lack robustness [13, 70]. The neglect or incomplete modeling of toxicity is not a problem specific to wind power LCAs, however, but applies to the LCA literature in general [13]. For marine ecological impacts from emissions to water, robust impact assessment methods are in the early stage of development (in the general case, unresolved issues may be exemplified by contradictory results for toxic effects of long-term metal releases, as discussed in [63], and effects of particle emissions [71]) – this is unfortunate for LCA research on offshore wind power, for which there are operations taking place in ocean waters which need to be modeled.

Another significant gap in knowledge is that represented by a lack of comprehensive evaluations of non-renewable (abiotic) resource demands. As with toxicity, this is a much debated impact category in the LCA community for which there is no consensus on impact assessment methods [13]. In the broader literature (e.g., [72, 73]), concerns have been raised about future shortage of supply of neodymium, a metal belonging to the group of rare-earth elements that is increasingly employed in permanent magnets in wind turbine generators. At the same time, the in-use stocks of neodymium have been found to be significant, suggesting that recycling may to some extent alleviate future constraints on primary resource supply [74].

Sustainability assessments of wind power need also adequately consider site-specific impacts, such as visual impacts, habitat change, and bird and bat collisions (see, e.g., Sections 7.6.2 and 7.6.3 in [1] for a summary). There is, however, little tradition for including such impact categories in LCA, and they are more frequently assessed using other environmental impact assessment methods (e.g., cost-benefit analysis, as in [75]).

6.3 Life cycle phases: research coverage, research agreement and quality of knowledge

Table 3 summarizes our overall judgments of the current knowledge about potential environmental burdens associated with four life cycle phases of wind power systems. The evaluation builds on previous sections of this paper and discussions provided in Sections 6.3.1-6.3.3. Extended life cycles (e.g., with respect to network integration or re-powering of systems) are discussed in Section 6.5.

6.3.1 Production of components

Production of system components forms a natural part of any wind power LCA. Discrepancies concerning values for embodied energy and emissions in materials contribute to differences in impact indicator results. In some cases, values for the emissions embodied in materials are meant to be different across studies; this may be, for example, because the assumed energy mix in production is different (see, e.g., [17, 52]). In other cases, discrepancies may be due to different LCA databases being utilized, or arise because, in the face of uncertainty about the exact types of materials that go into the components, analysts make different assumptions about material types (e.g., steel alloys).

Table 3. Authors' overall judgments regarding research coverage of life cycle phases in existing studies (the number of asterisks indicates the degree to which we find studies include the life cycle phase in their scope), the degree to which research results are in agreement (low number of asterisks indicates research do not agree and that the reasons for the disagreements are hard to establish; more asterisks indicates higher level of agreement or that reasons for disagreements are well understood), and quality of knowledge (the number of asterisks indicates the degree to which we judge current knowledge to be sound and transparent). The latter indicator (quality of knowledge) depends on the research coverage and agreement, but also our (qualitative) evaluations of level of uncertainty and transparency.

Life cycle phase	Coverage	Agreement	Quality	Remarks
Production of components	******	****	****	Complete coverage (Section 4). Uncertainty about emissions embodied in materials. Detailed material compositions are often not known. Toxic emissions from manufacturing are poorly understood; issues of mineral resource pressures are not well understood (Section 6.2). Studies assuming European energy systems dominate. Few studies of very large wind turbines and offshore wind turbines in deep waters and/or far from shore (Section 4).
Transportation to site, on-site construction	****	***	***	Coverage is variable (Section 4). Onshore: not important according to most studies (results of [34] disagree; Section 5.1). Offshore: possibly important; modeling appears simplistic; NO_x from fuel oil-burning may be significant. Few studies of wind turbines in deep waters and/or far from shore (Section 4).
Operation and maintenance	****	***	***	Coverage is variable (Section 4). Offshore transportation and on-site activities: modeling appears simplistic; NO_x from fuel oil-burning may be significant. Empirical basis for assumptions about replacement of parts seems to be lacking. Few studies of wind turbines in deep waters and/or far from shore (Section 4).
End-of-life	***	****	**	Scarcely assessed in detail (Section 4). Future waste handling practices for rotor blades are unknown. Assessments using the avoided burden method are often lacking in transparency and may be inconsistent.

A general problem is that detailed material compositions of components are typically not available (by detailed we mean specifications of exact material type, e.g. steel alloy), and furthermore, that LCA databases provide life cycle inventories for only a limited selection of generic materials. This creates uncertainty, which we illustrate here using a simple calculation exercise: In one study [40], ferrous metal content in the wind turbine (800 kW onshore; foundation is excluded here) is comprised by 7% cast iron, 78% low-alloy steel and 15% high-alloy (chromium) steel; while in a second study [31], the corresponding shares are 16% cast iron and 84% reinforcing steel (2 MW onshore wind turbine). Both studies utilize the Ecoinvent LCA database to model materials manufacturing; we find the relevant GHG emission intensities in Ecoinvent are 1.48 kg CO_2e/kg (cast iron), 1.45 kg CO_2e/kg (reinforcing steel), 1.72 kg CO_2e/kg (low-alloy steel), and 4.50 kg CO_2e/kg (chromium steel) [41]. Hypothetically, assuming a 2 MW wind turbine contains 200 tonnes ferrous metals, has a lifetime of 20 years and capacity factor 25%, these values translate to either 4.9 g CO_2e/kWh (if adopting the ferrous metal shares of

[40]) or 3.3 g CO_2e/kWh (if adopting the shares of [31]) caused by the production of ferrous metals for the wind turbine. This exemplifies how modeling choices concerning material types – choices that are often not justified and scarcely discussed in LCA studies – may significantly influence total impact indicator values. Another potentially important, poorly understood factor is the composite materials used in the rotor blades and nacelle.

6.3.2 Transportation, on-site construction, and operation and maintenance

The overall picture emerging from the current LCA literature is that emissions associated with transportation and on-site construction are small or negligible (cf. Section 5.1). While this conclusion appears to be fairly well documented with respect to the energy use and GHG emissions for onshore wind farms, one could question to what extent it is valid also for offshore projects (for which installation is more complicated than onshore), and perhaps especially for NOx emissions (largely as a result of NOx, transportation and construction activities are dominant contributors to marine eutrophication and photochemical oxidant formation impact indicator values for the offshore wind farm modeled by [18]). The same argument may apply to transportation and construction activities associated with maintenance. To our understanding, existing LCAs of offshore wind farms rely on rather simplistic and theoretical calculations for modeling on-site operations, and consistency with real-world conditions has not yet been demonstrated.

LCA studies either neglect replacement of parts (e.g., [37, 40]) or variably assume that certain shares of components must be replaced (e.g., [27] assumes 50% gearbox replacement during lifetime, [36] one blade and 15% generator replacement, and [35] 5% complete wind turbine replacement). One study develops a high-maintenance scenario in which 1 generator, 1 gearbox and 1 set of blades requires replacement [32]. While assumptions are not uniform across studies, one can discern that gearboxes, generators and rotor blades are expected to be most susceptible to failure and replacement. An empirical basis for assumptions about replacement seems to be lacking, however (a similar point is made by [32]). One central question is how the assumed replacement rates relate to past experiences from operational wind farms [76]; another question is how to extrapolate information from past experiences to modern wind turbines and more immature application areas (e.g., wind farms in marine environments [77]). In our judgment, these questions are not adequately addressed in the LCA literature.

6.3.3 End-of-life

Since LCAs typically assume the bulk of materials contained in wind power systems will either remain in situ or be recycled to be returned to usage as raw materials, waste disposal is generally not an important contributor to emissions. Excluding 'new' lifecycles that are created when materials are recycled is common practice in LCA (cf. the cut-off allocation principle in open-loop recycling; see, e.g., [78]).

There is considerable uncertainty surrounding the fate of fiber-reinforced plastic materials used in the rotor blades: Unlike the well-established processes of recycling basic metals, recycling fiber-reinforced plastic composites represents a technological challenge, and little practical experience exists [79, 80]. While there is a consensus that the traditional practice of landfilling reinforced plastics is unsatisfactory, and regulatory measures to phase out landfilling of these materials are coming into place [80, 81], which waste treatment strategies that are viable and should be chosen remains an open question [79]. There are concerns about toxic emissions occurring in cutting the blades (which may be needed to ease transport) [81], from waste treatment if the materials are landfilled [24], and from flue gas and ashes if the materials are incinerated [79, 80]. Future LCA research may have to address waste handling of rotor blades in order to ensure environmentally sound end-of-life phase for wind turbines.

A significant number of studies credit the system with perceived emissions reductions from end-of-life recycling (avoided burden method; Table 1; Sections 4 and 5.1). However, applications of the avoided burden method sometimes use inappropriate methodologies and are generally lacking in transparency. The root of the problems appears to be that it is not widely recognized that the two issues of 1) including recycled content as input materials in the production phase and 2) crediting the system with prevented environmental burdens at the end-of-life cannot be viewed independently. The share of secondary inputs in the production phase should always be zero for the materials for which avoided burden is calculated; otherwise one would use one perspective to model benefits of recycling in the production phase, and a different (and inconsistent) perspective to model benefits of recycling at the end-of-life – effectively, one would double-count benefits of recycling. The crux of the issue is that analysts must decide whether benefits of recycling should belong to systems that use recycled materials (as is the implicit assumption if secondary materials are used as inputs in an LCA) or make available recyclable materials (as is the assumption if avoided burden method is applied), and not mix these two perspectives.

We are aware of one study [35] that uses the avoided burden method appropriately, assuming no secondary resources as inputs in production when the avoided burden method is applied. (Another study [21] in which the avoided burden method is used also assumes only virgin resource inputs in production, but the stated reason is lack of data on recycled content, and the assumption is inappropriately described as "very conservative".) One apparently inconsistent assessment is [31], where materials containing significant amounts of recycled content (i.e., cast iron, reinforcing steel and copper Ecoinvent processes [82]) are stated to be used in the production phase, while simultaneously, recycling credits are given for avoided production. Other LCAs use the avoided burden method while not specifying that only virgin resources are used in production.

6.4 Method for life cycle inventory and system boundary issues

In 2002, Lenzen and Munksgaard [5] recommended that future wind power LCA research employs hybrid LCA methodologies "in order to achieve system completeness while dispensing with the problem of selecting of a boundary for the production system". However, the current survey demonstrates that hybrid LCA studies on wind power are still relatively scarce – this fits into a general trend that despite its acknowledged advantages, hybrid techniques have not yet become standard practice in LCA [10]. Hybrid LCA is more challenging to conduct and requires additional data, which may be an explanation for its lack of use. Moreover, it is interesting to note that Wiedmann et al. [23] employ two hybrid LCA calculation techniques separately, and find that while the total emission estimates obtained by the two techniques are comparable, there are considerable differences in the relative contribution from IO sectors. This points to yet unresolved issues with IO-based calculations techniques.

Notwithstanding the data and methodological challenges of hybrid methods, hybrid LCA is the only technique that offers both process-level detail and a nearly complete coverage of the entire product system. While there is no consensus in the LCA community on how to measure the truncation bias of process-LCA, in all explorations into this issue surveyed by Majeau-Bettez et al. [10] it is found that process-LCA fails to account for 30% or more of total indicator values.

This predicates that the employment of hybrid LCA methodologies should be a goal of future LCA research on wind power; and that if hybrid techniques on the other hand are not applied, the problem of cut-off errors should at the least be recognized – in existing literature this is not the case.

6.5 Aspects of scale, temporal evolutions and network integration

In recent years, analysts have remarked on the insufficiency of static, unit-based analyses for evaluating implications of future wind energy developments [18, 25, 39, 44]. One shortcoming of existing research is the general failure to address the magnitudes of aggregated impacts: A transition away from conventional and towards lower-carbon energy systems in coming decades – as envisaged for example by contemporary climate change mitigation scenarios [3, 4] – will in itself cause harmful emissions. Due to the sheer scale of the transition, total emissions and resource use brought about by 'clean' energy technologies may be significant in the aggregate, even if unit-based assessments (i.e., assessments where indicator values are measured per kWh) indicate low impacts. In the literature, climate change mitigation scenario analyses explore energy transitions at the economy-wide level [3, 4], but do not consider emissions arising from building and operating non-fossil power plants; while conversely, LCAs of power generation predominantly have a purely micro-level focus. The integration of these two perspectives could potentially provide valuable new insights on the economy-wide effects of large-scale energy transitions (a similar point is made by [8]). Ideally, such scenario calculations incorporate some projections of future technological changes, as discussed below.

Inventories for wind power systems are not static, but change over time as new technological configurations are adopted, and due to economies of scale and changes in background economies. Projections of impacts of research and scientific developments on future technological designs – based on technology forecasting studies or learning curve studies [38, 83] – may provide LCA analysts with a basis for modeling future inventory changes, as demonstrated by Viebahn et al. [84] for concentrated solar power. Besides changes in wind power technology configurations, impact indicator values are influenced by the characteristics of background economies through relatively clean or dirty manufacturing; indeed, it is the current economies' preoccupation with fossil fuels which is the very reason why electricity from wind is not CO_2-free. The importance of background energy system characteristics is illustrated by the results of [52], where the embodied CO_2 is a factor of five lower for a wind turbine produced in Brazil compared to Germany; the difference stems entirely from the higher portion of renewable sources (hydro, biomass) in Brazil's energy supply. It is not just the energy mix as such which is important, however, but also the energy efficiency. Another important factor are the environmental impacts of metals supply which will change due to combined effects of technological advances in mining and manufacturing, changes in the portion of secondary to primary materials used, and reduction in ore grade [85-87]. Future research may address the effects of such changes through scenario analyses.

The final type of scaling or temporal aspect discussed here relates to the variable and (partly) unpredictable nature of wind power. Higher shares of intermittent electricity supply, such as electricity from wind, increase the overall costs of short-term balancing in the system (i.e., matching electricity supply with demand over seconds to days), reduce overall peak-load system adequacy (because the contribution of a wind power plant to peak-load capacity adequacy is smaller than for conventional technologies), and may require upgrades in the electricity transmission infrastructure to admit transfer of electric power to the load centers (see, e.g., Section 7.5.4 in [1] and p. 321-326 in [88]). In the literature, life cycle emissions of wind power and emission penalties due to the variability of wind power [89-91] are generally analyzed separately and lead to separate evaluations of emissions connected with wind power deployment; in a sense, these two areas of research form two independent departures from the notion that wind power is 'emissions-free', both aiming to provide a more complete picture. The potential exists to combine the assessments in these two research fields, as exemplified by the study by Pehnt et al. [39] discussed in Section 5.3 – this would indeed be congruent with the often stated goal of LCA to provide holistic assessments, but on the other hand it involves substantial methodological and data challenges. In any case, when interpreting results of current LCA studies it is important to bear in mind the failure of LCA research to account for emission penalties due to intermittency.

6.6 Comparison with competing technologies

A detailed exploration of how life cycle emissions for wind power compare with that of other power-generation technologies falls outside the scope of this paper, although a few points are noted here. In the LCA survey presented in Sathaye et al. [8], the interquartile range (i.e., the range between 25th and 75th percentile levels) for life cycle GHG emissions for wind power are 8-20 g CO_2e/kWh (median value 12 g CO_2e/kWh). The corresponding ranges (median values) for competing technologies are 8-45 (16) g/kWh for nuclear, 3-7 (4) g/kWh for hydro, 14-32 (22) g/kWh for concentrating solar, and 29-80 (46) g/kWh for solar photovoltaic power. Life cycle GHG emissions of electricity from coal and natural gas with carbon capture and storage (CCS) are estimated to 180-220 g CO_2e/kWh and 140-160 g/kWh, respectively, in [92]; the corresponding numbers without CCS are around 1000 g/kWh for coal and 500-600 g/kWh for natural gas [8, 92]. Judging from these figures, the carbon footprint of wind power is significantly lower than that of fossil-based power with CCS, and is comparable or lower than that of other important non-fossil power generation technologies. Likewise, comparisons of life cycle emissions of NOx, SO_2, NMVOC and particles of multiple power generation technologies in Sathaye et al. [8] suggest good environmental performance for wind power.

Some research suggests that toxicity impacts may be of relatively high importance. Two studies of offshore wind power find, respectively, that a wind farm scores 2-6 times worse in toxicity impact categories than a natural gas combined cycle plant [35], and that wind electricity is slightly worse than the average German electricity with respect to human toxicity [22]. A different picture is presented by other publications, whose findings suggest that wind power grossly outperforms European [46] and Spanish [31] average electricity mixes with respect to human toxicity.

7 Final remarks and recommendations

Despite the considerable variability in results, and the limitations of current knowledge that have been mentioned, we conclude that existing LCA research provides many insights into and gives a fairly good overall understanding of the life cycle environmental impacts of wind power in terms of cumulative fossil energy demand and associated pollution. Discrepancies between studies can likely be explained by a combination of actual differences in the systems studied (e.g., small versus large wind turbines), key assumptions (e.g., capacity factor and lifetime), data inconsistencies (e.g., emission intensities of materials), and differences in methodologies and approaches (e.g., process-LCA or hybrid IO-LCA, accounting of recycling benefits). Previous

LCA reviews [1, 5, 7] have duly noted that the large gap between low and high values limit the usefulness of results to decision-makers, and that compliance with some standardized sets of methods and assumptions in future analyses would be advantageous.

The problems of confusion and uncertainty due to variability in results, and incomprehensibility due to the complex networks of operations that are studied and many assumptions that are made, need to be given due attention. One measure that can be taken to alleviate these problems – in conformity with the guiding principle that LCAs should be transparent [9] – is to make process-level inventory input data available together with LCA publications: Such a step would increase the transparency as to how results are obtained and help give clarity on why results differ across studies, and allow for proper meta-analyses of wind power LCAs [93]. Furthermore, making inventory input data at the level of unit processes available can contribute to a cumulative build-up of knowledge, rather than having efforts going into repetitions of sometimes cumbersome data collection processes.

This review has shown that to date, the largest research efforts have been devoted to studying typical onshore wind turbines or wind farms in European locations, placing most emphasis on the production life cycle stage. Future research may focus attention on system types or life cycle phases for which research is still relatively scarce or robust assessments are lacking. This may include:

- Systems that are produced and operated under conditions of other regions than Europe.
- Large wind turbines (> 3 MW) and offshore systems in deep waters and/or far from shore.
- Installation and operation and maintenance phases, in particular for offshore systems.

Wind power LCAs have traditionally had their domain in assessing potential environmental impacts caused by one small reference unit (1 kWh of electricity), have primarily focused on fossil energy-related emissions, and have predominantly employed a process-LCA methodology. Such assessments have proved valuable in the past and are likely to continue to play a role in future research. At the same time, given the sizeable number of published studies that are similar with regards to goal and scope, one could wish that research had made further strides in analyses with different or broader scopes, or more sophisticated methodologies. In this respect, we call for future research efforts to be directed into:

- The employment of hybrid LCA methodologies.
- Broadening the scope with regards to environmental impacts, as far as available impact assessment methods allow it. In particular, we call for more detailed explorations of toxicity and mineral resource depletion.
- Exploring technology evolution through scenario analyses, addressing for example the scale of environmental burdens at regional or global levels, changes in life cycle inventories as key technologies or background economies change, or emission penalties due to intermittency.

In all cases, future studies should avoid inconsistent modeling of recycling benefits.

