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Renewable Energy 26 (2002) 339–362

RENEWABLE ENERGY

www.elsevier.com/locate/renene

Energy and CO_2 life-cycle analyses of wind turbines—review and applications

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Received 25 May 2001; accepted 25 June 2001

Abstract

Despite the fact that the structure and technology of most modern wind turbines differs little over a wide range of power ratings, results from existing life-cycle assessments of their energy and CO_2 intensity show considerable variations. While the range of energy intensities reflects economies of scale, their scatter is due to discrepancies in the energy contents of materials and the analyses' methodology and scope. Furthermore, energy intensities depend crucially on the country of manufacture, turbine recycling or overhaul after the service life, and the choice of tower material. In addition, CO_2 intensities vary with national fuel mixes. Measures of life-cycle energy or CO_2 emissions can be employed in policy and planning, especially for comparative risk and sustainability assessments, and source switching and capacity growth scenarios. If these measures are to assist decision-making, uncertainties in life-cycle assessments should be minimised by compliance to a standardised methodology, and by use of input–output-based hybrid techniques. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Wind turbine; Energy intensity; CO_2 intensity; Life-cycle assessment

1. Introduction

Energy analysis was developed for the assessment of both direct and indirect ('embodied') energy requirements for the provision of goods and services [1]. A

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PII: S0960-1481(01)00145-8

bottom-up approach, *process analysis*, was taken, where energy requirements of the main production processes and some important contributions from suppliers of inputs into the main processes are assessed in detail (for example by auditing or using disparate data sources), and where the system boundary is usually chosen with the understanding that the addition of successive upstream production stages has a small effect on the total inventory. At the Institute for Energy Analysis, which was established in Oak Ridge, Tennessee in 1974, guidelines were set up for the investigation of energy supply and conversion systems—including wind turbines (WTs)—in terms of the net energy output [2] or the energy service delivered to the consumer [3]. More recently, process analysis was adopted in the official guidelines for life-cycle assessment (LCA) set out by the Society of Environmental Toxicology And Chemistry (SETAC; [4]), which in turn are widely used in LCAs of energy systems such as the ExternE project of the European Commission [5], the DECADES project of the International Atomic Energy Agency and others [6,7], the German GEMIS project of the Öko-Institut and the Gesamthochschule Kassel [8], or the Swiss GaBE project [9]. It was already recognised in early studies, that process analyses carry significant systematic errors due to the unavoidable truncation of the system boundary. It was therefore suggested by Herendeen, Hannon, and others at the Center for Advanced Computation in Urbana, Illinois, to employ input–output analysis in order to account for energy requirements originating from inputs out of upstream supply chains of infinite order [10]. Since this statistical, top-down approach suffers from various shortcomings such as aggregation and allocation errors, Bullard and co-workers [11] developed a hybrid analysis technique, combining advantages of process and input–output analysis, that is completeness and specificity. With the increasing recognition of the threat of anthropogenic climate change, the emphasis in assessments of energy supply and conversion systems shifted from net energy to embodied greenhouse gas emissions. Nevertheless, greenhouse gas analyses were still carried out using process, input–output, and hybrid techniques (for a reference list, see [12]).

The aim of this article is to review existing energy and CO_2 life-cycle analyses of wind turbines in order to determine the causes for the widely varying results of numerous previous studies. In particular, we consider the *energy* and *greenhouse gas intensity*, that is the ratio of the primary energy consumed, or CO_2 emitted for the construction, operation, and decommissioning, per unit of output of electrical energy over the lifetime of the device. This quantity is most often used in life-cycle studies on energy devices.

The framework of this article is as follows. In Section 2 a survey of 72 energy and CO_2 analyses of wind turbines is presented. Further, the influence of different parameters (for example lifetime, load factor, power rating, country of manufacture, vintage year, and methodology and scope of analysis) on the results from these studies is examined. In Section 3 we analyse uncertainties of estimates of energy requirements at the component level. Section 4 illustrates some applications of energy intensities in planning and policy. Finally the paper is concluded in Section 5.