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A.2 Supplementary content for paper I (published electronically in online version)

Description of content

The supplementary information contains 13 tables. Table S1 provides the raw data of the quantitative analysis in terms of system characteristics and impact indicator and emission estimate results. In some cases, results reported in the original publications were processed (e.g., to convert units, or to calculate greenhouse gas emission intensity from reported CO_2, CH_4, and N_2O emissions). Table S2 shows results in terms of assumed capacity factor values for five wind power system categories. Tables S3-S13 provides impact indicator results for five wind power system categories, corresponding to Fig. 2 in the main article. In Tables S2-S13, the number of estimates exceeds the number of studies if more than one estimate was surveyed from one study. In some cases, the total sample size (represented by the column “Total” in Tables S2-S13) slightly exceeds the sum of the shown sub-sample sizes; this is because estimates for wind farm portfolios were not assigned a specific wind power system type, but were included in the total sample.

Tables S1-S13

Tables S1-S13 are shown below.

Table S1. Overview of studies and estimates surveyed for quantitative analysis. Cit. = Citation number in main manuscript. Site: Ons = Onshore; Off = Offshore. Size: Wind turbine nominal capacity (kW). LT = Lifetime (years) : ‘*’ means longer lifetimes for some components. CF = Capacity factor (%). RC = Recycling credits: ‘x’ means that the system is credited with impact potentials that are perceived to be avoided through recycling of materials at the end-of-life; ‘(x)’ means system is credited, but results without credits are also presented. Geo. = Geographical scope: Eur = Europe; Asi = Asia; NA = North America; Oth = Onshore other/unspecified; Off = Offshore (all regions). Scores: Energy = Energy intensity (kWh/kWh); GHG = greenhouse gases (g CO_2e/kWh). CO_2 = Carbon dioxide (g/MWh); CH_4 = Methane (g/MWh); CO = Carbon monoxide (g/MWh); NH_3 = Ammonia (g/MWh); NMVOC = Non-methane volatile organic compounds (g/MWh); N_2O = Nitrous oxide (g/MWh); NO_2/NO_x = Mono-nitrogen oxides (g/MWh); Part. = Particles/dust (g/MWh); SO_2/SO_x = Sulfur oxides (g/MWh); ‘*’ indicates average value of multiple results. The table continues on the next page.

Cit.	**Methods and assumptions**								**Stressor and impact indicator scores**											**Remarks**
	Year	Site	Size	LT	CF	RC	Geo.	Method	Energy	GHG	CO_2	CH_4	CO	NH_3	NMVOC	N_2O	NO_x	Part.	SO_2	
[16]	2012	Ons	5	25	23.0		NA	Process	0.118	42.7										
[16]	2012	Ons	20	25	22.0		NA	Process	0.062	25.1										
[16]	2012	Ons	100	25	24.0		NA	Process	0.037	17.8										
[17]	2012	Ons	2000	20	34.1	x	Eur	Process	0.033	9.7										Europe estimate.
[17]	2012	Ons	2000	20	20.8	x	Eur	Process	0.032	8.8										Direct-drive. Europe.
[18, 19]	2011	Ons	2500	20	23.4		Oth	Hybrid		22.5	19.9	77	259	3.0	48	2.2	61		81	
[18, 19]	2011	Off	2500	25	37.5		Off	Hybrid		21.2	18.7	73	282	3.1	56	2.4	82		76	
[20]	2011	Ons	1250	20	24.9	x	Asi	EEIOA	0.047	7.6										
[21]	2011	Ons	3000	20		x	Eur	Process	0.025	7.0	5.8	14	5		2.1		14	6	16	
[22]	2011	Off	5000	20	44.5		Off	Process	0.137	32.0										Apha Ventus
[23]	2011	Off	2000	20	30.0		Off	Hybrid		33.4*	29.2*	115*				2.1*				Two hybrid methods
[26]	2010	Mix	Mix	20	28.7		Eur	Process		15.0	13.0	29	120	0.14	2.8	0.5	27	12	26	Wind farm portfolio
[27]	2009	Ons	850	20	33.9		Oth	Hybrid	0.048	35.0										
[27]	2009	Ons	3000	20	33.3		Oth	Hybrid	0.043	31.6										
[28]	2009	Ons	0.4	20	16.9		NA	Process		45.7										Residential off-grid
[30, 31]	2009	Ons	2000	20	22.8	(x)	Eur	Process	0.025*	6.6*										Related: [32]
[33]	2009	Ons	1650		45.0	x	Oth	Process	0.020		3.0									
[34]	2009	Ons	0.25	20	20.0	(x)	Eur	Process	0.333	46.4										
[34]	2009	Ons	4500	20	30.0	(x)	Eur	Process	0.083	15.8										Concrete tower
[35]	2009	Off	5000	20	53.0	(x)	Off	Process	0.054	11.5										Floating offshore
[36]	2008	Ons	660	20	19.0		Eur	Process	0.052		14.2		98			0.002	56	67	85	
[37]	2008	Ons	Mix	20	30.2		Asi	Process	0.014		3.6									Wind farm portfolio
[38]	2008	Off	2000	20*	46.2		Off	Process		8.1	7.6	17	52	0.53	4.0	0.2	22	14	23	GHG calculated here
[39]	2008	Off	5000				Off	Process		22.0										Consequential LCA
[40,41]	2007	Ons	30	20	8.0		Eur	Process	0.193	55.6	51.6	129	337	5.36	39.4	1.3	159	171	172	
[40,41]	2007	Ons	150	20	9.5		Eur	Process	0.117	32.3	29.6	88	140	1.95	19.8	1.3	77	84	98	
[40,41]	2007	Ons	600	20	14.0		Eur	Process	0.065	18.2	16.7	47	77	1.03	10.1	0.7	41	58	55	
[40,41]	2007	Ons	800	20	20.0		Eur	Process	0.042	11.7	10.7	32	64	0.69	6.7	0.4	26	36	34	
[40,41]	2007	Off	2000	20	30.0		Off	Process	0.049	14.7	13.6	37	77	0.80	8.5	0.5	34	40	39	

Table S1, cont.

Cit.	**Methods and assumptions**								**Stressor and impact indicator scores**											**Remarks**
	Year	Site	Size	LT	CF	RC	Geo.	Method	Energy	GHG	CO_2	CH_4	CO	NH_3	NMVOC	N_2O	NO_x	Part.	SO_2	
[44]	2006	Ons	1500				Eur	Process	0.033	11.0	10.2	24	97	0.03	26.1	0.2	31	42	40	
[44]	2006	Off	2500				Off	Process	0.031	9.0	8.9	10			2.4		21	11	35	
[45]	2006	Ons	1.5	20	19.0	(x)	Eur	Process	0.139*		53.2*									Rooftop wind turbine
[46]	2006	Ons	3000	20	30.0	x	Eur	Process	0.027		4.6		8			0.2	18		22	
[46]	2006	Off	3000	20*	54.2	x	Off	Process	0.028		5.2		20			0.2	21		22	
[47]	2006	Ons	1650	20	40.8	x	Eur	Process	0.030	7.1	6.6	11	27	0.01	4.8	0.4	29	6	19	
[48]	2006	Ons	342.5	25	25.6		NA	Process	0.042		13.8									
[48]	2006	Ons	600	20	19.9		NA	Process	0.091		34.4									
[48]	2006	Ons	750	30	28.6		NA	Process	0.036		17.9									
[49]	2005	Ons	300	30	20.0		Asi	Process		29.5										
[49]	2005	Ons	400	30	20.0		Asi	Process		20.3										Wind-fuel-cell
[50]	2005	Ons	500	20			NA	Process	0.025	20.9										
[51]	2004	Ons	2000	20	32.2	x	Eur	Process	0.032	7.0	6.8	4	22	0.01		0.2	59		22	
[51]	2004	Off	2000	20*	46.2	x	Off	Process	0.038	7.8	7.6	6	26	0.01		0.2	58		22	
[52]	2004	Ons	550				Oth	Hybrid	0.070*		19.8*									Geograph. scenarios
[53]	2004	Ons	500	20	24.7		Eur	Process	0.020											
[53]	2004	Ons	1500	20	24.7		Eur	Process	0.020											
[54]	2003	Ons	600	20	28.5		Eur	Process		7.5	7.2	6			1.5		15	8	22	
[54]	2003	Ons	1500	20	28.5		Eur	Process		12.2	11.7	14			2.2		23	14	58	Deep foundation
[54]	2003	Ons	1500	20	28.5		Eur	Process		12.6	12.1	15			2.4		24	14	58	Shallow foundation
[54]	2003	Off	2500	20	45.7		Off	Process		9.8	9.6	7			1.0		16	12	42	Tubular + Monopile
[54]	2003	Off	2500	20	45.7		Off	Process		8.3	8.0	7			1.1		14	11	29	Lattice + Tripod
[54]	2003	Ons	4500	20	45.7		Eur	Process		8.9	8.4	15			3.3		26	11	44	Concrete tower
[56]	2002	Ons	250	15			Asi	Process	0.025		7.9									
[57]	2002	Ons	600	20	23.6		NA	EEIOA		7.3										
[58]	2000	Ons	500	20	25.1		Eur	Process	0.033		9.7						30		20	
[58]	2000	Off	500	20	28.5		Eur	Process	0.049		16.5						50		30	
[59]	2000	Ons	600	20	22.8		Eur	Process	0.065	18.1										
[59]	2000	Ons	600	20	22.8		Eur	EEIOA	0.074	16.0										

Table S2. Capacity factor assumptions (%) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum	8.0	9.5	20.8	30.0	8.0
25th percentile	17.4	20.0	24.8	39.3	22.4
Mean	18.2	22.2	31.2	43.3	28.9
Median	19.5	22.8	30.0	45.7	28.5
75th percentile	21.5	25.1	33.9	46.2	33.6
Maximum	23.0	28.6	45.7	54.2	54.2
Std. deviation	5.4	5.1	7.5	8.4	10.6
No. studies	2	7	10	7	28
No. estimates	6	17	16	10	51

Table S3. Energy intensity results (kWh/kWh) and number of estimates and studies surveyed for 5 wind power system categories. Energy intensity refers to the ratio between total life cycle energy demand and electricity generated during the lifetime.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum	0.062	0.020	0.020	0.028	0.014
25th percentile	0.118	0.035	0.025	0.034	0.030
Mean	0.169	0.053	0.035	0.055	0.060
Median	0.139	0.045	0.032	0.049	0.042
75th percentile	0.193	0.067	0.033	0.052	0.065
Maximum	0.333	0.117	0.083	0.137	0.333
Std. deviation	0.103	0.027	0.017	0.037	0.058
No. studies	5	14	11	7	27
No. estimates	5	16	13	7	42

Table S4. Greenhouse gas emissions (g CO_2e/kWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum	25.1	7.3	6.6	7.8	6.6
25th percentile	42.7	14.9	7.2	8.6	8.9
Mean	43.1	19.5	12.0	16.2	18.9
Median	45.7	18.2	9.3	11.5	15.0
75th percentile	46.4	23.0	12.5	21.6	23.8
Maximum	55.6	35.0	31.6	33.4	55.6
Std. deviation	11.2	8.9	7.1	9.6	12.6
No. studies	5	11	13	11	28
No. estimates	5	12	14	11	43

Table S5. Carbon dioxide emissions (g CO_2/kWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	100 kW - 1 MW (onshore)	> 1 MW (onshore)	Offshore	Total
Minimum	51.6	7.2	3.0	5.2	3.0
25th percentile		10.2	6.0	7.7	7.6
Mean	52.4	16.5	8.9	12.5	14.8
Median	52.4	14.2	7.6	9.2	10.7
75th percentile		18.8	11.3	15.8	17.3
Maximum	53.2	34.4	19.9	29.2	53.2
Std. deviation	1.1	8.7	4.9	7.3	11.9
No. studies	2	9	9	10	21
No. estimates	2	11	10	10	35

Table S6. Methane emissions (g CH_4/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	100 kW - 1 MW (onshore)	> 1 MW (onshore)	Offshore	Total
Minimum		6	4	6	4
25th percentile			13	7	10
Mean	129	43	22	34	35
Median	129	40	15	13	16
75th percentile			17	46	45
Maximum		88	77	115	129
Std. deviation		34	23	40	37
No. studies	1	3	8	8	13
No. estimates	1	4	8	8	22

Table S7. Carbon monoxide emissions (g CO/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	100 kW - 1 MW (onshore)	> 1 MW (onshore)	Offshore	Total
Minimum		63.8	4.7	19.9	4.7
25th percentile			11.7	26.0	26.0
Mean	337.4	94.6	69.6	91.3	100.6
Median	337.4	87.3	24.5	51.5	76.9
75th percentile			79.3	76.9	120.0
Maximum		140.1	259.2	282.2	337.4
Std. deviation		33	99	109	101
No. studies	1	3	5	5	12
No. estimates	1	4	6	5	17

Table S8. Ammonia emissions (g NH_3/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum		0.69	0.005	0.009	0.005
25th percentile					0.03
Mean	5.36	1.22	0.80	1.12	1.30
Median	5.36	1.03	0.02	0.67	0.69
75th percentile					1.95
Maximum		1.95	3.17	3.14	5.36
Std. deviation		0.6	1.6	1.4	1.7
No. studies	1	2	4	4	9
No. estimates	1	3	4	4	13

Table S9. Non-methane volatile organic compounds emissions (g NMVOC/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum		1.5	2.1	1.0	1.0
25th percentile			2.3	1.4	2.3
Mean	39.4	9.5	12.7	12.1	12.8
Median	39.4	8.4	3.3	3.2	4.0
75th percentile			15.5	7.4	15.0
Maximum		19.8	48.3	55.8	55.8
Std. deviation		7.7	17.9	21.6	17.1
No. studies	1	3	7	6	10
No. estimates	1	4	7	6	19

Table S10. Nitrous oxide emissions (g N_2O/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum		0.002	0.18	0.17	0.002
25th percentile			0.20	0.20	0.20
Mean	1.31	0.61	0.63	0.93	0.76
Median	1.31	0.55	0.23	0.36	0.44
75th percentile			0.35	1.72	1.31
Maximum		1.32	2.18	2.39	2.39
Std. deviation		0.5	0.9	1.0	0.8
No. studies	1	3	4	6	12
No. estimates	1	4	5	6	17

Table S11. Mono-nitrogen oxides emissions (g NO_x/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum		15	14	14	14
25th percentile		27	23	21	21
Mean	159	41	32	35	40
Median	159	35	26	22	28
75th percentile		52	31	50	54
Maximum		77	61	82	159
Std. deviation		22	17	23	31
No. studies	1	5	8	9	16
No. estimates	1	6	9	9	26

Table S12. Total particulates or particles/dust emissions (g/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum		8	6	11	6
25th percentile		36	7	11	11
Mean	171	51	15	18	34
Median	171	58	12	12	14
75th percentile		67	14	14	42
Maximum		84	42	40	171
Std. deviation		30	14	13	41
No. studies	1	4	6	5	9
No. estimates	1	5	6	5	18

Table S13. Sulfur oxides emissions (g SO_x/MWh) and number of estimates and studies surveyed for 5 wind power system categories.

	< 100 kW (onshore)	**100 kW - 1 MW (onshore)**	**> 1 MW (onshore)**	**Offshore**	**Total**
Minimum		20	16	22	16
25th percentile		25	22	23	22
Mean	172	52	40	35	46
Median	172	44	40	30	35
75th percentile		78	58	39	57
Maximum		98	81	76	172
Std. deviation		33	22	17	34
No. studies	1	5	8	9	16
No. estimates	1	6	9	9	26

A.3 Note concerning capacity factor values (supplementary note added in this thesis)

The finding in section 3.1 and paper I that LCAs tend to assume higher capacity factor values than indicated by realized wind power generation could be conceived as fitting into a broader pattern of too optimistic capacity factor assumptions in the literature: Boccard (2009) argues that while capacity factors of 30-35% are generally assumed, the fleet-wide average for Europe is below 21%, and similar discrepancies exist for offshore wind power, according to Boccard (2009).

In some respects the presentation of current evidence on realized wind power generation in paper I may appear not entirely consistent with a similar presentation given in IPCC's recent Special Report on Renewable Energy Sources and Climate Change Mitigation (Wiser et al. 2011). However, I would argue that several issues in Wiser et al. (2011) in sum cause the presentation to be overly positive:

i) While Boccard (2009) reports a mean realized value for EU in 2003-2007 of 20.8%, with numbers ranging from 18.3% (Germany) to 26.1% (UK), Wiser et al. (2011) inappropriately cite Boccard (2009) on that "European country-level average capacity factors range from 20 to 30%". A later study (Kaldellis and Zafirakis 2011) presents EU capacity factor figures where the total mean for the years 2003-2007 appears to be approximately 19% (> 20% for the single year 2007) (figure 11 in the reference), which also appears not consistent with the 20-30% range maintained by Wiser et al. (2011).

ii) Wiser et al. (2011) state that "the average capacity factor for US (...) is above 30%", citing Wiser and Bolinger (2010), but refrain from citing Boccard (2009) here despite that Boccard (2009) reports a US value of 25.7% and remarks that he is unable to reproduce results from work by Wiser and Bolinger using the same original data source.

iii) Wiser et al. (2011) cite Lemming et al. (2009) on a claim that offshore projects typically show capacity factors of 35-45%. However, as far as I can see Lemming et al. (2009) provide little support here, but states that "a typical offshore installation has an utilization time of 3000 hours or more" – that is, a capacity factor 34% or more. The value 34% or more is roughly in line with a general expectation of 35% deduced in Feng et al. (2010) based on experiences from early offshore wind farms. Wiser et al. (2011) add that “some offshore plants in the UK (...) have experienced capacity factors of roughly 30%...”, where 29.5% is an average value for UK round 1 offshore wind farms (Feng et al. 2010).

iv) Wiser et al. (2011) state that “average capacity factors in China are reported at roughly 23%”, a number which may be traced to an interview in Cyranoski (2009). Yang et al. (2012) (published after Wiser et al. 2011) estimate 16-17% for China. It is reported that 25% (IEA 2011) or 30% (Yang et al. 2012) of installed capacity in China by the end of 2010 and 28% by the end of 2011 (Qi, 2012) is not connected to the grid, in part explaining the very low mean realized capacity factor value (Yang et al. 2012).

As for average global capacity factor values, Jacobson (2009) reports a current average of 20.5%, Kaldellis and Zafirakis (2011) report about 20% for the year 2007, and Arvesen and Hertwich (2011) (paper II) 23.8% for the year 2007. Lenzen (2010) reports 24.5% for 2008, but appears to use the end-of-year capacity value as opposed to the mid-year value or similar to calculate the capacity factor; if this is so, the capacity factor should be higher than 24.5%.

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Appendix B: Paper II and associated content

Paper II and corrigendum

Arvesen, A. and E. G. Hertwich. 2011. Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment. *Environmental Research Letters* 6(4): 045102.

Arvesen, A. and E. G. Hertwich. 2012. Corrigendum: Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment. *Environmental Research Letters* 7(3): 039501.

The version of paper II included here is based on the last submitted manuscript to the journal. Minor deviations between the version included here and the final published version may occur. Due to an error in the model used to compute results for the originally published paper, a corrigendum was published with corrected results. Figures given in the version of the paper included here are the corrected results.