2. Energy and CO_2 intensities of wind turbines and influencing parameters

The first comprehensive review of energy analyses concerning renewable energy sources—including WTs—was presented by Mortimer in 1991 [13]. Full-energy-chain (FENCH) studies and net energy analyses were reviewed more recently by van de Vate [14,15] and by the International Atomic Energy Agency (IAEA) [16]. A number of mostly process analyses of electricity generation systems are discussed in proceedings published by the IAEA [17,18], and by the OECD and International Energy Agency [19]. The fourth IAEA advisory group meeting within the DECADES project dealt particularly with wind energy [20]. Aggregated yet comprehensive results on the energy requirement of many WT over a wide power rating range can be found in studies carried out by Hagedorn and Ilmberger [21], and, using the European EUROWIN database, by Schmid et al. [22]. Since it would be beyond the scope and length of a journal article to discuss every of the numerous case studies, an overview of energy and CO_2 analyses of WTs in order of increasing power rating is given in Table 1.

Before discussing the results of the literature survey, we make a few preliminary notes:

1. In the studies mentioned in Table 1, it is assumed that WTs operate in a utility grid for fossil fuel substitution, and not as stand-alone devices.
2. The energy intensity η for a plant of power rating P and load factor λ, is defined as the ratio of the energy requirement E for construction, operation, and decommissioning and the electricity output of the plant over its lifetime T:

$$\eta = \frac{E}{P \times 8760 h\, y^{-1} \times \lambda \times T} \quad (1)$$

3. Table 1 contains only WTs equipped with steel towers. These are most often used (and analysed), because concrete towers have to be built in a time-consuming and costly step-by-step process at the turbine site. Moreover, the energy intensity depends critically on the choice of tower material (see Section 2.4).
4. Some studies identify a number of sites (coastal, near-coastal, interior) for the installation of identical WTs ([23–26]). In these cases, only the site option with the lowest energy intensity was included in Table 1. These are exclusively coastal or off-shore sites (roughness classes 1 and 0), with average wind speeds usually greater than 6 m s^{-1} at 10 m above ground.
5. Understanding the results from the studies presented in Table 1 often posed a problem, especially when the documentation was incomplete, the methodology not transparent, materials and components aggregated, and when varying definitions for payback times, output ratios, or energy factors were used. In particular, the high values for η in references [27–29] could not be explained.

As already observed by van de Vate [14] on the basis of only six studies, a considerable scatter exists in the values of both energy and CO_2 intensity. While energy

Table 1
Overview of energy and CO_2 analyses of horizontal-axis wind turbines[a]

Ref.	Year of study	Location	Energy Intensity $(\frac{kWh_{in}}{kWh_{el}})$	CO_2 intensity $(\frac{gCO_2}{kWh_{el}})$	Power rating (kW_{el})	Life time (y)	Load factor (%)	Analysis type	Scope as stated	Turbine type	$\varnothing_r$ (m)	*H* (m)	Rated wind speed (m/s)	Remarks
[30]	1992	Germany[o]	0.089		0.3	20	38.8	PA	CDMOT	3-bl	1.5	11.6	9.0	75% recycling
[31]	1983	Germany[o]	≈0.43		2	15	45.7	AEI	CM					Average values
[32]	1998	Argentina[c]	≈0.17	≈42	2.5	20	22.0	PA	CMT(O)	2/3-bl				Incl. storage
[33]	1981	USA[o]	1.016		3	20	26.8	I/O	CMO		4.3	20	10.1	Excl. storage
[31]	1983	Germany[o]	≈0.29		6	15	45.7	AEI	CM					Average values
[31]	1983	Germany[o]	≈0.20		12.5	15	45.7	AEI	CM					Average values
[34]	1997	Denmark[o]	0.120		15	20	20.5	I/O	CMO	1980	10	18		Vintage model
[34]	1997	Denmark[o]	0.123		22	20	19.9	I/O	CMO	1980	10.5	18		Vintage model
[35]	1991	Germany[o]	0.085		30	20	14.4	PA	CGMOT	2-bl	12.5	14.8	13	Hsw-30
[36]	1996	Switzerland[o]	0.321	52	30	20	7.9	PA	CDGMOT	2-bl	12.5	22	11.4	Simplon
[34]	1997	Denmark[o]	0.100		30	20	19.0	I/O	CMO	1980	11	19		Vintage model
[32]	1998	Argentina[c]	0.120	≈29	30	20	22.0	PA	CMT(O)	2/3-bl				
[31]	1983	Germany[o]	≈0.12		32.5	15	45.7	AEI	CM					Average values
[35]	1991	Germany[o]	0.049		33	20	29.4	PA	M	2-bl	14.8	22	11	MAN-Aeromann
[37]	1991	Germany[o]	0.053		45	20	33.5	PA	M		12.5			
[34]	1997	Denmark[o]	0.066		55	20	20.6	I/O	CMO	1980	16	20		Vintage model
[38]	1990	Denmark[o]	0.014		95	20	25.2	PA	M(C)	3-bl	19	22.6		On-shore farm (6)
[35]	1991	Germany[o]	0.068		95	20	20.5	PA	CGMT	3-bl	19	22.6		On-shore farm (6)
[35]	1991	Germany[o]	0.051		95	20	20.5	PA	M	3-bl	19	22.6		Tellus 95
[27]	1991	Japan[o]	0.252	71.7[e]	100	20	31.5	I/O	CMT					
[35]	1991	Germany[o]	0.060		100	20	20.9	PA	M	2-bl	34	24.2	8	Hütter 100
[28]	1992	Japan[o]	0.345	95.6[e]	100	20	31.5	I/O	CMOT					10% auxiliary power
[39]	1992	Japan[o]	0.033	33.7	100	30	28.0	I/O	CMOT		30		13	Upwind propeller

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Table 1
Continued

Ref.	Year of study	Location	Energy Intensity $(\frac{kWh_{in}}{kWh_{el}})$	CO_2 intensity $(\frac{gCO_2}{kWh_{el}})$	Power rating (kW_{el})	Life time (y)	Load factor (%)	Analysis type	Scope as stated	Turbine type	$\varnothing_r$ (m)	*H* (m)	Rated wind speed (m/s)	Remarks
[39]	1992	Japan[o]	0.054		100	30	40.0	I/O	CMOT	1983	30		10	Downwind propeller
[24]	1996	Germany[o]	0.120	17	100	20	31.4	PA	CMO	3-bl	20	30		
[29]	1996	Japan[o]	0.436	123.6[e]	100	30	20.0	I/O	CMO					Downwind propeller
[40]	1996	Japan[o]	0.456	123.7[e]	100	20	18.0	I/O	CMO	1984	30			Demonstration plant
[41]	2001	Japan[o]	0.160	39.4	100	25	34.8	I/O	CMT		30	30		NO_x & SO_x calculated
[42]	1990	Denmark[o]	0.021	8.81	150	25	30.1	PA	M					
[35]	1991	Germany[o]	0.049		150	20	25.6	PA	M	3-bl	23	30	13	AN-Bonus 150
[36]	1996	Switzerland[o]	0.202	28	150	20	7.6	PA	CDGMOT	3-bl	23.8	30		Grenchenberg
[35]	1991	Germany[o]	0.037		165	20	23.2	PA	M	3-bl	25	32	13.5	Adler 25
[40]	1996	Japan[o]	0.171	47.4[e]	170	20	22.5	I/O	CMO		27			Mitsubishi-2
[35]	1991	Germany[o]	0.053		200	20	21.0	PA	M	3-bl	26	30	13	Adler 26
[37]	1991	Germany[o]	0.031		225	20	39.9	PA	M		27			
[32]	1998	Argentina[c]	≈0.08	≈18	225	20	22.0	PA	CMT(O)	2/3-vl				
[35]	1991	Germany[o]	0.064		265	20	19.0	PA	M	2-bl	52	30.5	8.5	Voith 52/265.8
[43]	1990	Germany[o]	0.031		300	20	28.9	PA	CMT	3-bl	32	34	11.5	Enercon-32
[37]	1991	Germany	0.037		300	20	39.9	PA	M		32			
[30]	1992	Germany[c]	0.027		300	20	41.9	PA	CDGMOT	3-bl	32	34		75% recycling
[44]	1993	Germany[o]	0.046	11[e]	300	20	22.8	PA	CDMOT					Recycling
[45]	1994	Germany[o]	0.022		300	20	22.8	PA	MO(D)					O calculated with AEI
[40]	1996	Japan[o]	0.118	34.9[e]	300	20	18.0	I/O	CMO		28			Mitsubishi-1
[46]	1995	UK[o]	0.042	9.1	350	20	30.0	PA	M	3-bl	30	30	≈15	
[40]	1996	Japan[o]	0.088	24.1[e]	400	20	18.0.0	I/O	CMO		31			MICON