The final published paper is available at: http://stacks.iop.org/1748-9326/6/i=4/a=045102

The corrigendum is available at: http://stacks.iop.org/1748-9326/7/i=3/a=039501

B.1 Paper II

Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment

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ABSTRACT

We investigate the potential environmental impacts of a large-scale adoption of wind power to meet up to 22% of the world's growing electricity demand. The analysis builds on life cycle assessments of generic onshore and offshore wind farms, meant to represent average conditions for global deployment of wind power. We scale unit-based findings to estimate aggregated emissions of building, operating and decommissioning wind farms towards 2050, taking into account changes in the electricity mix in manufacturing. The energy scenarios investigated are the International Energy Agency's BLUE scenarios. We estimate 2.3-3.5 Gt CO_2-eq climate change, 2.9-4.5 Mt N-eq marine eutrophication, 16-24 Mt NMVOC photochemical oxidant formation, and 13-20 Mt SO_2-eq terrestrial acidification impact category indicators due to global wind power in 2007-50. Assuming lifetimes 5 years longer than reference, total climate change indicator values are reduced by 8%. In the BLUE Map scenario, construction of new capacity contributes 64%, and repowering of existing capacity 37%, to total cumulative greenhouse gas emissions. Total emissions of wind electricity range between 5% and 23% of the direct emissions of replaced fossil-fueled power plants. For all impact categories, indirect emissions of displaced fossil power are larger than total emissions caused by wind power.

Keywords: carbon footprint, hybrid life cycle assessment, renewable energy scenario, environmental management, climate mitigation scenario

1 Introduction

In recent years, increasing concerns over security of energy supply and harmful climate change have fuelled interest in the development of renewable energy technologies. Electric power generation by wind turbines is a fast-growing technology, with global installed capacity growing at an average annual rate of around 25% over the past ten years [1]. Furthermore, typically foreseen paths to renewable energy supply and climate stabilization imply a massive expansion of the wind power industry and its supply network in coming decades. Despite the renewable nature of wind energy conversion, non-renewable resource inputs and emissions occur in the life cycle of wind energy systems. The potential environmental impacts generated throughout a product's life cycle can be quantified and assessed by the method of life cycle assessment (LCA).

In the literature, climate change mitigation scenario analyses explore pathways leading to de-carbonized energy supply at the economy-wide level, but do not take into account the greenhouse gas emissions in the production of the power plants; while conversely, conventional, unit-based LCAs of power generation do not address aspects of scale and time. In the broader context of climate change mitigation an integration of the two perspectives can be valuable in establishing a more complete understanding of the environmental effects of proposed transitions away from fossil and towards lower-carbon energy systems. Examining the economy-wide environmental costs and benefits of wind power, the current study represents an early research attempt in this direction.

In the present study we estimate aggregated emissions caused by global wind power development towards 2050, following energy scenarios by the International Energy Agency (IEA) [2]. The analysis builds on the LCAs of generic onshore and offshore wind farms, meant to represent average conditions for global onshore and offshore wind power development. We employ a hybrid LCA methodology, that is, we combine physical, process-based inventories and monetary, input-output based inventories. Utilizing the extensive set of life cycle inventories for fossil-based power generation technologies in the Ecoinvent database, the scenario analysis includes an integrated LCA modeling of emissions reduction due to increased global wind power employment. The scenario analysis incorporates the temporal distribution of emissions and replacement of components at their end-of-life, as well as changing electricity mix in manufacturing.

2 Hybrid LCA: methods and data

In an LCA, a systematic mapping of emissions generated throughout a network of operations allows one to evaluate potential environmental impacts associated with or necessitated by a product or service throughout its lifetime. Two approaches to LCA prevail: process-LCA, a bottom-up technique defining and describing operations in physical terms, and environmentally extended input-output analysis (EE-IOA), utilizing monetary data at the level of economic sectors. Process-LCA facilitates the use of physical data specific for the operations under consideration, but may suffer from significant cut-off errors. EE-IOA, on the other hand, has the advantage of more complete system coverage, but it comes at the expense of precision level. Hybrid methods combining process-LCA and EE-IOA can potentially exploit advantages of both approaches.

An LCA model can be expressed mathematically by

$$d = Ce = CF(I - A)^{-1} y \tag{1}$$

where the vector d represents total impact indicator values, and the vector e contains life cycle inventory analysis results, such as emissions values. C is a matrix of characterization factors, F is a matrix of stressor intensities, and I is the identity matrix. In a product system, outputs of processes/sectors serve as inputs supporting the production of new outputs. Relations between physical processes and economic sectors are described by the direct requirements matrix, A, where each element in A represents the flow from one producing process/sector to a consuming process/sector. Ultimately, all activities serve to satisfy a demand given by the vector y.

The direct requirements matrix reveals the structure of the hybrid LCA model employed [3]:

$$A = \begin{bmatrix} A^{ff} & 0 & 0 \\ A^{pf} & A^{pp} & 0 \\ A^{nf} & 0 & A^{nn} \end{bmatrix} \tag{2}$$

We distinguish between three types of processes and sub-systems: 1) processes defined specifically for this study, together comprising the foreground system (index f); 2) processes defined in an LCA database, together comprising the LCA database background system (index p); and 3) processes represented by economic sectors in an input-output (IO) dataset, together comprising the IO background system (index *n*). Linkages among processes in the foreground system are described in the matrix A^{ff}. Similarly, A^{pp} and A^{nn} describe internal linkages within the LCA background and IO background systems, respectively. Inputs to the foreground system from the LCA and IO background systems are accounted for in A^{pf} and A^{nf}. Table 1 gives a summary of activities and the sub-systems in which they are modeled.

Table 1. Distribution of activities by modeling sub-system.

Activity	Sub-system	Physical/monetary
Final manufacturing and assembly of main components	Foreground	Physical
Operation and maintenance	Foreground	Physical
Installation and decommissioning	Foreground	Physical
Supply of electricity to foreground system	LCA database background	Physical
Supply of selected materials and material processing to foreground system	LCA database background	Physical
Supply of all other inputs to foreground system	IO database background	Monetary

As the LCA database background system we use a matrix representation of the Ecoinvent database [4]. The IO background system is a two-region (Europe, rest of world) environmentally extended IO model for the year 2000, constructed using input-output tables from Eurostat [5] and GTAP 6 [6], and air emissions data from World Resources Institute [7] and Eurostat [8]. All inputs from the IO background system to foreground processes are made from the Europe region.

The matrix representing inputs to the foreground system from the IO background system (A^{nf}) is constructed in the following step-wise approach: 1) Each foreground process is assigned to an IO sector. The foreground processes are assigned the same input distributions as their belonging IO sectors. 2) Inputs are scaled according to the costs (with value added deducted) apportioned to the specific foreground processes. 3) Inputs from the IO background that are already covered by the LCA database background system are removed.

We alter the relative shares of power generating technologies in the LCA database and IO background systems to match the global electricity mix in 2007 (unit-based analysis). The alteration is performed consistently in the matrices A^{pf}, A^{nf}, A^{pp}, and A^{nn}. In the scenario analysis, the procedure is repeated for every year, so that the electricity mix used in the entire LCA database and IO background systems is always consistent with the IEA scenarios.

3 Life cycle inventories

We model hypothetical 120 MW (onshore) and 250 MW (offshore) wind farms. The lifetime of the onshore wind power system is assumed to be 20 years, for offshore it is 25 years. For the unit-based analysis, we assume onshore and offshore average wind load factors of 23.6% and 37.5%, respectively, which correspond with values for the reference year 2007 in the scenario analysis (table 3). Our system of analysis comprises the wind turbines with foundations, internal electrical connections, and cabling and a high-voltage transformer for connection to the electricity grid. In addition, the analysis covers installation, operation and maintenance, and decommissioning. For the electrical connections, we utilize data gathered by Jorge et al. [9].

Our data set covers eight air pollutants: ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), mono-nitrogen oxides (NO_x), nitrous oxide (N_2O), non-methane volatile organic compounds (NMVOC), and sulfur oxides (SO_x). The relevant impact assessment categories for these stressors are: climate change, marine eutrophication, photochemical oxidant formation, and terrestrial acidification. ReCiPe 1.03 characterization factors are used [10]. Emissions data for NH_3 are missing for the rest-of-the-world region of the IO background system.

In the following, we outline life-cycle inventory data collection. Metal requirements for all components, as well as composites used in the rotor blades and nacelle, concrete used in the foundations, and electricity used by foreground processes, are modeled in the LCA database background system. Other inputs to the foreground are covered by inputs from the IO background system. In cases where emissions values are not known for foreground processes, we estimate them based on consumption of gas and oil. Further accounts of inventories and assumptions are provided in the supplementary information.

3.1 Wind turbine and foundation

Total weights of rotor blades, hub, and nacelle, respectively, are obtained for 2 MW and 3 MW wind turbines by the manufacturer Vestas [11]. We take averages for the two turbines to model a hypothetical 2.5 MW wind turbine, which is used both onshore and offshore. The tower mass is 78 t/MW for onshore (hub height 105 m), for offshore it is 52 t/MW (hub height 80 m), consistent with tower weights used in an LCA by Vestas [12]. We model the tower as made of low-alloy steel, and the rotor blades as consisting of glass-reinforced plastics. To achieve a higher resolution for the nacelle with respect to components and material types, we utilize relative shares (by component and material type) of [13] together with own assumptions (Tables S5-S10 in supplementary information). Wire drawing for copper content in the generator and transformer, and sheet rolling of steel content in the tower are included.

Direct energy requirements (electricity, heat, gas, and oil) and emissions of CO_2 for a wind turbine manufacturer are established from Vestas reports. We take the averages of values reported for the years 2007, 2008, and 2009 [14], and adjust to take into account that around 80% of the towers are supplied to Vestas rather than manufactured in-house. The adjustment builds on data in [15] and causes energy use to increase by 3-10% from non-adjusted values. We model onshore gravity-based foundations made of reinforced concrete (1000 t), and offshore foundations made of steel (300 t at water depth 20 m), with aluminum anodes to prevent corrosion.

3.2 Electrical connections

Based on a survey of wind power projects, we assume 0.4 km of internal cabling and 0.3 km cabling for connection to grid is required per MW wind farm capacity. Submarine cables are steel armored. Material and energy requirements are derived from manufacturer data and previous LCAs [16-19]. Because data on energy use in manufacturing of infield cables is missing, we assume equal energy per weight ratios for internal and external cables. Each wind farm is connected to a high-voltage transformer, for which material composition and direct energy inputs during manufacturing we derive from reports by manufacturers [20, 21]. The offshore transformer platform is modeled as one wind turbine foundation.

3.3 Installation and decommissioning

The installation phase includes transportation to site and on-site construction activities. Diesel consumption for on-site activities for an onshore wind farm comes from reported measurements [22]. We convert reported life cycle energy to direct energy equivalent. When shifting to offshore sites, it is assumed that on-site diesel consumption scale proportional to the installation costs. Transportation of one wind turbine is modeled as 10 lorries (32t capacity) with pilot cars traveling 600 km; and onshore and offshore foundations, respectively, as 40 and 10 lorries traveling 50 km and 200 km. Electrical connections travel 200 km by lorry. For the offshore case, transportation with barge (30 km) comes in addition.

Demolition is modeled as identical to installation. Composite materials in the rotor blades and nacelle are assumed to be 50% incinerated and 50% recycled. Apart from this, waste disposal is not taken into consideration, as it is assumed that most other materials contained in the system will be returned to the technosphere for recycling or remain in situ without causing further environmental burdens.

3.4 Operation and maintenance

A case study [22] indicates that around 50 kg of diesel will be consumed per year per MW for inspections. Helicopter operation (100 hours per wind turbine) is added for the offshore wind farm. Based on the presumption that the gearbox is the component most vulnerable to failure, we assume 50% (onshore) and 70% (offshore) of gearboxes will have to be replaced during the lifetime. Replacement parts are transported by lorry (600 km) and barge (offshore).

3.5 Level and distribution of costs

To determine the inputs from the IO background system to the foreground (that is, to establish A^{nf}), cost numbers must be assigned to each of the processes in the foreground. We assume total capital cost is 1250 Euro/kW (onshore) and 2200 Euro/kW (offshore), and that variable costs amount to 1.2 Eurocent/kWh (onshore) [23]. Figures for the variable costs of offshore wind farms are scarce in the public domain, though they are known to substantially exceed the variable costs of onshore wind projects [23]. We set variable costs of offshore wind power to 1.6 Eurocent/kWh. Cost numbers are converted from 2007 to 2000 prices using average annual inflation rate.

A breakdown of costs by foreground processes is established by synthesizing data from different sources. For the capital costs of the onshore wind farm, as a starting point we take the cost distribution of a wind project in Europe, as estimated by [23]. Then, we disaggregate the costs of the actual wind turbine into main wind turbine components [23]. The cost breakdown for the offshore wind turbine is identical to that of the onshore unit, except for the wind turbine tower, which is assigned a lower cost offshore to reflect lower height (we scale costs for the offshore tower in proportion to the tower mass). For capital expenditures other than wind turbine costs, we use the cost breakdown of [24] for the offshore wind farm. Further disaggregations are based on [25] and own assumptions. We add costs for decommissioning (equal to costs of installation). Service and spare parts constitute 26% of the variable costs for an onshore wind farm [26], for an offshore wind farm 60% (own assumption).

4 Scenario modeling

The IEA has produced a series of scenarios describing ways in which global energy-related CO_2 emissions can be reduced by 50% by 2050, relative to 2005. Of these, the BLUE Map scenario represents the least-cost alternative. The BLUE hi REN scenario has an additional assumption of 75% renewable electricity supply by 2050 (table 2) [2].

Table 2. Selected characteristics of IEA's Baseline, BLUE Map, and BLUE hi REN energy scenarios [2].

	2007	**Baseline 2050**	**BLUE Map 2050**	**BLUE hi REN**
Global electricity production from wind (TWh)	173	2149	4916	8193
Share of renewables in electricity production (%)	18	22	48	75
Share of wind in electricity production (%)	0.9	4.7	12.2	21.8
Average generation cost increase from baseline (2050) (%)			19	31
Total energy-related CO_2 emissions (Gt/yr)	28.9	57.0	14.0	12.9

In essence, our scenario analysis consists of scaling onshore and offshore unit-based findings to match future developments given in the BLUE Map and BLUE hi REN scenarios, using time series modeling. Table 3 summarizes future wind power developments towards 2050. For the BLUE hi REN scenario, only 2007 and 2050 values are given; therefore, linear interpolation is used to establish intermediate values. For both scenarios, we use linear interpolation to determine intermediate data points not reported in table 3.

Table 3. Global wind power development by BLUE Map and BLUE hi REN scenarios [2]. Numbers without superscripts are obtained from [2, 27]. [1]Calculated by authors based on an annual onshore production of 173.1 TWh in 2007 [2, 27], and by assuming mid-year onshore capacity was (94.7+73.2)/2, where 94.7 GW is the onshore capacity at the end of 2007 according to [2, 27] and 73.2 GW the onshore capacity at the end of 2006 according to [1]. [2]Calculated by authors from production and capacity numbers in [2, 27]. [3]Assumed by authors. [4]Calculated based on onshore and offshore load factors and capacity numbers. [5]Based on linear interpolation. [6]Assuming equal average load, and equal onshore and offshore shares, in BLUE hi REN as in BLUE Map.

	2007	**2030**	**2050**
BLUE Map scenario			
Annual electricity production (TWh)	173	2933	4916
Cumulative capacity at end of year (GW)	96.3	1134	1737
of which offshore (GW)	1.6	214	444
Average load onshore (%)	23.6[1]	27.4[2]	29.0[2]
Average load offshore (%)	37.5[3]	41.7[2]	43.2[2]
Average load (%)	23.8[4]	30.1[4]	32.6[4]
BLUE hi REN scenario			
Annual electricity production (TWh)	173	4463[5]	8193
Cumulative capacity at end of year (GW)	96.3	1691[6]	2869[6]
of which offshore (GW)	1.6	320[6]	733[6]

We incorporate changes in electricity mix by altering the relative shares of power generation technologies in the direct requirements matrix, *A,* consistent with the IEA scenarios (see table S21 in the supplementary information for electricity mix towards 2050). Simplifying assumptions are necessary to deal with incomplete coverage of futuristic power generation technologies in the LCA and IO data sets. We assume fossil power with carbon capture and storage eliminates 90% of in-plant CO_2 emissions. Non-fossil energy technologies accounting for small percentages of total generation in 2007-2050 are only partly modeled (biomass, waste) or not modeled (geothermal, ocean). As the IO background system lacks a proper representation of solar power, solar power in the IO background (Europe region) is moved to the LCA database system.

To allow for the temporal distribution of emissions to be taken into account, the demand vector y for the wind power system is broken down into three components:

$$y = y_{start} + y_{oper}\tau + y_{end} \tag{3}$$

where y_{start} represents direct requirements prior to operation (construction; $t'=0$), y_{oper} annual average operation and maintenance direct requirements, and y_{end} direct requirements at the end-of-life (decommissioning; $t'=\tau$). The elements of y_{start} and y_{end} are measured on a per added capacity basis (e.g., t/MW), while y_{oper} is measured per capacity per year (e.g., t/MW/year). τ is the lifetime, and $t'=\{1, \ldots, \tau\}$ the age of a wind power system.

Denote by $K_{new}(t)$ and $K_{repow}(t)$ added capacities and repowering of existing capacities, respectively, in year *t,* and by $K_{oper}(t)$ average total capacity in operation over year *t*. With end-of-year onshore and offshore operating capacity values for the years 2007, 2030 and 2050 (table 3) together with end-of-year capacity values for 2006 [1], and assuming linear growth in cumulative capacity in 2007-2030 and 2030-2050, we establish K_{new} and K_{oper} for 2007-2050. We assume constant lifetimes (τ) of 20 years (onshore) and 25 years (offshore); longer lifetimes are considered in the sensitivity analysis. Statistics on annual added capacities from 1996 and onwards (onshore) and for 2006 (offshore) [1] are used to determine K_{repow} values for 2017-2027 (onshore) and 2032 (offshore); for succeeding years K_{repow} equals K_{new} with a time lag of τ. Implicit in K_{new}, K_{repow} and K_{oper} are changes in load factors (table 3). Time series data for K_{new}, K_{repow} and K_{oper} values used in the scenario analysis are provided in the supplementary information (table S22).

While equation 3 separates requirements occurring prior to, during and after the operating lifetime, it does not incorporate time as a variable; nor does it reflect scale or the need for repowering. We express the economy-wide direct requirements of building, operating and decommissioning wind power systems in year *t* as

$$\tilde{y} = y_{start}K_{new}(t) + y_{start}K_{repow}(t) + y_{oper}K_{oper}(t) + y_{end}K_{repow}(t) \tag{4}$$

where the first term on the right-hand side represents construction of new capacity and the second term construction of replaced capacity. The third and fourth terms express, respectively, direct requirements associated with operating and decommissioning wind farms. Absolute emissions $\tilde{e}(t)$ are then calculated year-by-year as

$$\tilde{e}(t) = F\left(I - A(t)\right)^{-1}\tilde{y}(t)\text{, for t=}\{2007, \ldots, 2050\} \tag{5}$$

Because we take into account changes in the electricity mix, A is a function of time. The calculation is performed separately for onshore and offshore wind power.