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Table 1
Continued

Ref.	Year of study	Location	Energy Intensity $(\frac{kWh_{in}}{kWh_{el}})$	CO_2 intensity $(\frac{gCO_2}{kWh_{el}})$	Power rating (kW_{el})	Life time (y)	Load factor (%)	Analysis type	Scope as stated	Turbine type	$\varnothing_r$ (m)	*H* (m)	Rated wind speed (m/s)	Remarks
[47]	1997	Denmark[o]	0.020	15.9	400	20	22.8	PA	M(O)					Excl. imports
[35]	1991	Germany[o]	0.048		450	20	20.0	PA	GM	3-bl	35	36	18	AN-Bonus 450
[48]	1994	Germany[o]		18.2[e]	500	20	27.4	I/O	CM					Incl. factory buildings
[26]	1994	Germany[o]	0.068	8.1	500	20	36.5	PA	M	2/3-bl	39	41		
[23]	1998	Germany[o]	0.042		500	20	29.6	PA	CGMOT	3-bl	40.3	44		Enercon E-40
[23]	1998	Germany[o]	0.065		500	20	29.6	I/O	CGMOT	3-bl	40.3	44		Enercon E-40
[49]	2001	Brazil[o]	0.069		500	20	29.6	I/O	CGMOT	3-bl	40.3	44		E-40;Transp.D⟶Brazil
[50]	2000	Denmark[o]	0.033	9.7	500	20	25.1	PA	M(DT)	3-bl		41.5		On-shore farm (18)
[50]	2000	Denmark[o]	0.047	16.5	500	20	28.5	PA	GM(DT)	3-bl	39	40.5	16	Off-shore farm (10)
[34]	1997	Denmark[o]	0.037		600	20	26.5	I/O	BCDEG MOT	3-bl	47	≈50	15	
[51]	2000	Belgium[o]	0.033	9.2[e]	600	20	34.2	PA	DM(O)					
[51]	2000	Belgium[o]	0.036	7.9[e]	600	20	34.2	I/O	DM(O)					1980 I/O tables
[52]	1980	UK[c]	0.080		1000	25	18.3	I/O	CM		46		18.4	On-shore farm(5)
[52]	1980	UK[c]	0.165		1000	25	18.3	I/O	CM		46		18.4	
[53]	1996	Germany[o]		14[e]	1000	20	18.5	PA	CMO	3-bl	54	55		HSW 1000
[53]	1996	Germany[o]		22[e]	1000	20	18.5	I/O	CMO	3-bl	54	55		HSW1000
[24]	1996	Germany[c]	0.035	10	1000	20	36.2	PA	CMO	3-bl	60	50		
[54]	1977	USA[c]	0.023		1500	30	50.4	I/O	BCEMT	2-bl	≈60	≈50	10.5	Steel truss tower
[34]	1997	Denmark[c]	0.030		1500	20	38.4	I/O	CMO	3-bl	64	55	17	Off-shore