Finally, utilizing the set of life cycle inventories for coal, natural gas, and oil-fired power stations in the Ecoinvent database, a life cycle approach is taken to evaluate economy-wide greenhouse gas emissions savings from wind power. The evaluation is performed on the assumption that *additional* wind electricity (measured in TWh) in the BLUE Map scenario, compared with IEA' baseline scenario, replaces fossil-based power. The quantifications of direct and indirect reduced emissions are done year-by-year in the scenario analysis, taking into account temporal evolutions in additional wind electricity in BLUE Map compared with the baseline, relative shares of onshore and offshore wind power, and relative shares of energy carriers (coal, natural gas, oil) in fossil power generation towards 2050. Only conventional fossil power is replaced; wind power is not assumed to displace power plants with carbon capture.

5 Results

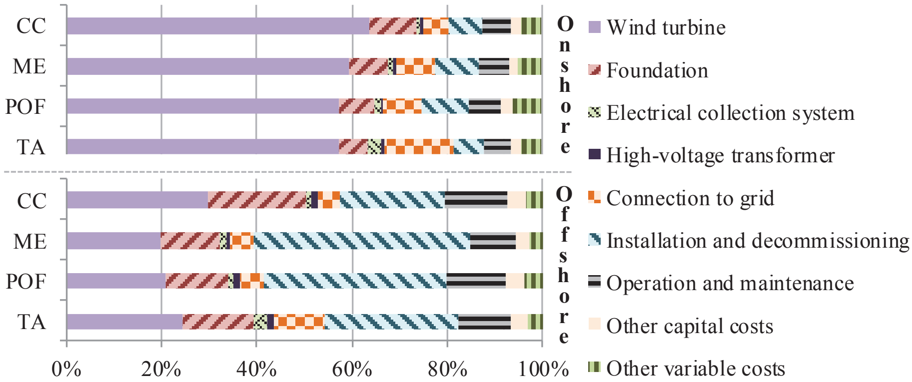

Figure 1. Life cycle emissions of onshore and offshore wind power in the reference year 2007 by main components. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification**.**

According to our unit-based analysis results, the delivery of 1 kWh of electricity from onshore wind energy conversion causes 22.5 g CO_2-eq climate change, 0.024 g N-eq marine eutrophication, 0.128 g NMVOC photochemical oxidant formation, and 0.123 g SO_2-eq terrestrial acidification impact potentials. The corresponding values for offshore wind power are 21.2 g CO_2-eq, 0.032 g N-eq, 0.157 g NMVOC, and 0.129 g SO_2-eq. For the onshore case, the wind turbine is the most important single component, contributing 57-64% to total emissions (figure 1). Of this, the tower holds shares of 31-38%, the nacelle 28-39%, and the rotor (including hub) 24-29%. The wind turbine is a much less dominant contributor to the emissions of ocean-based systems (20-30%), for which installation and decommissioning become more important (22-46%). The foundation contributes 6-10% (onshore) and 12-21% (offshore).

Figure 2 shows the breakdown of the contribution of electricity, materials and manufacturing processes to the total emissions of components of the wind park. For climate change and terrestrial acidification category indicators, significant portions (27-29%) of total emissions are caused by fossil-fuel burning in the power sector, reflecting the need to use fossil-based electricity of today to develop the renewable energy systems of tomorrow. Manufacturing of metals and metal products is responsible for 8-29% of total emissions. Transportation causes 22-23% of eutrophication, but only 6% of climate change impact potential.

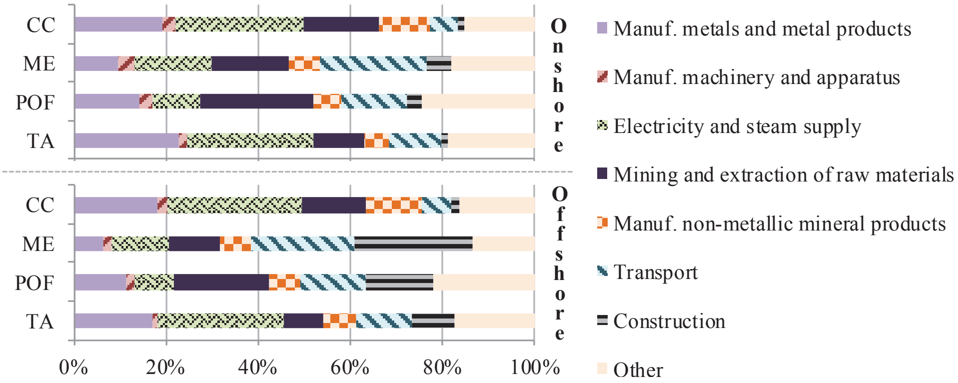

Figure 2. Life cycle emissions of onshore and offshore wind power in the reference year 2007 by main emissions source. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification. Manuf. = Manufacture of.

Our scenario analysis yields cumulative greenhouse gas (GHG) emissions due to wind power development of 2.3 Gt and 3.5 Gt CO_2-eq, for the BLUE Map and BLUE hi REN scenarios respectively, in the time period 2007-2050 (figure 3). Corresponding values for other impact categories are 2.9 (4.5) Mt N-eq, 16 (24) Mt NMVOC, and 13 (20) Mt SO_2-eq for the BLUE Map (BLUE hi REN) scenario. Looking at GHG emissions, construction of new capacity dominates (64% of cumulative emissions in 2050 in BLUE Map scenario), although repowering becomes increasingly important (37% in 2050). Due to the combined effects of increased load factor, shift from land to ocean sites, and cleaner electricity mix in manufacturing, the GHG emission intensity, as calculated with the unit-based analysis with current-year technologies, is reduced to less than 14 g/kWh in 2050 (figure 3). Assumed lifetimes and future capacity factors are two important sources of uncertainty and are addressed in the sensitivity analysis (section 6).

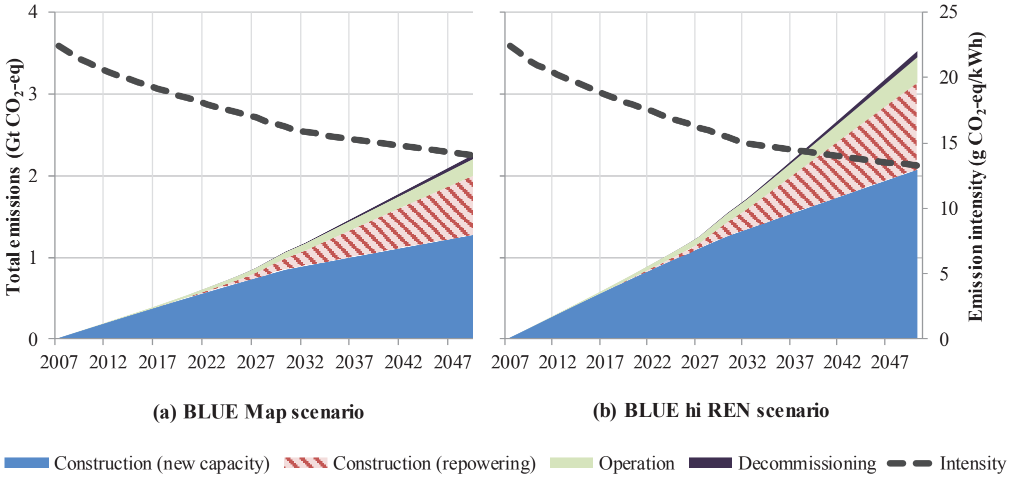

Figure 3. Cumulative GHG emissions due to the construction, operation and demolition of wind power systems and GHG emission intensity of current-year wind electricity (2007-2050) for the BLUE Map (a) and BLUE hi REN (b) scenarios.

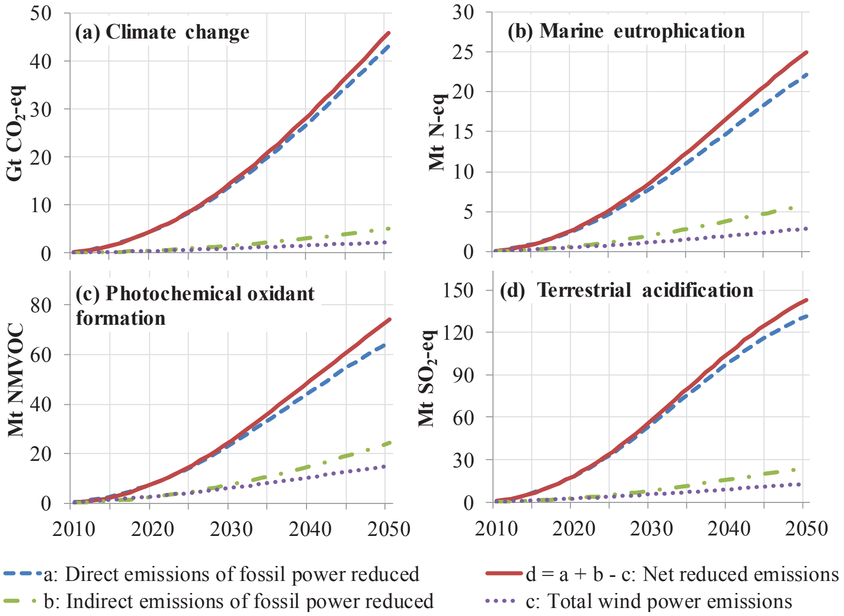

Figure 4. Cumulative gross (broken blue line) and net (solid red line) reduced emissions of wind power 2010-2050 by four impact categories for the BLUE Map scenario.

Figure 4 compares the cumulative emissions from wind power to the reduction of emissions from fossil power plants replaced by the additional wind power capacity (2010-2050). Gross reduced emissions is the direct emissions of fossil-fueled power plants replaced by the additional wind electricity in the BLUE Map scenario, compared with IEA's baseline scenario. Net reduced emissions is the difference of the life cycle emissions of the replaced fossil fuel power stations (assuming a mix of fossil energy carriers as modeled year-by-year in the scenario analysis) and the total life cycle emissions caused by wind power. Indirect emissions are the part of the life cycle emissions not occurring directly at the power plant. At the most, emissions of wind energy amount to 23% of gross reduced emissions (photochemical oxidant formation); at the least 5% (climate change). For all impact categories investigated, our measure of net reduced emissions exceeds gross reduced emissions because the fuel-chain emissions of displaced fossil power are larger than the total life cycle emissions of wind power.

Numerical results in tabulated form are available in the supplementary information.

6 Sensitivity analysis

Table 4. Combinations of total capacity factor value (%) and lifetime (years) assumptions used in sensitivity analysis for the years 2007, 2030 and 2050. Lifetime is constant over the modeling period. CF = Capacity factor. LT = Lifetime. Reference case assumptions are consistent with results reported in section 4.

Scenario	**Capacity factor (%)** 2007	2030	2050	**Lifetime (years)**
Low CF	23.8	28.3	30.0	20 (onshore), 25 (offshore)
Reference	23.8	30.1	32.6	20 (onshore), 25 (offshore)
Reference + Long LT	23.8	30.1	32.6	25 (onshore), 30 (offshore)
High CF	23.8	31.9	35.2	20 (onshore), 25 (offshore)
High CF + Long LT	23.8	31.9	35.2	25 (onshore), 30 (offshore)

The sensitivity analysis investigates the influence of capacity factors and lifetimes on estimated cumulative GHG emissions of wind power. In addition to the reference case, four scenarios are constructed to represent more pessimistic and optimistic assumptions, respectively, as summarized in table 4. As shown in table 5, the alternative capacity factor scenario assumptions yield changes of 5-8% in cumulative emissions, compared with the reference case. Table 5 illustrates that prolongation of system lifetimes can potentially reduce emissions significantly. Returning to the emissions trends depicted in figure 3, it can be noted that assuming longer lifetimes effectively reduces the contribution from repowering (red striped area in figure 3), but does not affect emissions that are caused by new capacity additions (blue solid area); an elimination of emissions caused by repowering thus determines an upper limit of the reductions that can be achieved through lifetime extensions.

Table 5. Results of sensitivity analysis: total cumulative GHG emissions results for BLUE Map and BLUE hi REN scenarios in 2030 and 2050. Reference case results are consistent with results reported in section 5. Results are in units of Gt CO_2-eq. Numbers in parentheses give relative change compared with reference.

	BLUE Map		**BLUE hi REN**	
	2030	2050	2030	2050
Low CF	1.1 (+5.0%)	2.5 (+6.7%)	1.6 (+4.7%)	3.7 (+6.4%)
Reference	1.1	2.3	1.5	3.5
Reference + Long LT	0.96 (-10%)	2.1 (-7.8%)	1.4 (-9.3%)	3.3 (-7.5%)
High CF	1.0 (-6.7%)	2.1 (-7.7%)	1.4 (-7.0%)	3.2 (-8.0%)
High CF + Long LT	0.90 (-16%)	2.0 (-15%)	1.3 (-16%)	3.0 (-15%)

7 Discussion and conclusions

The climate change impact indicator value of 22.5 g CO_2-eq/kWh for an onshore wind farm is comparatively high; other recent estimates for onshore wind farms consisting of multi-megawatt turbines are in the range of 5-16 g CO_2-eq/kWh [12-13, 28-29]. The estimated GHG intensity of 21.2 g CO_2-eq/kWh for offshore wind electricity (with assumed lifetime of 25 years) compares with 5 g CO_2/kWh in [12], 12 g CO_2-eq/kWh in [30], 22 g/kWh in [31], and 32-33 g/kWh in [32, 33] (generally assuming lifetimes of 20 years). Differences in results across studies may stem from differences in the types of wind power systems that are studied (e.g., offshore wind farms in either shallow [12] or deep [32, 33] waters), assumed values of key parameters (capacity factor and lifetime), background system characteristics (e.g., relatively dirty or clean manufacturing), and scope and methodologies (e.g., process-LCA or hybrid LCA) [33, 34].

We identify four factors that are of relevance when comparing the emission intensity estimates of this study with that of previous research. One, we assumed a relatively low average load of 23.6% for the onshore wind farm. Correspondingly, [12-13, 28-29] assume 30%, 23%, 33%, and 30%, respectively, for onshore wind electricity. Realized values during 2003-2007 have been estimated to average at 20.8% for Europe and 25.7% for the US [35]. Two, the lifetime of the offshore wind farm is set to 25 years in the present study, as opposed to the 20 years typically chosen in previous LCAs. Three, unlike most previous studies we employ a hybrid LCA methodology, thereby achieving a more complete system definition. In our analysis, which has a fairly simple physical foreground system, the IO background system generates 45% and 61%

(climate change), 51% and 47% (marine eutrophication), 67% and 66% (photochemical oxidant formation), and 46% and 55% (terrestrial acidification) of onshore and offshore total emissions, respectively. Finally, in the current study benefits of recycling are incorporated by having a mix of primary and secondary materials as inputs into materials production, instead of crediting the system with emissions that are perceived to be avoided through future recycling of materials contained in the system.

Considerable uncertainty exists in the results of the scenario analysis, among other reasons because of the long time frame considered. Hence, results of the scenario analysis should be interpreted with care. Some uncertainties relate to assumed values of input parameters – notably, capacity factors and lifetimes (cf. the sensitivity analysis). Uncertainties also arise from simplifications that were necessary for the scenario analysis. Two simplifications may be replaced by more sophisticated modeling in the future: One, technological improvements were captured only through a shift towards development in ocean waters, and an improved capacity factor. Technology foresight and evolutions studies based on current research and design work or learning curves studies may provide a better basis for modeling design changes. Two, the background economy modeled here changes only in terms of the energy mix it uses. Improvements in efficiency or increased effort to extract ever-more scarce resources are not taken into account. Also, for reasons of data availability, our model is skewed towards European technology, not fully mirroring a globalized production network.

Evaluating emission penalties due to intermittency is outside the scope of this article, but is nevertheless an important concern for wind power. High wind power penetration requires an upgrade in electricity infrastructure, may need to be supplemented by energy storage technologies, and may lead to altered operation of thermal and hydro power plants. Ideally, environmental implications of such effects are included in LCAs of wind power, yet this is not done in the extant literature. The exception is [31], whose results suggest additional CO_2 emissions from fossil-fired power stations of 18-70 g per kWh electricity from wind (assuming a wind electricity penetration of 12% in Germany in 2020) [31]. However, such results are inherently region-specific and sensitive to characteristics of the electricity systems.

Our quantification of emissions reductions due to increased use of wind power should be interpreted in light of the assumption that additional wind power in the BLUE Map scenario substitutes fossil power. The reason for making this assumption is to achieve consistency and comparability with IEA's own reported reductions from their baseline emission trend. Essentially, the quantifications of reduced emissions presented here are means to enhance understanding; they are not attempts to establish 'true' values for emissions savings from wind power as such. On average over the modeled time period, 725 g direct fossil CO_2 is reduced per additional kWh generated from wind energy, consistent with IEA's [2] reported contributions by wind power to CO_2 reductions in the BLUE Map scenario, relative to the baseline.

By one account [36], global CO_2 from fossil-fuel burning, cement production and land use in 2000-2049 should not exceed 1000 Gt, if we are to limit global warming to 2 °C above pre-industrial levels. With 320 Gt already emitted in 2000-2009 [37] the remaining budget for 2010-2049 is 680 Gt. In this perspective, emissions caused by wind power expansion may seem not insignificant, considering that they represent life cycle emissions of one technology only. Besides, the BLUE scenarios are unlikely to be consistent with the 2 °C target; thus even more wind electricity may be needed.

The present work advances current state of knowledge by aggregating unit-based findings to study economy-wide environmental costs and benefits of large-scale adoptions of wind power. Despite the real-world load factors and hybrid LCA methodology, and despite incorporating repowering of wind electricity systems as well as the temporal distribution of emissions in a scenario-based assessment, we find that emissions of wind power are low when contrasted with the emissions of fossil-based power. For climate change in particular, reduced emissions grossly exceed the emissions caused by wind power expansion. For the assessed impact categories, it appears that the true environmental benefits of wind power largely depend on the extent to which electricity from wind actually leads to a phase-out of fossil-based electricity without carbon capture.

Acknowledgment

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B.2 Supplementary data associated with paper II (published electronically in online version)

Content

- A: Supplementary accounts of methods and data
- B: Supplementary accounts of results

The supporting information contains 31 tables.

A Supplementary accounts of methods and data

A.1 IO sector classifications

Table S1 lists the economic sectors of the Europe-region of the input-output (IO) background system. Assumptions were made to disaggregate the original sector “Electricity, gas, steam and hot water supply (40)” into six sectors (sectors 32-37 in table S1), according to energy source.

Table S1. Sector classification of input-output background system (Europe region).

	Sector name
1	Agriculture, hunting and related service activities (01)'
2	'Forestry, logging and related service activities (02)'
3	'Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)'
4	'Mining of coal and lignite; extraction of peat (10)'
5	'Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying (11)'
6	'Mining of uranium and thorium ores (12)'
7	'Mining of metal ores (13)'
8	'Other mining and quarrying (14)'
9	'Manufacture of food products and beverages (15)'
10	'Manufacture of tobacco products (16)'
11	'Manufacture of textiles (17)'
12	'Manufacture of wearing apparel; dressing and dyeing of fur (18)'
13	'Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)'
14	'Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)'
15	'Manufacture of pulp, paper and paper products (21)'

16	'Publishing, printing and reproduction of recorded media (22)'
17	'Manufacture of coke, refined petroleum products and nuclear fuels (23)'
18	'Manufacture of chemicals and chemical products (24)'
19	'Manufacture of rubber and plastic products (25)'
20	'Manufacture of other non-metallic mineral products (26)'
21	'Manufacture of basic metals (27)'
22	'Manufacture of fabricated metal products, except machinery and equipment (28)'
23	'Manufacture of machinery and equipment n.e.c. (29)'
24	'Manufacture of office machinery and computers (30)'
25	'Manufacture of electrical machinery and apparatus n.e.c. (31)'
26	'Manufacture of radio, television and communication equipment and apparatus (32)'
27	'Manufacture of medical, precision and optical instruments, watches and clocks (33)'
28	'Manufacture of motor vehicles, trailers and semi-trailers (34)'
29	'Manufacture of other transport equipment (35)'
30	'Manufacture of furniture; manufacturing n.e.c. (36)'
31	'Recycling (37)'
32	Electricity, gas, steam and hot water supply from hard coal'
33	Electricity from nuclear power'
34	Electricity from natural gas'
35	Electricity from petroleum'
36	Electricity from hydro'
37	Electricity from wind'
38	'Collection, purification and distribution of water (41)'
39	'Construction (45)'
40	'Sale, maintenance and repair of motor vehicles and motorcycles; retail sale services of automotive fuel (50)'
41	'Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)'
42	'Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)'
43	'Hotels and restaurants (55)'
44	'Land transport; transport via pipelines (60)'
45	'Water transport (61)'
46	'Air transport (62)'
47	'Supporting and auxiliary transport activities; activities of travel agencies (63)'
48	'Post and telecommunications (64)'
49	'Financial intermediation, except insurance and pension funding (65)'
50	'Insurance and pension funding, except compulsory social security (66)'
51	'Activities auxiliary to financial intermediation (67)'
52	'Real estate activities (70)'
53	'Renting of machinery and equipment without operator and of personal and household goods (71)'
54	'Computer and related activities (72)'
55	'Research and development (73)'
56	'Other business activities (74)'
57	'Public administration and defence; compulsory social security (75)'
58	'Education (80)'
59	'Health and social work (85)'
60	'Sewage and refuse disposal, sanitation and similar activities (90)'
61	'Activities of membership organisation n.e.c. (91)'
62	'Recreational, cultural and sporting activities (92)'
63	'Other service activities (93)'
64	'Private households with employed persons (95)'

A.2 Life cycle inventories

Tables S2-S18 account for physical and monetary inventories for the onshore and offshore wind power systems. The monetary inventories are used to scale inputs from the IO background system to the foreground system (matrix A^{nf}; see also tables S19 and S20). For the onshore wind farm, total capital costs is 1250 Euro/MW, and variable costs 1.2 Eurocent/kWh (2007 prices). For the offshore wind farm, the corresponding numbers are 2200 Euro/kW and 1.6 Eurocent/kWh. In addition, we add costs for decommissioning (equal to costs of installation), assuming that decommissioning is excluded in the initial numbers (cf. section 3.5 in main article). All prices are in 2007 Euro (tables S2-S18).

Table S2. Inventories: product system

Product system summary			**1 kWh**
	Onshore	Offshore	
Foreground process inputs per kWh			
Wind turbine, misc.	9.69E-9	4.87E-9	unit
Rotor blades	9.69E-9	4.87E-9	unit
Hub, incl. nose cone	9.69E-9	4.87E-9	unit
Bed frame/plate	9.69E-9	4.87E-9	unit
Generator	9.69E-9	4.87E-9	unit
Gearbox	9.69E-9	4.87E-9	unit
Low-voltage transformer	9.69E-9	4.87E-9	unit
Nacelle other	9.69E-9	4.87E-9	unit
Tower	9.69E-9	4.87E-9	unit
Foundation	9.69E-9	4.87E-9	unit
Electrical collection system	4.88E-8	8.70E-8	t
High-voltage transformer	2.02E-10	4.87E-11	unit
Connection to grid	2.57E-7	2.45E-7	t
Installation	9.69E-9	4.87E-9	unit
Dismantling	9.69E-9	4.87E-9	unit
Operation and maintenance	9.69E-9	4.87E-9	unit
Other capital costs	1.68E-9	3.56E-9	10^6 Euro
Other variable costs	5.75E-9	4.38E-9	10^6 Euro

Comments

The electrical collection system consists of 22 kV cables, and connection to grid 132 kV cables (measured in metric tonnes of cable). Monetary inputs to the categories “Other capital costs” and “Other variable costs” are established from own evaluation of cost breakdowns presented in Blanco 2009, EWEA 2009, ODE 2007 and DWI 2002. “Other capital costs” and “Other variable costs” are modeled entirely in the IO background system.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- DWE. *Studie zur aktuellen Kostensituation 2002 der Windenergienutzung in Deutschland [Study of the costs of wind energy in 2002 in Germany]*; Deutsches Windenergie Institut: Germany, 2002; http://www.wind-

energie-de.
- EWEA. *The Economics of Wind Energy*; European Wind Energy Association: 2009; http://www.ewea.org.
- ODE. *Study on the costs of offshore wind generation. A report to the Renewables Advisory Board (RAB) & DTI*; Offshore Design Engineering; URN Number 07/779: UK, 2007.

Table S3. Inventories: wind turbine, misc.

Wind turbine, misc.			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Electricity	113391	113391	kWh
Heat, waste incineration	22388	22388	kWh
Heat, cogeneration	22388	22388	kWh
Gas *	12900	12900	kWh
Diesel oil *	39221	39221	kWh
Direct emissions			
CH_4	0.62	0.62	kg
CO_2	1.92E4	1.92E4	kg
N_2O	0.40	0.40	kg
NH_3	0.07	0.07	kg
NO_x	146	146	kg
CO	37.7	37.7	kg
NMVOC	17.1	17.1	kg
SO_x	3.36	3.36	kg

Comments

* Direct emissions from burning fossil fuels are accounted for in the emission intensity matrix F, while indirect (supply-chain) emissions are assumed to be covered by inputs from IO-background system.

“Wind turbine, misc.” should be interpreted as representing wind turbine assembly plus some unspecified manufacturing of wind turbine components (this concerns in particular the tower). Electricity, heat, gas, and oil use, as well as emissions of CO_2, are derived from reports published by the wind turbine manufacturer Vestas (as explained in the main manuscript). We do not distinguish the manufacturing of onshore wind turbines from offshore wind turbines. As is noted in the main article, numbers are adjusted to take into account towers supplied to Vestas (only around 20% of towers were manufactured in-house by Vestas). The adjustment causes energy use to increase by 3-10% from non-adjusted values.

Non-CO_2 emissions are estimated from consumption of gas and oil. The assumption is made that 50% of heat consumption comes from waste incineration, and 50% from cogeneration.

Sources
- *Vestas annual report 2009;* Vestas: 2010; http://www.vestas.com.
- *Vestas Towers, Rudkøbing. Environmental and occupational health & safety statement 2009*; Vestas: http://www.vestas.com.

Table S4. Inventories: rotor blades

Rotor blades	**1 unit**

	Onshore	Offshore	
Technosphere inputs			
Glass-reinforced plastics	20.56	20.56	t
IO background economy	0.536	0.536	10^6 Euro

Comments

The weight of the rotor blades is obtained from manufacturer product brochures (Vestas), as explained in the main manuscript. We assume the rotor blades are made of glass-reinforced plastics. Except for the tower, we do not distinguish onshore wind turbines from offshore wind turbines. Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.
- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.

Table S5. Inventories: hub, incl. nose cone

Hub, incl. nose cone			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Steel, low alloy	7.42	7.42	t
Cast iron	12.5	12.5	t
Glass-reinforced plastics	0.50	0.50	t
IO background economy	0.127	0.127	10^6 Euro

Comments

The weight of the hub is obtained from product brochures (Vestas). The source is not clear what exactly is included in the "hub". We make assumptions to disaggregate the total hub weight into steel, cast iron, and reinforced plastics portions. We assume the actual rotor hub, which serves the purpose of holding the blades in position, weighs 12.5 t and is made of cast iron. In addition come reinforced plastics for the nose cone. We model the remainder of the total hub weight as low-alloy steel. Except for the tower, we do not distinguish onshore wind turbines from offshore wind turbines. Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.
- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.

Table S6. Inventories: bed frame/plate

Bed frame/plate			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Steel, low alloy	5.87	5.87	t
Cast iron	10.6	10.6	t
IO background economy	0.068	0.068	10^6 Euro

Comments

Total nacelle weight is obtained from manufacturer product brochures (Vestas). The bed frame constitutes 23% of the nacelle in terms of weight (Martínez et al., 2009). Main frames can be cast iron or steel fabrications. We assume the main frame consists of cast iron (around 40%) and low-alloy steel (around 60%) parts. Except for the tower, we do not distinguish onshore wind turbines from offshore wind turbines. Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.
- Martínez, E.; Sanz, F.; Pellegrini, S.; Jiménez, E.; Blanco, J., Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int. J. Life Cycle Assess.* **2009,** *14*, (1), 52-63.

Table S7. Inventories: generator

Generator			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Silicon, metallurgical grade	0.31	0.31	t
Steel, low alloy	6.70	6.70	t
Copper	3.14	3.14	t
Wire drawing, copper	3.14	3.14	t
IO background economy	0.083	0.083	10^6 Euro

Comments

Total nacelle weight is obtained from manufacturer product brochures (Vestas). The generator constitutes 14% of the nacelle in terms of weight, and is made from electrical steel (modeled as silicon plus low-alloy steel) and copper (Martínez et al., 2009). We add wire drawing for copper content in the generator. Except for the tower, we do not distinguish onshore wind turbines from offshore wind turbines. Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.
- Martínez, E.; Sanz, F.; Pellegrini, S.; Jiménez, E.; Blanco, J., Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int. J. Life Cycle Assess.* **2009,** *14*, (1), 52-63.

Table S8. Inventories: gearbox

Gearbox			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Steel, high alloy (chromium)	12.56	12.56	t
Cast iron	12.56	12.56	t
IO background economy	0.312	0.312	10^6 Euro

Comments

Total nacelle weight is obtained from manufacturer product brochures (Vestas). The gearbox constitutes 35% of the nacelle in terms of weight, and is made from equal amounts of cast iron and high-alloy steel. Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.

Table S9. Inventories: low-voltage transformer

Low-voltage transformer			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Silicon, metallurgical grade	0.24	0.24	t
Steel, low alloy	5.18	5.18	t
Copper	2.36	2.36	t
Wire drawing, copper	2.36	2.36	t
IO background economy	0.087	0.087	10^6 Euro

Comments

Total nacelle weight is obtained from manufacturer product brochures (Vestas). The transformer constitutes 11% of the nacelle in terms of weight, and is made electrical steel (modeled as silicon plus low-alloy steel) and copper (Martínez et al., 2009). Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.
- Martínez, E.; Sanz, F.; Pellegrini, S.; Jiménez, E.; Blanco, J., Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int. J. Life Cycle Assess.* **2009,** *14*, (1), 52-63.

Table S10. Inventories: nacelle, other

Nacelle, other			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Steel, low alloy	1.44	1.44	t
Steel, high alloy (chromium)	8.14	8.14	t
Glass-reinforced plastics	3.14	3.14	t
IO background economy	0.287	0.287	10^6 Euro

Comments

Total nacelle weight is obtained from manufacturer product brochures (Vestas). “Nacelle, other” represents the main shaft plus the nacelle cover. Again, we adopt relative weight shares by component from (Martínez et al., 2009). The main shaft is expected to be made of high-grade steel or iron. We use a mix of 85% chromium steel (high alloy) and 15% low-alloy steel to model the main shaft. The nacelle cover is modeled as reinforced plastics. Monetary inputs are derived from cost distributions presented in Blanco 2009.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- *Product brochures V80-2.0MW and V90-3.0MW*; Vestas: http://www.vestas.com.
- Martínez, E.; Sanz, F.; Pellegrini, S.; Jiménez, E.; Blanco, J., Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int. J. Life Cycle Assess.* **2009,** *14*, (1), 52-63.

Table S11. Inventories: tower

Tower			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Steel, low alloy	196	130	t
Sheet rolling, steel	196	130	t
IO background economy	0.635	0.422	10^6 Euro

Comments

The tower mass is 78 t/MW for onshore (hub height 105 m), for offshore it is 52 t/MW (hub height 80 m), consistent with tower weights used in an LCA by Vestas (2006).We add sheet rolling for steel content in the tower. Monetary inputs are derived from cost distributions presented in Blanco 2009. The cost of the offshore tower is lower due to lower hub height (starting with the cost of an onshore tower, we scale costs for the offshore tower in proportion to the tower mass). The extension of the tower below surface is modeled as part of the substructure (Table S12).

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- *Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines*; Vestas: 2006; http://www.vestas.com.

Table S12. Inventories: substructure

Foundation			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Concrete	970		t
Steel, reinforcing	30		t
Steel, low alloy		300	t
Aluminum		2.5	t
IO background economy	0.203	1.02	10^6 Euro

Comments

We model onshore gravity-based foundations made of reinforced concrete, and offshore substructures made of steel (water depth approximately 20 m). Assumptions for foundation weights (1000 t onshore and 300 t offshore) are made based on an overall evaluation of numbers reported in different sources (Onshore: Vestas, 2006; Ecoinvent, 2007; Martínez et al., 2009; Ardente et al, 2009. Offshore: Vestas, 2006; Ecoinvent, 2007; Crown Estate, 2009; Talisman Energy, 2005). Submarine foundations have galvanic anodes (modeled as 2.5 t aluminum) to prevent corrosion. Monetary inputs are derived from cost distributions presented in Blanco 2009, EWEA 2009 and ODE 2007.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- EWEA. *The Economics of Wind Energy*; European Wind Energy Association: 2009; http://www.ewea.org.
- ODE. *Study on the costs of offshore wind generation. A report to the Renewables Advisory Board (RAB) & DTI*; Offshore Design Engineering; URN Number 07/779: UK, 2007.
- *Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines*; Vestas: 2006; http://www.vestas.com.
- *Life cycle inventory database v2.1*; Ecoinvent; Swiss Centre for Life Cycle Inventories: 2007; http://www.ecoinvent.ch/.

- Martínez, E.; Sanz, F.; Pellegrini, S.; Jiménez, E.; Blanco, J., Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int. J. Life Cycle Assess.* **2009,** *14*, (1), 52-63.
- Ardente, F.; Beccali, M.; Cellura, M.; Lo Brano, V., Energy performances and life cycle assessment of an Italian wind farm. *Renew. Sust. Energ. Rev.* **2008,** *12*, (1), 200-217.
- Crown Estate. *A guide to an offshore wind farm. Published on behalf of The Crown Estate; Crown Estate: 2009;* http://www.thecrownestate.co.uk/guide_to_offshore_windfarm.pdf
- Talisman Energy. *Beatrice Wind Farm Demonstrator Project. Environmental Statement;* Talisman Energy: 2005; http://www.beatricewind.co.uk/environmental_statement.pdf

Table S13. Inventories: electrical collection system (internal cables)

Electrical collection system (internal cables)			**1 t**
	Onshore	Offshore	
Technosphere inputs			
Copper	0.43	0.22	t
Lead		0.19	t
Steel, low alloy		0.46	t
Zinc coating (galvanizing)		28.8	m^2
Electricity	1116	1116	kWh
Gas *	213	213	kWh
IO background economy	9.32E-3	3.56E-3	10^6 Euro
Direct emissions			
CH_4	1.5	1.5	g
CO_2	4.28E4	4.28E4	g
N_2O	0.07	0.07	g
NH_3	0	0	g
NO_x	13.7	13.7	g
CO	1.6	1.6	g
NMVOC	0	0	g
SO_x	0.42	0.42	g

Comments

* Direct emissions from burning fossil fuels are accounted for in the emission intensity matrix F, while indirect (supply-chain) emissions are assumed to be covered by inputs from IO-background system.

Onshore cable: Data source for the material inventories for the onshore cable is Parker Scanrope AS (2008). The cable has total mass 5.03 t/km. In addition to copper (43% of total weight), the cable also contains HDPE sheets (31% of total weight), XLPE (18%), and filler yarns (8%). These materials are not modeled in the LCA database system, but are assumed to be covered by inputs from the IO background system. Steel armoring is assumed not to be required onshore.

Offshore cable: Data sources for the material inventories for the offshore cables are Parker Scanrope AS (2008) and NEEDS (2008). We assume steel armoring is galvanized steel. We take the average of the material needs reported by the two sources to arrive at a hypothetical cable with a total mass of 18 t/km. In addition to metals (around 73% of total weight), the cables contain HDPE, XLPE, and filler yarns. These materials are not modeled in LCA database system, but are assumed to be covered by inputs from the IO background system. Crown Estate (2009) states that the mass of a typical cable used in electrical collection systems of offshore wind farms is around 20 t/km.

Monetary inputs are derived from cost distributions presented in Blanco 2009, EWEA 2009 and ODE 2007. The numbers on energy use obtained from ABB (2008).

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- EWEA. *The Economics of Wind Energy*; European Wind Energy Association: 2009; http://www.ewea.org.
- ODE. *Study on the costs of offshore wind generation. A report to the Renewables Advisory Board (RAB) & DTI*; Offshore Design Engineering; URN Number 07/779: UK, 2007.
- *Technical specifications of 5 MW, 22kV, 70 mm^2 copper conductor*; Parker Scanrope AS (http:/www.scanrope.no); 2008; Personal communication.
- *Life cycle approaches to assess emerging energy technologies. Final report on offshore wind technology*; New Energy Externalities Development for Sustainability consortium (NEEDS): 2008; http://www.needs-project.org
- *A guide to an offshore wind farm. Published on behalf of The Crown Estate; Crown Estate: 2009;* http://www.thecrownestate.co.uk/guide_to_offshore_windfarm.pdf
- *Miljörapport för år 2007 [Environmental report 2007];* ABB, High Voltage Cables: Sweden, 2008.

Table S14. Inventories: high-voltage transformer

High-voltage transformer			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Steel, low alloy	65.8	410	t
Copper	14.5	24.2	t
Aluminum	1.19	3.3	t
Silicon, metallurgical grade	1.77	2.96	t
Electricity	7.01E4	1.17E5	kWh
Gas *	2.98E5	4.97E5	kWh
IO background economy	1.44	21.5	10^6 Euro
Direct emissions			
CH_4	2147	3578	g
CO_2	6.01E7	1.00E8	g
N_2O	107.3	178.9	g
NH_3	0	0	g
NO_x	1.92E4	3.20E4	g
CO	2254	3757	g
NMVOC	0	0	g
SO_x	590.4	983.9	g

Comments

* Direct emissions from burning fossil fuels are accounted for in the emission intensity matrix F, while indirect (supply-chain) emissions are assumed to be covered by inputs from IO-background system.

The transformer capacity is 150 MVA for the onshore wind farm, for the offshore wind farm it is 250 MW. Inventories are scaled according to the capacity. Electrical steel is modeled as silicon plus low-alloy steel. Monetary inputs are derived from cost distributions presented in Blanco 2009, EWEA 2009 and ODE 2007.

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- EWEA. *The Economics of Wind Energy*; European Wind Energy Association: 2009; http://www.ewea.org.
- ODE. *Study on the costs of offshore wind generation. A report to the Renewables Advisory Board (RAB) & DTI*; Offshore Design Engineering; URN Number 07/779: UK, 2007.
- *Environmental product declaration. Power transformer 250 MVA* ; ABB: 2003; http://www.abb.com.