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Table 1
Continued

Ref.	Year of study	Location	Energy Intensity $(\frac{kWh_{in}}{kWh_{el}})$	CO_2 intensity $(\frac{gCO_2}{kWh_{el}})$	Power rating (kW_{el})	Life time (y)	Load factor (%)	Analysis type	Scope as stated	Turbine type	$\varnothing_r$ (m)	*H* (m)	Rated wind speed (m/s)	Remarks
[23]	1998	Germany[o]	0.046		1500	20	31.0	PA	CGMOT	3-bl	66	67		Enercon
[23]	1998	Germany[o]	0.071		1500	20	31.0	I/O	CGMOT	3-bl	66	67		E-66
[25]	1999	Germany[c]	0.038		1500	20	31.0	PA	CDGMOT		66	67		no gear box
[25]	1999	India[c]	0.032		1500	20	45.9	PA	CDGMOT		66	67		E-66; Transp.D⟶India
[31]	1983	Germany[o]	≈0.79		3000	20	45.7	AEI	CM	2-bl	100	100		GROWIAN prototype
[35]	1991	Germany[o]	0.065		3000	20	30.4	PA	GM	2-bl	100	100	12	GROWIAN I
[37]	1991	Germany	0.045		3000	20	34.2	PA	M		80			
[55]	1996	UK[o]		≈25	6600	20	29	I/O	CDMO					System not specified

[a] Notes: $\varnothing_r$=rotor diameter, AEI=method of multiplying total cost with a national average energy intensity, [c]=conceptual, bl=blades, B=Business management, C=Construction, D=Decommissioning, [e]=CO_2 equivalents including CH_4 and N_2O, E=Engineering, G=Grid connection, *h*=Tower height, I/O=Input–output-based hybrid analysis, M=Manufacture, [o]=operating, O=Operation, PA=Process analysis, T=Transport, ()=partly covered.

intensities span almost two orders of magnitude from 0.014 to 1 $kWh_{in}kWh_{el}^{-1}$, CO_2 intensities are between 7.9 and 123.7 g CO_2 kWh_{el}^{-1} for unit power ratings between 0.3 and 3000 kW.[1] Capacity factors vary from 7.6% to 50.4%, implying that some studies investigate WTs on very poor locations on shore, and others on extreme, off-shore locations. Finally, Table 1 demonstrates that the scope chosen for life-cycle analysis varies considerably. Some studies examine only manufacture, whereas other studies include further life-cycle stages such as construction, decommissioning, grid connection, operation and transport.

Apart from differences in analysis methodology and scope, the scatter in energy intensities can be caused by economies of scale ('bigger is better'), and by differences in lifetime, load factor, technology (type and maturity), and country of manufacture. The influence of these factors on the energy intensity of WTs will be examined in Sections 2.1–2.6.

2.1. Influence of lifetime, load factor, and power rating

It is obvious that an increase in the assumed lifetime and load factor of a WT causes a decrease of its energy intensity, because the lifetime electrical output increases. This influence can be eliminated by normalising the modelled energy intensity η to a load factor of 25%, and a lifetime of 20 years according to

$$\eta_{\mathrm{norm}} = \eta\frac{\lambda \quad T}{25\%20y} = \frac{E}{P{\times}8760h\,y^{-1}{\times}25\%{\times}20y}. \qquad (2)$$

η_{norm} is related to the normalised *energy payback time*, that is the time it takes the WT to generate the primary-energy equivalent of its energy requirement *E*, via $t_{\mathrm{payback}}=\eta_{\mathrm{norm}}{\times}T{\times}\varepsilon_{\mathrm{fossil}}$. The latter factor is the conversion efficiency (assumed to be 35%) of conventional power plants that are to be displaced by WTs.