Table S15. Inventories: connection to grid (external cables)

Connection to grid (external cables)			**1 t**
	Onshore	Offshore	
Technosphere inputs			
Copper	0.24	0.28	t
Steel, low alloy	0	0.27	t
Lead	0.39	0.29	t
Zinc coating (galvanizing)		8.2	m^2
Electricity	1116	1116	kWh
Gas [*]	213	213	kWh
IO background economy	0.009	0.013	10^6 Euro
Direct emissions			
CH_4	1.5	1.5	g
CO_2	4.28E4	4.28E4	g
N_2O	0.07	0.07	g
NH_3	0	0	g
NO_x	13.7	13.7	g
CO	1.6	1.6	g
NMVOC	0	0	g
SO_x	0.42	0.42	g

Comments

[*] Direct emissions from burning fossil fuels are accounted for in the emission intensity matrix F, while indirect (supply-chain) emissions are assumed to be covered by inputs from IO-background system.

Onshore cable: Data source for the material inventories for the onshore cable is Eltra (1999). The total cable weight is 36.1 t/km. We add zinc coating (galvanizing). In addition to metals, the cables also contain paper (11% of total weight), insulation oil (11% onshore), and miscellaneous (7% onshore). These materials are not modeled in Ecoinvent, but are assumed to be covered by inputs from the IO background system.

Offshore cable: Data source for the material inventories for the onshore cable is NEEDS (2008) (132 kV steel-armored cable). The total cable weight is 67 t/km. According to the source, in addition to metals, the cable also contains HDPE sheets. Crown Estate (2009) states that the mass of a typical cable used in transmission to shore is around 60 t/km.

Monetary inputs are derived from cost distributions presented in Blanco 2009, EWEA 2009 and ODE 2007. The numbers on energy use obtained from ABB (2008).

Sources

- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- EWEA. *The Economics of Wind Energy*; European Wind Energy Association: 2009; http://www.ewea.org.

- ODE. *Study on the costs of offshore wind generation. A report to the Renewables Advisory Board (RAB) & DTI*; Offshore Design Engineering; URN Number 07/779: UK, 2007.
- *Miljörapport för år 2007 [Environmental report 2007];* ABB, High Voltage Cables: Sweden, 2008.
- *Ressourceoppgørelse for 132/150 kV oliekabel [Resource account for 132/150 kV oi-filled cable]*; Doc nr. 50810; Eltra: Denmark, 1999.
- *Life cycle approaches to assess emerging energy technologies. Final report on offshore wind technology*; New Energy Externalities Development for Sustainability consortium (NEEDS): 2008; http://www.needs-project.org
- *A guide to an offshore wind farm. Published on behalf of The Crown Estate; Crown Estate: 2009;* http://www.thecrownestate.co.uk/guide_to_offshore_windfarm.pdf

Table S16. Inventories: installation

Installation			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Diesel, on-site activities [*]	6042	37912	kWh
Transport passenger (pilot) car [*]	6000	6000	km
Transport lorry (32 t capacity) [*]	8000	8000	km
Transport lorry (16 t capacity) [*]	200	1000	km
Transport barge [*]		18400	tkm
IO background economy	0.163	1.02	10^6 Euro
Direct emissions			
CH_4	0.66	0.80	kg
CO_2	8011	1.15E4	kg
N_2O	0.30	13.0	kg
NH_3	0.07	0.07	kg
NO_x	78.4	2395	kg
CO	15.9	23.7	kg
NMVOC	2.23	6.08	kg
SO_x	0.38	1.20	kg

Comments

[*] Direct emissions from burning fossil fuels are accounted for in the emission intensity matrix F, while indirect (supply-chain) emissions are assumed to be covered by inputs from IO-background system.

Diesel consumption for on-site activities for an onshore wind farm comes from reported measured data (Ardente et al. 2008). We convert reported life cycle energy to direct energy equivalent. When shifting to offshore sites, it is assumed that on-site diesel consumption scale proportional to the installation costs. Monetary inputs are derived from cost distributions presented in Blanco 2009, EWEA 2009 and ODE 2007.

Sources

- Ardente, F.; Beccali, M.; Cellura, M.; Lo Brano, V., Energy performances and life cycle assessment of an Italian wind farm. *Renew. Sust. Energ. Rev.* **2008,** *12*, (1), 200-217.
- Blanco, M. I., The economics of wind energy. *Renew. Sust. Energ. Rev.* **2009,** *13*, (6-7), 1372-1382.
- EWEA. *The Economics of Wind Energy*; European Wind Energy Association: 2009; http://www.ewea.org.
- ODE. *Study on the costs of offshore wind generation. A report to the Renewables Advisory Board (RAB) & DTI*; Offshore Design Engineering; URN Number 07/779: UK, 2007.

Table S17. Inventories: operation and maintenance

Operation and maintenance			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Gearbox replacement	0.5	0.7	unit
Diesel, inspections (passenger car) *	2500	3125	kg
Operation, helicopter *		100	h
Transport lorry (16 t capacity) *	600	600	km
Transport barge *		380	tkm
IO background economy	0.319	1.664	10^6 Euro
Direct emissions			
CH_4	0.11	0.15	kg
CO_2	7793	1.64E4	kg
N_2O	0.30	0.37	kg
NH_3	0.20	0.25	kg
NO_x	29.3	36.5	kg
CO	6.57	8.32	kg
NMVOC	0.99	1.22	kg
SO_x	0.25	17.2	kg

Comments

* Direct emissions from burning fossil fuels are accounted for in the emission intensity matrix F, while indirect (supply-chain) emissions are assumed to be covered by inputs from IO-background system.

We adopt the assumption of Ardente et al. 2008 that around 50 kg of diesel will be consumed per year per MW for inspections by car, and the assumption of NEEDS (2008) that 4 hours of helicopter operation is required per year of operation of each offshore wind turbine.

Monetary inputs are derived from cost distributions presented in Blanco 2009, EWEA 2009 and DWE 2002.

Sources

- DWE. *Studie zur aktuellen Kostensituation 2002 der Windenergienutzung in Deutschland [Study of the costs of wind energy in 2002 in Germany]*; Deutsches Windenergie Institut: Germany, 2002; http://www.wind-energie-de.
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Table S18. Inventories: decommissioning

Decommissioning			**1 unit**
	Onshore	Offshore	
Technosphere inputs			
Same inputs as for installation (table S16), plus:			
Disposal, glass, municipal incineration	7.87	7.87	kg
Disposal, plastics, mixture, municipal incineration	4.26	4.26	kg

Direct emissions
Same as for installation (table S16)

Comments
Demolition is modeled as identical to installation. Composite materials in the rotor blades and nacelle are assumed to be 50% incinerated and 50% recycled. For the incineration of the composite materials, we assume shares of 35% plastics and 65% glass.

Tables S19 and S20 provide key numbers that are used to link the foreground system with the input-output background system (that is, to construct matrix A^{nf}). The upper panels give the cost shares apportioned to each of the foreground processes; the center panels specify which IO sectors are used to represent the specific foreground processes (the foreground processes are assigned the same input distributions as their belonging IO sectors); and the lower panels specify inputs from the IO background system that are removed to avoid double counting.

Table S19. Key characteristics of linking of onshore wind power foreground system with IO background system: Cost breakdown for foreground processes (% of total cost per kWh generated) (upper panel); IO sectors used to represent foreground processes (%) (center panel); and inputs from IO sectors that are set to zero to avoid double counting (lower panel).

	Rotor blades	**Hub, incl. nose cone**	**Bed frame/ plate**	**Generator**	**Gearbox**	**LV transformer**	**Nacelle other**	**Tower**	**Foundation**	**Electrical collection system**	**HV transformer**	**Connection to grid**	**Installation**	**Decommissioning**	**Operation and maintenance**	**Other capital costs**	**Other variable costs**
Share of absolute costs per kWh (%)																	
	12.5	2.9	1.6	1.9	7.2	2.0	6.7	14.8	4.7	1.1	0.7	8.0	3.8	3.8	7.5	4.7	16.1
IO sectors used to represent foreground processes (%)																	
Manufacture of rubber and plastic products	90						25										
Manufacture of other non-metallic mineral products									30								
Fabricated metal products, except machinery and equipment		95	100				10	100									
Machinery and equipment	10			50	100	20	30										
Electrical machinery and apparatus		5		50		80	35			100	100	100			75		
Construction									70				100	100	25	10	
Insurance and pension funding services, except compulsory social security services																	10
Computer and related services																	20
Research and development services																45	
Other business services																45	70
Purchases from IO sectors that are set to zero (0 indicates purchase is set to zero)																	
Rubber and plastic products	0						0										
Manufacture of other non-metallic mineral products	0						0		0								
Manufacture of basic metals		0	0	0	0	0	0	0	0	0	0	0			0		
Electricity	0	0	0	0	0	0	0	0		0	0	0					

Table S20. Key characteristics of linking of offshore wind power foreground system with IO background system: Cost breakdown for foreground processes (% of total cost per kWh generated) (upper panel); IO sectors used to represent foreground processes (%) (center panel); and inputs from IO sectors that are set to zero to avoid double counting (lower panel).

	Rotor blades	Hub, incl. nose cone	Bed frame/ plate	Generator	Gearbox	LV transformer	Nacelle other	Tower	Foundation	Electrical collection system	HV transformer	Connection to grid	Installation	Decommissioning	Operation and maintenance	Other capital costs	Other variable costs
Share of absolute costs per kWh (%)																	
	5.8	1.4	0.7	0.9	3.4	0.9	3.1	4.6	11.1	0.7	2.3	5.1	11.1	11.1	17.8	8.7	11.4
IO sectors used to represent foreground processes (%)																	
Manufacture of rubber and plastic products	90						25										
Manufacture of other non-metallic mineral products																	
Fabricated metal products, except machinery and equipment		95	100				10	100	100		50						
Machinery and equipment	10			50	100	20	30										
Electrical machinery and apparatus		5		50		80	35			100	50	100			75		
Construction													100	100	25	10	
Insurance and pension funding services, except compulsory social security services																	10
Computer and related services																	20
Research and development services																45	
Other business services																45	70
Purchases from IO sectors that are set to zero (0 indicates purchase is set to zero)																	
Rubber and plastic products	0						0										
Manufacture of other non-metallic mineral products	0						0										
Manufacture of basic metals		0	0	0	0	0	0	0	0	0	0	0			0		
Electricity	0	0	0	0	0	0	0	0		0	0	0					

A.3 Scenario modeling

Shown in table S21 is the global electricity supply mix in 2007, 2030 and 2050 used in the scenario analysis. The BLUE Map and BLUE hi REN scenarios are investigated in the current study.

Table S21. Global electricity supply by source and scenario in 2007, 2030 and 2050 (IEA 2010). *For the BLUE hi REN scenario, only 2007 and 2050 values are given; linear interpolation has been used here to establish values for the year 2030. Source: IEA, 2010. International Energy Agency. *Energy Technology Perspectives 2010*. Paris.

	2007	**Baseline 2030**	**Baseline 2050**	**BLUE Map 2030**	**BLUE Map 2050**	**BLUE hi REN 2030**	**BLUE hi REN 2050**
Nuclear (%)	13.8	10.7	10.5	19.2	23.9	12.3*	11.6
Oil (%)	5.7	1.9	0.7	2.6	0.6	2.1*	0.5
Coal (%)	41.6	44.5	44.5	18.2	0.6	13.6*	0.9
Coal + CCS (%)	0.0	0.0	0.0	5.2	11.8	1.7*	2.4
Gas (%)	20.9	20.6	22.6	13.7	10.7	12.0*	7.9
Gas + CCS (%)	0.0	0.0	0.0	0.8	4.5	1.4*	2.0
Hydro (%)	15.6	13.6	11.6	17.6	14.3	15.9*	16.0
Biomass/waste (%)	1.3	2.4	2.7	6.4	5.4	4.9*	6.6
Biomass + CCS (%)	0.0	0.0	0.0	0.3	0.8	0.3*	0.4
Geothermal (%)	0.3	0.5	0.6	1.1	2.5	2.7*	3.7
Wind (%)	0.9	4.5	4.7	10.5	12.2	15.2*	21.8
Ocean (%)	0.0	0.0	0.1	0.2	0.3	1.0*	1.5
Solar (%)	0.0	1.2	2.0	4.2	12.4	16.9*	24.6
Total production (TWh)	19756	34286	45970	27993	40135	29330*	37656

Table S22 shows K_{new}, K_{repow} and K_{oper} values used in the scenario analysis (see section 4 in main article for an explanation of the variables). The end-of-period K_{oper} values shown in the table S22 are slightly lower than corresponding values in table 3 in the main article because K_{oper} represents mid-year values, whereas capacity values shown in table 3 are measured at the end of the year. Comparing BLUE Map scenario values in table S22 and table 3 (main article), it can be observed, for example, that $96.3 + 45 \cdot (2030-2008+1) = 1131$, where 96.3 GW is the end-of-year total wind power capacity in 2007 (table 3), 45 GW/year is the total newly added capacity annually in 2008-2030 (table S22), and 1131 GW is approximately the total installed capacity at the end of 2030 (table 3) (a small deviation occurs due to rounding off in table 3 and table S22). Similar relationships hold for BLUE hi REN scenario values, for the period 2031-2050, and for separate onshore and offshore capacity values also.

Table S22. Values for K_{new}, K_{repow} and K_{oper} used in BLUE Map and BLUE hi REN scenario analysis.

	Onshore			Offshore			Total		
	2007	2008-2030	2031-2050	2007	2008-2030	2031-2050	2007	2008-2030	2031-2050
BLUE Map									
K_{new} (GW/year)	22	36	19	0.7	9.2	11	22	45	30
K_{repow} (GW/year)	0	8.5	36	0	0	8.4	0	8.5	44
K_{oper}, end-of-period value (GW)	84	902	1284	1.3	210	438	85	1111	1722
BLUE hi REN									
K_{new} (GW/year)	22	56	38	0.7	14	21	22	69	59
K_{repow} (GW/year)	0	11	56	0	0	12	0	11	68
K_{oper}, end-of-period value (GW)	84	1344	2118	1.3	313	722	85	1656	2840

B Supplementary accounts of results

Table S23 and table S24 show, for the onshore and offshore wind farm, respectively, breakdowns of emissions by main categories. The results are the same as shown in figure 1 in the main article, with the wind turbine category in figure 1 disaggregated into nine sub-categories in tables S23 and S24. Offshore wind power systems are more resource demanding than their onshore counterparts. For greenhouse gas emissions, the gains in wind load factor and lifetime when shifting to offshore locations outweigh emissions incurred by higher resource requirements. In the other impact categories, the onshore wind power system exhibits the lowest impact indicator values.

The higher emissions shares of installation and decommissioning for the offshore wind farm, compared with the onshore wind farm, stem in part from emissions from diesel burning in transportation and construction activities offshore, and in part from the offshore wind power system having higher inputs from the input-output background system. Because copper use drives up the impact potentials in the terrestrial acidification impact category, cabling contributes more to acidification impact potentials than to other impact indicators. It can be noted that the current data situation in the Ecoinvent LCA database for composite materials is unsatisfactory, leading to uncertain results for the rotor blades.

Table S24. Results of unit-based analysis for onshore wind farm: emissions and impact indicator values per functional unit by category.

	CH_4	CO_2	N_2O	NH_3	NO_x	CO	NMVOC	SO_x	Climate change	Marine eutrophication	Photochemical oxidant formation	Terrestrial acidification
Wind turbine, misc. (%)	1.9	4.5	0.9	0.4	4.4	0.2	0.5	2.9	4.2	4.3	2.4	3.1
Rotor blades (%)	21.7	13.7	24.4	17.1	12.6	10.9	16.5	11.1	14.7	12.7	13.9	11.9
Hub, incl. nose cone (%)	2.9	2.7	2.3	1.8	2.6	3.7	2.5	2.1	2.7	2.6	2.6	2.2
Bed frame/plate (%)	1.8	1.8	1.2	1.1	1.6	2.5	1.4	1.3	1.8	1.6	1.6	1.4
Generator (%)	1.7	2.2	2.0	4.1	2.9	2.3	2.0	5.8	2.1	2.9	2.6	4.9
Gearbox (%)	6.1	6.7	6.4	4.1	7.2	9.2	6.9	6.9	6.6	7.1	7.2	6.8
LV transformer (%)	1.5	1.8	1.9	3.3	2.4	2.0	1.9	4.5	1.8	2.4	2.3	3.8
Nacelle other (%)	6.3	5.7	8.2	6.6	5.7	7.5	6.3	5.5	5.8	5.7	6.1	5.6
Tower (%)	21.6	24.7	11.2	12.3	20.7	28.4	14.0	17.4	24.1	20.6	18.7	18.0
Foundation (%)	7.3	10.4	5.1	5.7	8.0	6.2	7.7	5.0	10.0	8.0	7.6	5.9
Electrical collection system (%)	0.6	0.8	1.0	2.5	1.3	0.8	1.0	3.3	0.8	1.3	1.2	2.7
HV transformer (%)	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.8	0.5	0.6	0.6	0.7
Connection to grid (%)	4.6	5.4	7.1	13.1	8.1	5.8	7.0	17.7	5.4	8.2	7.9	14.8
Installation (%)	3.2	3.5	4.5	3.8	4.6	3.8	6.3	2.7	3.5	4.6	5.1	3.3
Decommissioning (%)	3.2	3.5	4.5	3.8	4.6	3.8	6.3	2.7	3.5	4.6	5.1	3.3
Operation and maintenance (%)	5.6	6.3	6.7	5.1	6.3	6.4	7.7	5.4	6.2	6.3	6.8	5.6
Other capital costs (%)	2.7	1.7	3.5	4.3	2.0	1.9	3.6	1.6	1.9	2.0	2.5	1.9
Other variable costs (%)	6.9	3.9	8.3	10.2	4.6	4.0	8.0	3.5	4.2	4.7	5.8	4.2
Total (CO_2 and climate change: g/kWh; Other: g/MWh)	77.0	19.9	2.2	3.2	61.0	259.2	48.3	80.6	22.5	24.0	128.4	122.6

Table S24. Results of unit-based analysis for offshore wind farm: emissions and impact indicator values per functional unit by category.

	CH_4	CO_2	N_2O	NH_3	NO_x	CO	NMVOC	SO_x	Climate change	Marine eutrophication	Photochemical oxidant formation	Terrestrial acidification
Wind turbine, misc. (%)	1.0	2.4	0.4	0.2	1.6	0.1	0.2	1.5	2.2	1.6	1.0	1.5
Rotor blades (%)	11.5	7.4	11.2	8.7	4.7	5.0	7.1	5.9	7.9	4.8	5.7	5.7
Hub, incl. nose cone (%)	1.5	1.5	1.1	0.9	1.0	1.7	1.1	1.1	1.5	1.0	1.1	1.1
Bed frame/plate (%)	0.9	1.0	0.6	0.6	0.6	1.2	0.6	0.7	0.9	0.6	0.7	0.7
Generator (%)	0.9	1.2	0.9	2.1	1.1	1.1	0.9	3.1	1.1	1.1	1.1	2.3
Gearbox (%)	3.2	3.6	2.9	2.1	2.7	4.2	3.0	3.7	3.5	2.7	3.0	3.2
LV transformer (%)	0.8	1.0	0.9	1.7	0.9	0.9	0.8	2.4	1.0	0.9	0.9	1.8
Nacelle other (%)	3.3	3.1	3.7	3.4	2.1	3.5	2.7	2.9	3.1	2.1	2.5	2.7
Tower (%)	7.6	8.8	3.4	4.1	5.2	8.7	4.0	6.2	8.5	5.2	5.1	5.7
Foundation (%)	18.0	21.2	9.9	9.6	12.5	25.4	10.7	16.9	20.5	12.4	13.1	14.9
Electrical collection system (%)	1.0	1.4	0.8	2.6	1.2	0.9	0.7	3.9	1.3	1.2	1.1	2.9
HV transformer (%)	1.3	1.2	1.6	1.3	1.0	1.7	1.7	1.3	1.2	1.0	1.3	1.2
Connection to grid (%)	4.0	4.9	4.6	10.1	4.8	4.2	4.3	14.6	4.8	4.8	4.9	10.9
Installation (%)	10.6	10.8	15.4	12.2	22.9	11.0	17.0	8.9	11.0	22.8	19.2	14.0
Decommissioning (%)	10.6	10.8	15.4	12.2	22.9	11.0	17.0	8.9	11.0	22.8	19.2	14.0
Operation and maintenance (%)	12.5	12.9	15.0	12.1	9.4	13.2	16.6	11.8	12.9	9.4	12.4	11.0
Other capital costs (%)	5.6	3.7	6.4	8.6	2.9	3.5	6.1	3.4	3.9	3.0	4.1	3.5
Other variable costs (%)	5.5	3.1	5.8	7.8	2.6	2.8	5.3	2.8	3.4	2.7	3.6	3.1
Total (CO_2 and climate change: g/kWh; Other: g/MWh)	73.1	18.7	2.4	3.1	81.5	282.2	55.8	75.9	21.2	32.0	157.1	129.3

Table S25. Results of unit-based analysis for onshore wind farm: emissions and impact indicator values per functional unit by main emissions source. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification.

	CH_4	**CO_2**	**N_2O**	**NH_3**	**NO_x**	**CO**	**NMVOC**	**SO_x**	**CC**	**ME**	**POF**	**TA**
Manuf. metals and metal products (%)	0.34	21.5	1.9	1.0	9.5	62.4	6.7	30.4	19.2	9.4	14.3	22.7
Manuf. machinery and apparatus (%)	0.1	3.1	0.7	0.3	3.7	1.0	2.1	1.4	2.7	3.6	2.7	2.0
Electricity and steam supply (%)	2.1	31.2	7.2	0.6	17.2	1.8	0.7	34.4	28.0	17.0	10.4	27.5
Mining and extraction of raw materials (%)	63.5	12.2	9.3	12.7	16.6	7.4	40.1	8.6	16.5	16.6	24.5	11.1
Manuf. non-metallic mineral products (%)	0.3	12.0	13.5	1.7	7.0	4.0	6.1	4.8	11.0	7.0	6.2	5.2
Transport (%)	1.0	6.5	3.2	1.0	23.3	9.1	4.9	7.2	6.0	23.0	14.1	11.3
Construction (%)	0.0	1.5	0.6	0.1	5.3	0.5	2.0	0.1	1.4	5.2	3.3	1.5
Other (%)	32.7	12.0	63.7	82.6	17.4	13.7	37.5	13.1	15.2	18.2	24.5	18.7
Total (CO_2 and CC: g/kWh; Other: g/MWh)	77.0	19.9	2.2	3.2	61.0	259.2	48.3	80.6	22.5	24.0	128.4	122.6

Table S26. Results of unit-based analysis for offshore wind farm: emissions and impact indicator values per functional unit by main emissions source. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification.

	CH_4	**CO_2**	**N_2O**	**NH_3**	**NO_x**	**CO**	**NMVOC**	**SO_x**	**CC**	**ME**	**POF**	**TA**
Manuf. metals and metal products (%)	0.40	20.4	2.0	1.2	6.4	62.0	6.1	25.0	18.1	6.4	11.5	17.0
Manuf. machinery and apparatus (%)	0.0	2.4	0.6	0.3	1.7	0.8	1.6	1.2	2.1	1.7	1.6	1.3
Electricity and steam supply (%)	2.8	32.9	6.8	0.8	12.8	1.9	0.7	38.7	29.4	12.7	8.5	27.3
Mining and extraction of raw materials (%)	60.0	9.5	5.2	9.4	10.9	7.1	39.1	6.9	13.7	10.9	20.7	8.5
Manuf. non-metallic mineral products (%)	0.5	13.4	16.0	1.7	6.9	4.6	6.8	7.6	12.3	6.8	6.6	7.0
Transport (%)	1.2	6.9	4.0	0.9	22.5	9.0	4.4	7.6	6.3	22.3	14.3	12.4
Construction (%)	0.0	1.6	4.8	0.1	26.1	0.5	2.8	0.1	1.5	25.9	14.6	9.3
Other (%)	35.0	12.9	60.7	85.6	12.7	14.2	38.5	13.0	16.4	13.3	22.1	17.2
Total (CO_2 and CC: g/kWh; Other: g/MWh)	73.1	18.7	2.4	3.1	81.5	282.2	55.8	75.9	21.2	32.0	157.1	129.3

Shown in tables S25 and S26 are emissions by source (cf. figure 2 in main article). CO_2 is the dominant contributor to climate change impact indicator values (around 90%). Nearly all marine eutrophication impact potentials are due to emissions of NO_x, with a small contribution from NH_3. SO_x causes the bulk of acidification impact potentials (50-60%), but NO_x also contributes significantly. Emissions in the photochemical oxidant formation category are for the most part caused by NO_x and NMVOC.

Table S27. Impact indicator values by system of origin (%) for onshore and offshore wind power systems. ROW = Rest of the world. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification**.**

	Onshore				**Offshore**			
	CC	ME	POF	TA	CC	ME	POF	TA
Foreground	2.0	5.2	2.7	1.5	1.7	30.7	16.2	11.1
IO background (Europe)	27.0	24.8	23.8	21.4	39.5	24.6	25.4	27.0
IO background (ROW)	17.6	26.2	42.8	25.0	21.6	22.4	40.9	27.5
LCA database	53.4	43.7	30.7	52.1	37.2	22.2	17.4	34.4

Table S27 shows the relative distribution of emissions by sub-system. The LCA database system generates 31-53% (onshore) and 17-37% (offshore) of total emissions. For the offshore case, the relatively high shares of foreground system emissions (except for climate change) are largely due to emissions of NO_x from barge operation. It can be noted that the quantifications of emissions from offshore operations are uncertain, as they rely on rather simplistic assumptions on activities and equipment. The photochemical oxidant formation impact category stands out with relatively high emissions occurring in the rest-of-the-world region of the IO background system. This is due to NMVOC emissions in the sector representing extraction of crude petroleum and natural gas in the rest-of-the-world region.

Total cumulative emissions caused by wind power in 2030 and 2050 are shown in table S28 for four impact categories; a breakdown of greenhouse gas emissions into contributions from construction of new capacity, construction of replaced capacity, operation, and decommissioning of wind farms is given in table S29 (corresponds with shaded areas in figure 3 in main article). Table S30 shows the emission intensity of current-year wind electricity, as calculated with the unit-based analysis with current-year mix of onshore and offshore wind power, capacity factors and electricity mix. Differences between BLUE Map and BLUE hi REN emission intensity values are due to differences in the electricity mix that is used upstream in the product systems.

Shown in table S31 are numerical values for measures of reduced emissions in 2030 and 2050 (cf. figure 3 in the main article).

Table S28. Cumulative emissions in 2030 and 2050 in BLUE Map and BLUE hi REN scenarios by four impact categories. Time period: 2007-2050.

	BLUE Map		**BLUE hi REN**	
	2030	2050	2030	2050
Climate change (Gt CO_2-eq)	1.1	2.3	1.5	3.5
Marine eutrophication (Mt N-eq)	1.3	2.9	1.8	4.5
Photochemical oxidant formation (Mt NMVOC)	6.6	16	9.7	24
Terrestrial acidification (Mt SO_2-eq)	6.1	13	8.7	20

Table S29. Cumulative greenhouse gas emissions (Gt CO_2-eq) in 2030 and 2050 due to the construction, operation and demolition of wind power systems for the BLUE Map and BLUE hi REN scenarios. Time period: 2007-2050.

	BLUE Map		**BLUE hi REN**	
	2030	2050	2030	2050
Construction (new capacity)	0.85	1.29	1.26	2.07
Construction (repowering)	0.14	0.75	0.17	1.06
Operation	0.08	0.21	0.11	0.31
Decommissioning	0.006	0.05	0.007	0.08
Total	1.07	2.31	1.55	3.52

Table S30. Emission intensity of current-year wind electricity in 2007, 2030 and 2050 by four impact categories for the BLUE Map and BLUE hi REN scenarios. The values shown are weighted averages of onshore and offshore wind power. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification**.**

		BLUE Map		**BLUE hi REN**	
	2007	2030	2050	2030	2050
CC (g CO_2-eq/kWh)	22.4	16.3	14.0	15.5	13.2
ME (g N-eq/MWh)	24.2	20.8	19.6	20.1	18.8
POF (g NMVOC/MWh)	129	111	105	108	102
TA (g SO_2-eq/kWh)	123	93.1	82.8	87.8	76.5

Table S31. Cumulative gross and net reduced emissions in 2030 and 2050 by four impact categories for the BLUE Map scenario. Impact categories: CC = Climate change; ME = Marine eutrophication; POF = Photochemical oxidant formation; TA = Terrestrial acidification**.** Time period: 2010-2050.

	CC (Gt CO_2-eq)		**ME (Mt N-eq)**		**POF (Mt NMVOC)**		**TA (Mt SO_2-eq)**	
	2030	2050	2030	2050	2030	2050	2030	2050
a: Direct emissions reduced	14	43	7.9	22	24	65	55	131
d = a + b - c: Net reduced emissions	15	46	8.8	25	25	74	57	143
b: Indirect emissions reduced	1.5	5.0	2.0	5.8	7.5	24	8.2	24
c: Total wind power emissions	0.97	2.2	1.15	2.8	6.1	15.1	5.5	12.9

Appendix C: Paper III and associated content

Paper III

Arvesen, A., C. Birkeland, and E. G. Hertwich. The importance of ships and spare parts in LCAs of offshore power. *Environmental Science and Technology*. Submitted for publication.

The paper is under review for publication.

Is not included due to copyright

Appendix D: Paper IV

Paper IV

Arvesen, A., R. M. Bright, and E. G. Hertwich. 2011. Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation. *Energy Policy* 39(11): 7448-7454.

The version of paper IV included here is based on the last submitted manuscript to the journal. Minor deviations between the version included here and the final published version may occur.

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Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation

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ABSTRACT

This article challenges the notion that energy efficiency and ‘clean’ energy technologies can deliver sufficient degrees of climate change mitigation. By six arguments not widely recognized in the climate policy arena, we argue that unrealistic technology optimism exists in current climate change mitigation assessments, and, consequently, world energy and climate policy. The overarching theme of the arguments is that incomplete knowledge of indirect effects, and neglect of interactions between parts of physical and social sub-systems, systematically leads to overly optimistic assessments. Society must likely seek deeper changes in social and economic structures to preserve the climatic conditions to which the human civilization is adapted. We call for priority to be given to research evaluating aspects of mitigation in a broad, system-wide perspective.

Keywords: Sustainable development, climate policy, limits to growth.

1 Introduction

An underlying premise of world energy and climate policy is that energy efficiency increases and ‘clean’ energy technologies will, with appropriate policy support in place, be capable of delivering degrees of climate change mitigation consistent with the target of limiting global warming to 2° C above pre-industrial levels. Consequently, world policy to mitigate climate change remains somewhat superficial; underlying driving forces of the problem, that is – more resource intensive lifestyles and larger populations (Hertwich and Peters, 2009; UNEP, 2010a) – remain largely unchallenged, and fundamental changes in economic structures are hardly being put on the agenda.

Policy-supporting reports published by the International Energy Agency (IEA, 2010a, b) and the Intergovernmental Panel on Climate Change (IPCC, 2007) are commonly perceived to demonstrate the ability of technological solutions to deliver formidable degrees of climate change mitigation under scenarios of continued strong growth in the world economy. However, one insight which is too often overlooked in the debate is that the engineering-economic models behind studies such as IEA (2010a, b) rest on simplifications of complex and interacting physical and social systems, as well as intentionally optimistic assumption for the mitigation scenarios. In essence, what the engineering-economic models produce are extrapolations of first-order effect estimates under assumptions of well-functioning markets, neglecting linkages between climate change and other environmental pressures, and indirect effects of mitigation measures. By indirect effects we mean all effects of an action other than the action's targeted effect. Hofstetter and colleagues (2002) explain the notion of indirect effects by means of an allegory of ripples in a pond: Dropping an object into the pond (metaphorically: implementing a mitigation measure) sends out patterns of ripples, where the water height symbolizes environmental effects and the patterns of ripples the spread of effects through economies. The water height is immediately reduced at the point where the object hits the water surface (that is, the measure is successful in achieving the targeted effect), but high(er) water levels may be found anywhere from the inner to the outermost ripples.

In this article, we highlight some of the simplifying assumptions in current energy and climate change mitigation scenarios, as exemplified by IEA (2010a, b), and present a part of the case that it is premature to draw conclusions on the adequacy of technological solutions on the basis of such model results. Further, we argue that current, largely reductionist approaches to impact and mitigation assessments, where interacting problems and solutions tend to be assessed in isolation or with too narrow system boundaries, may lead to underestimation of environmental impacts on the one hand and are likely to cause overestimation of our ability to mitigate climate change on the other hand. As a result, mitigation assessments are the basis of unfounded technology optimism in world energy and climate policy. At the outset, however, it is important clarify that our critique does not concern the development of impact and mitigation assessments under simplifying assumptions as such. Rather, the critique targets the specific *interpretation* of contemporary assessments that, in the words of Ausubel (1996), 'technology can spare the earth' and the neglect of results that point in a different direction.

The next section introduces the challenge of achieving sustainability. In section 3, we challenge the premises for world energy and climate policy by six arguments which, in our view, have not been sufficiently acknowledged in the climate policy arena. The overarching theme is that incomplete knowledge of 'ripple' effects, and neglect of interactions between physical and social sub-systems, systematically leads to overly optimistic assessments. Section 4 concludes.

2 Background: the challenge of sustainability

According to current mainstream climate models, cumulative global carbon dioxide (CO_2) emitted by fossil fuel-burning, cement production, and land use in 2000-2049 should not exceed 1000 gigatonnes (Gt) if we are to have 75% confidence in reaching the 2° C target (Meinshausen et al., 2009). With 321 Gt already emitted in 2000-2009, we are left with a remaining budget of 679 Gt for 2010-2049. Negative growth occurred in 2009 due to the financial upheaval and slowdown of the global economy, but positive emission growth is expected to return as economic growth is re-established (Friedlingstein et al., 2010). Thus, at the onset of the second decade of 2000-49, we have not only emitted disproportionally high quantities of CO_2, but face continued growth in emissions. Moreover, national emissions-reduction pledges submitted under the Copenhagen Accord (UNFCCC, 2009) are far from sufficient to reach the 2° C target, even under the optimistic assumptions that countries will meet the ambitious ends of their pledges and refrain from exploiting loopholes in the regulatory framework (Rogelj et al., 2010; UNEP, 2010b). Also, recent observations give rise to concerns that climate change is occurring more rapidly than expected (Richardson et al., 2009), and there is a real danger that the neglect of long-term feedback effects in mainstream climate models lead to significant underestimation. Even by aiming for less than 2° C warming, there is a risk of irreversible and abrupt changes in climate (Hansen et al., 2008; Rockström et al., 2009).

In addition to climate change, an array of global environmental problems requires attention of policy makers. As an example, loss of biodiversity poses serious threats to life-supporting ecosystem services. The current species extinction rate is estimated to be 100-1000 times greater than the natural background rate (MEA, 2005; Rockström et al., 2009). One recent study finds that most indicators of biodiversity are in decline with no significant reductions in the rate of decline, whereas pressures on biodiversity are increasing (Butchart et al., 2010). Reviewing existing assessments of environmental impacts and pressures, the International Panel for Sustainable Resource Management highlights the following pressures as prioritized (UNEP, 2010a): Habitat change, greenhouse gas (GHG) emissions, over-fertilizing with phosphorus and nitrogen, pollution causing human and ecotoxic effects, depletion of abiotic resources (fossil energy carriers and metals), and depletion of biotic resources (in particular, fish and wood). Rockström and colleagues (2009) suggest nine indicators for evaluating the state of Earth systems. Of these, three indicator values (climate change, loss of biodiversity, and interference with nitrogen cycle) already transgress levels that can be regarded as 'safe', and four indicator values (global freshwater use, land use change, ocean acidification, and interference with phosphorus cycle) may soon be exceeding their safe levels. The remaining two indicators (atmospheric aerosol loading and chemical pollution) are yet to be determined (Rockström et al., 2009). As is further discussed in the following chapter, it is often not meaningful to view climate change and its mitigation in isolation from other sustainability issues. It is important that sustainability in the broad sense is adequately considered in climate change mitigation.

3 Six issues not sufficiently addressed in the climate policy arena

In the following subsections, we provide six reasons why contemporary climate change mitigation assessments are, in the general case, likely to be overly optimistic. While these six reasons represent problems that are not necessarily independent, they are discussed separately for the sake of clarity (Sections 3.1-3.6).

3.1 Transitioning to 'clean' energy supply will in itself cause climate impacts

The absence of fossil fuel combustion in the operating phase of energy converters (e.g. photovoltaic solar cells, biomass-fueled motor vehicles) does not imply zero greenhouse gas (GHG) emissions. This is because emissions occur in a network of operations necessary to support the energy converting process, such as manufacturing of solar cells or production of fertilizers to grow biofuel crops. Similarly, employment of carbon capture technologies in fossil fuel power stations does not remedy upstream emissions in the fuel-chain, which will rather increase due to lowered power plant efficiency.

The method of life cycle assessment (LCA) is the preferred method for quantifying and assessing environmental impacts generated throughout a product's life cycle. Surveying a number of LCA studies of proposed solutions to climate change, Jacobson (2009) finds that power generation technologies cause life cycle GHG emissions of 2.8-7.4 g CO_2e/kWh (wind power), 8.5-11.3 g/kWh (concentrated solar), 9-70 g/kWh (nuclear), 14 g/kWh (tidal), 15.1-55 g/kWh (geothermal), 17-22 g/kWh (hydro), 19-59 g/kWh (solar photovoltaic), and 21.7 g/kWh (wave). Another study estimates 180-220 g/kWh and 140-160 g/kWh, respectively, for coal and natural gas power generation systems with carbon capture and storage (CCS), which compares with around 1000 g/kWh and 580 g/kWh for world average coal and natural gas power without CCS (Singh et al., 2011). Judging from these findings, non-fossil power generation technologies are far superior to fossil-fueled power stations; employment of CCS produces substantial GHG emissions savings, though the life cycle reduction is significantly lower than the capture ratio (capturing 90% of the carbon from coal power yields 74-78% reduction in life cycle GHG in Singh et al., 2011), and life cycle GHG emissions from fossil power with CCS exceed those of non-fossil technologies with up to one order of magnitude.

While the employment of LCA methodology is essential for making fair and consistent comparisons across technologies, it is important to recognize limitations to current LCA studies. First, conventional LCA methodology is known to suffer from systematic underestimation of impacts due to incomplete coverage of product systems: There is a limit to how many activities can be described in a bottom-up approach, hence unwanted exclusion of activities from the system of analysis will always be the case. There is no agreed upon methodology for quantifying the truncation bias of conventional LCA, and the results of existing inquiries are not uniform. Nevertheless, in all studies surveyed by Majeau-Bettez et al. (in preparation), it is found that conventional LCA misses out on 30% or more of total environmental impacts. Potentially, the problem of underestimation can be avoided by utilizing so-called hybrid LCA techniques, where economic input-output data is used to estimate missing inventories, and thereby complete the system (Suh et al., 2004).