Fig. 1 shows the normalised energy intensity obtained in the studies in Table 1 as a function of power rating. Open circles represent process analyses, while filled circles represent input–output-based analyses. The figure also contains four curves obtained from (1) a univariate logarithmic regression over all points shown in the diagram, (2) an approximation based on detailed detailed examinations on component level (see Section 2.2), (3) a regression of process analysis data of about 100 WTs contained in the EUROWIN study [22], and (4) a multivariate regression for maximum analysis breadth and depth (see Section 2.4).

After normalisation, and taking out a few extreme values (prototype plants, or

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[1] CO_2 intensities exhibit additional variability, because CO_2 coefficients depend on the fuel mix in the respective country of study. The CO_2 coefficients applied in the studies listed in Table 1 are between 120 and 280 g CO_2 $kWh_{primary}^{-1}$. These compound CO_2 coefficients result from a varying mix of fossil fuels (brown coal 342 g CO_2 $kWh_{calorific}^{-1}$, black coal 324 g CO_2 $kWh_{calorific}^{-1}$, fuel and heating oil 252 g CO_2 $kWh_{calorific}^{-1}$, gasoline and kerosene 241 g CO_2 $Kwh_{calorific}^{-1}$ natural gas 185 g CO_2 $Kwh_{calorific}^{-1}$ [56]) combined with renewable energies (nuclear 3–42 g CO_2 $Kwh_{primary}^{-1}$, hydro 1–21 g CO_2 $Kwh_{primary}^{-1}$, wind 3–43 g CO_2 $Kwh_{primary}^{-1}$, photovoltaics 8–67 g (CO_2 $Kwh_{primary}^{-1}$, solar–thermal electricity 12–49 g CO_2 $Kwh_{primary}^{-1}$; [12]).

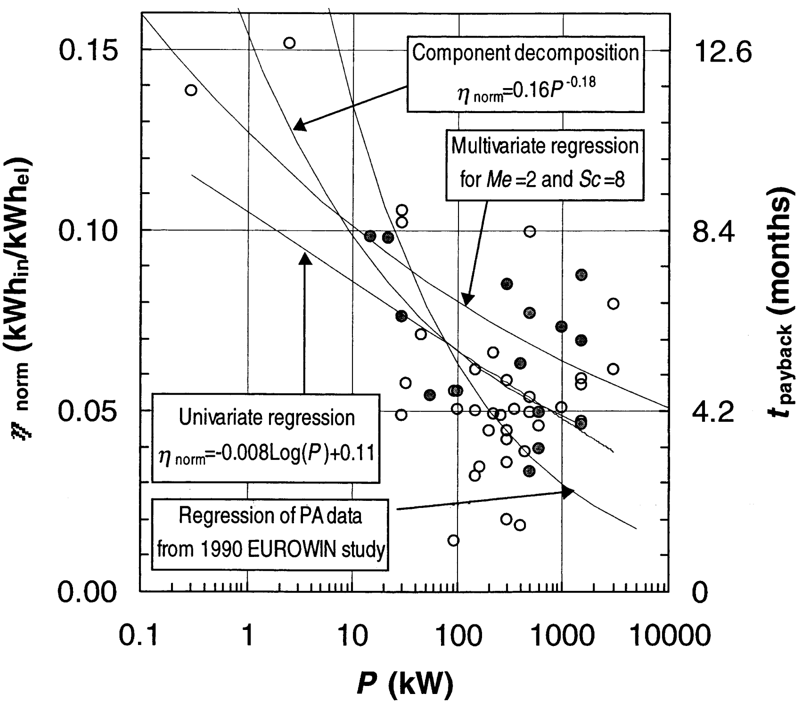

Fig. 1. Energy intensities normalised according to Eq. (2) as a function of power rating for the case studies listed in Table 1. Open circles: process analyses; filled circles: input–output analyses. The trend-lines mark (1) a univariate regression, (2) an approximation based on detailed examinations on component level ([21,22,30,35]; see Section 2.2), (3) a regression of process analysis data of about 100 WT contained in the EUROWIN study [22], and (4) a multivariate regression for maximum analysis breadth and depth (see Section 2.4).

lack of documentation), the range of energy intensities has decreased from almost two to about one order of magnitude. The mean energy intensity over all plants examined is 0.062 $kWh_{in}kWh_{el}^{-1}$, while the mean energy payback time is 5.2 months. In the univariate regression, the decrease of the energy intensity over the whole power rating range is significant at the 99%-confidence level. The process analysis data of about 100 WTs contained in the EUROWIN study [22] is in reasonable agreement with process analyses (open circles) for WTs above 10 kW. However, in a process analysis of 37 WTs, Hagedorn and Ilmberger [21] found a mean energy intensity of 0.049 $kWh_{in}kWh_{el}^{-1}$ (steel towers only), but no trend for power ratings between 10 and 3000 kW can be observed in their data.

2.2. Analysis at component level

A wind turbine comprises five main components: (1) rotor blades, (2) transmission, including pitch control, hub, mounting, main shaft, bearings and gear box, (3) generator, electronic controls and cables, (4) tower including yaw, and (5) foundation.

The relationship between the energy intensity and the power rating can be understood by examining wind velocity profiles and the energy requirement of WTs at the component level. The power rating is proportional to the product of rotor area A_r, and the cube of the wind velocity v_w at hub elevation h. For roughness class 1 (coastal and near-coastal sites), the wind velocity itself is proportional to h^{α}, where $0.15<\alpha<0.2$. Although there is not necessarily a technical relationship between the rotor diameter and the tower height [21], small WTs have comparably higher towers than large WTs because, even at low power ratings, WTs need an 'initial' minimum tower height in order to operate economically [35]. This is reflected in the data in Table 1, which yields that the rotor diameter d is proportional to $h^{1.5}$. Therefore,

$$P\sim A_r v_w^3 \sim d^2 v_w^3 \sim h^3 h^{0.5} = h^{3.5} \quad (3)$$

There are four German studies [21,22,30,35] that document the energy requirement of a number of WTs at the component level. Hagedorn and Ilmberger [21] report a proportionality of the energy requirement of fibre glass rotors to $A_r^{1.3}$. Considering Eq. (3) yields $E_{\mathrm{rotor}}\sim d^{2.6}\sim h^{3.9}\sim P^{1.1}$. This relationship reflects the fact that additional material has to be used in order to add stiffness to the rotor blades for compensating the larger wind forces. In contrast, the mass of towers—and therefore their energy requirement—was found to be proportional to $h^{2.8}\sim P^{0.8}$ [22,30], which indicates that the relative dimensions (such as thicknesses and lengths) of tower designs decrease slightly with increasing size. For transmissions, generators and foundations Pernkopf [35] found proportionalities to P, $P^{0.7}$, and $P^{0.7}$, respectively, whereas Schmid et al. [22] report $\sim P^{0.7}$ for the mass of generators, and $\sim d^{2.7}\sim h^{4.1}\sim P^{1.2}$ for the mass of the whole nacelle. The economies of scale for foundations are directly related to those for towers, because the weight of the foundation increases in accordance with tower height [35]. Summing up the functional relationships of all five components, the total energy requirement can be found to be proportional to $P^{0.82}$. Considering Eq. (2) the energy intensity η_{norm} is then proportional to about $P^{-0.18}$ (see Fig. 2). The contributions to η_{norm} at the component level are also in agreement with the data in Table 1, as shown in Fig. 1.

Fig. 2 indicates that WTs are relatively similar with regard to their material input over a wide range of power ratings. This small product differentiation is partly caused by the fact that WT design is dictated by market conditions and safety regulations [57].