Second, conventional LCA is dominated by *ceteris paribus* assumptions; it does not account for changes in the background economy in the case of widespread adoption of the product under study. A transition to de-carbonized energy supply will cause emissions in the background economy that are typically neglected in LCAs. For example, massive expansions of wind power necessitates updates in electricity infrastructure and/or energy storage technologies, and will, due to the fluctuating nature of wind power, lead to altered operation of hydro and thermal power plants. Additional CO_2 emissions of fossil-fired power plants caused by high wind power penetration have been estimated to 18-70 g per kWh electricity from wind (Pehnt et al., 2008). The additional emissions result solely from an increased need to operate thermal power stations at (sub-optimal) part-load in order to accommodate the fluctuating inputs of wind power (Pehnt et al., 2008). It needs to be emphasized, though, that such results depend heavily on the assumed characteristics of background energy systems.

Third, conventional LCA has its domain in assessing the impacts associated with the delivery of one (small) reference unit, but falls short of addressing the magnitudes of aggregated impacts. The aggregated impacts caused by adoption of energy solutions depend, among other things, on the pace of deployment, the temporal distribution of emissions, and replacement of existing systems at the end-of-life – factors that are not incorporated in conventional LCA. One study estimates GHG emissions brought about by a large-scale adoption of wind power to cover 22% of the world’s electricity demand in 2050 to 3 Gt CO_2e (Arvesen and Hertwich, in preparation). Notwithstanding the important simplifying assumptions of this study (e.g., the calculation takes into account cleaner electricity mix in manufacturing with time, but not other changes in the background economy), it may serve as a first indication of the magnitude of aggregate life cycle emissions caused by global deployment of wind power.

It is not known what will be the global life cycle climate impacts caused by transitioning to energy solutions perceived to be ‘clean’. It can be hypothesized, however, that the sum of all impacts is too large to be neglected.

3.2 Realized net climate change mitigation from energy efficiency is unlikely to live up to its expectations

Energy efficiency measures are essential in typically foreseen paths to climate stabilization (IEA, 2010a, b; IPCC, 2007; Pacala and Socolow, 2004). However, the true costs and benefits of energy efficiency are complicated and opaque, due to a number of socio-technical interactions manifesting themselves in two apparent paradoxical issues. The first issue, dealt with in Section 3.2.1, is linked with the fact that literature suggests that substantial amounts of energy can be saved at negative costs (IPCC, 2007; McKinsey 2009). This prompts the question that if there is a profit in reducing emissions, why does it not happen? The second issue, and the topic of Section 3.2.2, is the postulation and observation that through higher-order effects, energy efficiency gains may stimulate more energy consumption.

3.2.1 Negative costs

In essence, the occurrence of negative costs in mitigation assessments stems from two principle factors: *i*) market failures hindering the implementation of energy efficiency measures in real markets ('market failure factors'); and *ii*) discrepancies between what energy analysts assume to be optimal behavior and what is truly optimal from the point of view of individual end-users ('non-market failure factors'). Market failure factors include incomplete information, misplaced incentives and transaction costs. Two examples of non-market failure factors are high discount rates in the face of the irreversible nature of investments and uncertainty about future energy prices, and qualitative properties that favor conventional technologies over more efficient ones (Jaffe and Stavins, 1994; Linares and Labandeira, 2010).

Modeling results based on the utilization of negative-cost energy efficiency measures assumes that market failures and non-market failure factors can be easily overcome by climate policy. True, if, for example, policy measures such as information campaigns and appliance labels can create fully informed consumers or regulation removes inefficient alternatives, costs of gathering information will become zero once a successful new policy is in place. However, as long as conditions with incomplete information prevail, the costs are indeed 'real' in the sense that they must be borne – *de facto* hampering new investments. Misplaced incentives (landlord-tenant or principal-agent issues) and uncertainty in future energy (and carbon) prices are also likely to persist. Likewise, due to heterogeneity among end-users (Jaffe and Stavins, 1994; Linares and

Labandeira, 2010), individual end-users may be faced with costs that are indeed 'real' to them, even if corresponding costs do not exist for average user types modeled by energy analysts. While policies to utilize the tremendous energy efficiency potential are desirable, assessments that count on the easy utilization of full technical energy efficiency potential are overly optimistic.

3.2.2 Rebound effects

Rebound effects come into play when increased efficiency leads to reduced costs. On a micro-level, increased energy efficiency will reduce the price of an energy service, and thereby: *i)* may create more demand for the energy service; and/or *ii)* may increase income available for general consumption. This applies to consumers and producers alike. On the macro-level, increased efficiency in the production and use of energy will result in a multitude of supply and demand adjustments occurring over time in a path-dependent development (Roehrl and Riahi, 2000). Because gains in energy efficiency favors energy over other factors of production (e.g., labor), and because efficiency contributes positively to overall economic productivity, the combined impact of the adjustments in supply and demand will be more energy consumption. The total economy-wide rebound effect is the sum of all micro- and macro-level effects (Hertwich, 2005; Sorrell, 2007; Jenkins et al., 2011).

The main arguments to be made here are that economy-wide rebound effects are likely too large to be neglected, and furthermore, that rebound effects are underappreciated in contemporary climate change mitigation assessments. Influential reports providing policy guidance on climate change mitigation (e.g., IEA (2010a, b), McKinsey (2009)) take little or no regard of rebound effects; thus, the net gains of energy efficiency measures are likely systematically overrated in such studies. We substantiate this position by briefly summarizing the current state of knowledge on rebound effects.

Empirical estimates of 'direct rebound effects', understood here as the increase in consumption of an energy service due to an efficiency-induced price drop of acquiring that service, typically fall within a range of 10-30% of expected gains for consumer end-uses in developed countries (Greening et al., 2000; Sorrell et al., 2009). Owing to the higher price elasticities, larger direct rebound effects can be expected for developing countries – a limited amount of empirical evidence suggests 40-80% (Sorrell 2007; Jenkins et al., 2011).

Macro-level rebound effects are more difficult to ascertain empirically and model-based estimates vary widely. Proponents of large economy-wide rebound effects (‘backfire’) have historically relied on theoretical arguments and more indirect sources of evidence to support their case (Sorrell, 2009). Modeling attempts to quantify economy-wide rebound exist, but the methodologies are subject to criticism and the evidence remains inconclusive (compare, for example, the different positions of Schipper and Grubb, 2000 and Jenkins et al., 2011; summaries are provided by Sorrell, 2007, 2009).

Macro-level rebound effects can be linked to the bigger question of what is driving economic growth: If it is so that energy is a major driver for economic growth, this strengthens the argument for large rebound effects (Sorrell, 2009). According to conventional growth theories, energy can only play a minor role in generating economic growth, since the costs of energy are low compared to capital and labor costs. This view is contested by the analyses of e.g. Kümmel et al. (2010) and Warr and Ayres (2010), which indicate that capital, labor, and energy are in fact interdependent inputs, and that high-quality energy is a major driver for economic growth (Sorrell, 2009; Madlener and Alcott, 2009). Sorrel (2009) acknowledges that the identified relationships between high-quality energy and economic activity do not represent sufficient evidence to conclude that causality runs from energy to growth, but argues that the observations are consistent with theoretical arguments offered earlier.

Returning to our main argument, we see considerable grounds for concern that due to rebound effects, energy efficiency strategies will fail to live up to expectations as a contributor to climate change mitigation. There is universal agreement in the rebound literature that some rebound effect exists; thus, at the least, net gains of energy efficiency are smaller than suggested by simple engineering estimates. Furthermore, while the exact magnitude of economy-wide rebound remains unknown and disputed, our understanding of the current state of knowledge is that we take the ability of energy efficiency to deliver substantial reductions in greenhouse gas emissions for granted. Even the possibility of ‘backfire’, i.e. that economy-wide rebound exceeds 100%, cannot be completely ruled out.

3.3 Developing fossil energy with CCS and renewable energy in parallel may lower system-wide performance

‘Carbon lock-in’ refers to a situation where, due to a variety of forces, a type of inertia is present whereby efforts to implement greenhouse gas-saving measures are hindered; and thus fossil-fuel dependencies are perpetuated. The forces adding to lock-in may be of technological, institutional or social nature (Unruh, 2000). Arguably, a condition of carbon lock-in may explain the seemingly paradoxical situation where, theoretically, technological fixes to the climate change problem appear to exist and be affordable, but in practice, the diffusion of the technologies is slow (Unruh, 2000; 2002). Similar arguments arise, independently, also in the political science literature on energy technology (Moe, 2010).

Indeed, some of the arguments presented in the current paper are related to, and may be seen as part of, the concept of carbon lock-in, but an elaboration is beyond the scope of this paper. In this particular section, we discuss carbon lock-in in the context of one specific characteristic of typical climate change mitigation scenarios; namely, the future co-evolution of fossil energy with CCS and renewable energy. We point out that while envisaged least-cost pathways to climate stabilization involve fossil energy with CCS and renewable energy developing in tandem, system-wide performance is not maximized in such conditions. In short, this is because many of the forces that have created the carbon lock-in of today will continue to be exerted by fossil energy systems also in the future, even if these systems are combined with CCS. We elaborate on this argument below, after first briefly introducing factors that may lead to carbon lock-in and that are relevant for the present discussion.

While recognizing that explanations for carbon lock-in may be sought at the micro or macro level, and that forces acting within individual firms can also contribute to lock-in (Unruh, 2000), we here focus on externalities in networks of inter-related technologies and institutions. In society, such network externalities give rise to groups of compatible components forming clusters, with positive externalities reinforcing compatible components’ competitiveness and viability, while negative externalities raise barriers for incompatible elements. One example from the historical record is the co-evolution of roads, petrol-fueled automobiles and oil pipelines, and an array of related public and private institutions (Grübler et al., 1999; Unruh, 2000; Moe, 2010). Unruh (2000) recognizes three types of macro-level network effects. The first relates to connections and dependencies among industry actors, such as coordination to produce complimentary products and the introduction of standards and conventions. Such relationships create favorable conditions for complimentary industries, but create barriers for new solutions. The second type has to do with the way in which projects are financed: Profitable firms tend to direct financing back to their own core competencies, and risk-aversive lenders may have a similar preference towards existing solutions. Finally, externalities arise from private and public institutions with bonds to technological systems; some examples are user-created organizations, educational establishments and professionals representing certain disciplines, industry associations and regulatory frameworks (Unruh, 2000).

Returning to the case of CCS, our concerns stem from two observations. First, comparative climate change mitigation model runs tend to find that scenarios with co-evolutions of fossil energy with CCS and renewable energy show significantly lower mitigation costs than scenarios with only non-fossil energy (IEA, 2010a; Krey and Clarke, 2010). In one assessment (IEA, 2010a), excluding CCS from the set of available options raises overall costs to achieve stabilization by 70% (IEA, 2010a). The second observation is that implementing CCS on a large scale will prolong the life spans of systemic factors adding to carbon lock-in, compared with the case if only non-fossil solutions were implemented. For example, as investors into long-lived capital assets in connection with fossil fuels will expect returns on their investments, premature (in economic terms) efforts to phase out fossil fuels may be met with resistance. More broadly, policy-makers will have to withstand additional rounds of lobbyism and many other influences from groups disadvantaged by a phase-out of fossil energy (regardless of whether CCS is used), and, because industries facilitating the use of fossil energy resources are kept alive, the tendency for investments to be directed to fossil fuel-based technologies will to some degree persist.

Our intent here is not to argue against CCS as such. Indeed, developing CCS may be beneficial for other reasons. From another viewpoint, due to CCS being more compatible with current systems than competing renewable power generation technologies, developing large-scale CCS may be regarded as a means to overcome lock-in barriers to climate change mitigation in the short-term (Unruh and Carrillo-Hermosilla, 2006; Praetorius and Schumacher, 2009). Also, one could argue that a pragmatic approach to climate policy warrants that an opportunity is kept open for the fossil fuel industry to radically reduce its emissions. This does not, however, alter the fact that fossil energy with CCS will, in the overall picture, not exert synergistic effects on renewable energy deployment, but conversely, raise barriers. Similarly, renewable energy systems can raise barriers for CCS. Our main concern, and the key point of this discussion, is the imbalance between the envisaged least-cost pathways to climate stabilization (i.e., pathways in which fossil energy with CCS and renewable energy develop in parallel), and the pathways in which systemic forces (externalities) are aligned in such a way that system-performance is advanced (i.e., pathways in which fossil energy is phased out altogether).

3.4 The notion of absolute decoupling is not supported by historical records

The concept of decoupling lies at the heart of the technology optimism permeating current climate policies. Decoupling can refer either to a decline in environmental impact per unit of economic output (relative decoupling), or to an absolute decrease in environmental impact as income grows (absolute decoupling). If the latter measure is expressed in units of tonnes of CO_2 per year, the former would be in units of CO_2 per dollar or similar. It is important to distinguish between these two interpretations (Jackson, 2009). Evidence of relative decoupling has been put out to justify an optimistic view on technological fixes to environmental problems (Ausubel, 1996). However, as have been noted repeatedly (Arrow et al., 1995; Jackson, 2009; Speth, 2008), only limited conclusions can be drawn from relative measures; it is vital also to address absolutes. The historical records provide no evidence to suggest that sufficient absolute decoupling of climate change impact can take place in coming decades (Jackson, 2009). While this does not rule out the possibility that absolute decoupling can take place in the future, it does show that future developments in many aspects must be fundamentally different from historic developments.

Furthermore, when studying decoupling trends of post-industrialized countries, shifting trading patterns obscure the picture and lead to too optimistic conclusions. This is because of a shift of dirty manufacturing activities to less wealthy nations. For example, in recent decades, CO_2 emitted in China to produce products for export has increased rapidly (Weber et al., 2008). Correspondingly, significant increases with time are evident in estimates of CO_2 embodied in imports to wealthy nations from China (Reinvang and Peters, 2008; Weber and Matthews, 2007). From the results of Wiedmann and colleagues (2010), analyzing production and consumption based emissions for the UK in the period 1992-2004, one may observe that an apparent 5% decline in CO_2 (derived from domestic emissions inventories reported to UNFCCC), turns into a 8% increase, if changes in emissions embodied in international trade are taken into consideration. A recent study by Peters et al. (2011) confirms the general validity of these anecdotal reports, estimating that the net emission transfer to post-industrialized countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008 – a growth that more than outweighs the wealthy nations' emissions reductions commitments under the Kyoto Protocol.

A further element which may be noted is that rooted in climate change mitigation scenarios (IEA, 2010a, b) is an assumption that sufficient capital can be made accessible to finance the (capital-intensive) transition away from conventional and towards lower-carbon energy systems. However, investments in renewable energy assets – and sustainability-focused investments in general – tend to bring long-term payoffs, not short-term profits (Jackson, 2009). The ability of current financial systems to foster sufficient long-term investments in sustainability is yet to be demonstrated.

3.5 Linkages between environmental pressures are likely to complicate mitigation

Due to incomprehensible complexities in biophysical and social systems, impact and mitigation assessments must to a large extent take a reductionist approach to understanding and addressing environmental problems, largely neglecting linkages between individual pressures and systems. As is pointed out by van der Voet and Graedel (2010), not only do linkages connect systems with strong dynamic behavior, but the linkages are in themselves dynamic – this contributes to the complexity.

The notion that individual problems can be assessed and treated in isolation is problematic on at least two levels. First, there is a danger that interactions among different problems give rise to nonlinearities which go unaccounted for in impact assessments. For example, biodiversity loss may increase ecosystems vulnerability to climate change, and nitrogen-phosphorus pollution may weaken marine ecosystems so that less carbon is absorbed from the atmosphere (Rockström et al., 2009). Second, approaching many biophysical limits simultaneously implies a high risk of problem shifting, that is, solving one problem while generating another; and deployment of solutions to overcome one biophysical limit may be hindered by other physical constraints. In a simpler world where GHG emissions were the only environmental pressure, one would not need to consider effects of renewable energy systems on ecosystems, impediments to development of new technologies due to mineral resource scarcity, and water demand following employment of new energy solutions. In reality, achieving sustainable energy supply requires technologies that can deliver sufficient degrees of de-carbonization in spite of, and without adding unacceptable momentum to, ecosystem degradation and resource scarcities.

3.6 Future demands for energy services may be underestimated

We here call attention to two reasons why the potential for future demand for energy services may be underestimated. First, current engineering-economic models are based on satisfying existing categories of energy demand. Even if demand in these categories is assumed to grow, there is a natural limit: upscaling demand for already known consumption categories cannot account for all growth in energy use in the long term, because in reality, new categories of demand arise and grow – sometimes to become important in the aggregate. This is what happened with rail transport in the 19th century, what may be happening with air transport in the 20th and 21st centuries, and what may start to happen with space tourism in the 21st century. The issue of entirely new categories of demand emerging over time may be seen as special type of rebound effect (Sorrell 2009; Jenkins et al., 2011), and is thus related to the discussion in Section 3.2.2.

A second problem with contemporary energy scenarios is that linkages between energy requirements and other (non-energy) resource constraints (cf. Section 3.5) are not considered. It is conceivable that such linkages may give rise to unanticipated growth in already existing categories of energy demand. This is what may happen with energy use associated with pumping, treatment, and desalination of water as freshwater increasingly is becoming scarce in many places (UNEP, 2010a; UNESCO, 2009), and with energy requirements of primary metal extraction as the quality of available metallic ore resources deteriorate (Norgate, 2010; Norgate and Jahanshahi, 2010).

4 Final remarks

Technological solutions are vital in solving global environmental problems, including climate change. However, the conception of technology as a panacea for global environmental problems lacks solid justifications. In this article, we have challenged the notion that energy efficiency and 'clean' energy technologies can deliver amounts of climate change mitigation sufficient to deem fundamental changes in social and economic structures to be unnecessary. The famous wedge analogy introduced by Pacala and Socolow (2004), where, conceptually, different mitigation strategies add up to form a stabilization triangle, is, while intuitive, not accurate. In reality, often it is not reasonable to view climate change mitigation strategies in isolation from each other, as independent of the baseline trends below which the stabilization wedges are conceptualized, and without taking into consideration other environmental pressures not directly related to climate change.

A thorough understanding of how 'ripple' effects of mitigation measures play out on a macro scale lies in the future, but, as is to some extent reflected in this article's list of references, a fair amount of relevant research findings already exists for evaluating the system-wide effects of mitigation measures. The urgency of tackling climate change makes this a crucially important area of research. Equally important is research investigating how indirect, countervailing effects of mitigation measures may be addressed and how real mitigation at the system-wide level may be realized. If society becomes receptive to the idea that developed nations abandon growth-oriented economies, researchers will be asked to investigate ways in which a new macro-economy, which does not require growth to preserve economic stability, can be developed (Jackson, 2009; Victor 2010). Yet another salient issue is increasing the resiliency of financial institutions to reward sustainability-focused investments that bring long-term benefits.

More profound changes in social and economic structures may render possible degrees of climate change mitigation beyond what can be achieved by technology within current frameworks. The importance of preserving the climatic conditions to which the human civilization is adapted, and restoring the ecological basis on which all human activities rely, can hardly be overstated. If the optimism on behalf of technological solutions is misconceived, scholars and policy makers must start now to explore ways in which mitigation can be realized also through alternative avenues.

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