2.3. *Influence of methodology, scope, and maturity*

In order to examine the influence of methodology, scope and technological maturity on η_{norm}, a multivariate regression was carried out in the form

$$\log(\eta_{\mathrm{norm}}) = k_1\log(P) + k_2\log(Me) + k_3\log(Sc) + k_4\log(Y) + k_5, \quad (4)$$

where Me and Sc are dummy variables, and Y is the vintage year. While Me is 1 for process analyses and 2 for input–output analyses, Sc was set to the number of letters in the column 'Scope' in Table 1. A regression over 47 WTs yielded $k_1=-0.092\pm0.035$, $k_2=0.361\pm0.194$, $k_3=0.108\pm0.094$, and $k_5=-1.103\pm0.091$. k_1 and

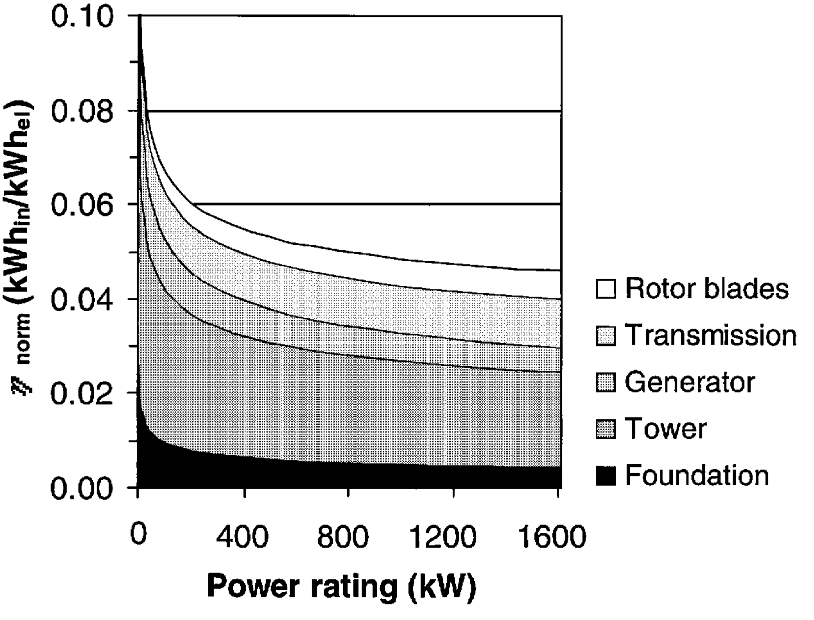

Fig. 2. Contributions to η_{norm} of five WT component groups as a function of power rating (derived from [21,22,30,35]). 'Transmission' includes hub, shaft and gear box.

k_5 are significant at the 99%-confidence level, while k_2 and k_3 are significant at the 90%- and 75%-confidence level, respectively. The vintage year has to be discarded from the variables because of a positive correlation between *Y* and *P*, which is higher than the correlation between all other pairs of variables. This correlation reflects the average power rating increase with time. Eq. (4) is plotted for *Me*=2 (input–output-based analysis) and *Sc*=8 (BCDEGMOT) in Fig. 1. Summarising, it appears that the energy intensity of WTs increases with decreasing power rating (economies of scale) and increasing scope, and under a change from process to input–output analysis.

2.4. Influence of technology

In their analysis of 37 1-, 2-, and 3-blade horizontal-axis propeller-type turbines as well as Darrieus and horizontal-Darrieus rotors with power ratings between 10 and 3000 kW, Hagedorn and Ilmberger [21] found some preferred configurations of generator type and rotor type, but they emphasise the role of the material used for constructing the tower. The energy requirement of concrete towers appears to be half that of steel towers. A mean energy intensity (process analysis, scope M) of about 0.049 $kWh_{in}kWh_{el}^{-1}$ for steel-tower WTs, and 0.041 $kWh_{in}kWh_{el}^{-1}$ for concrete-tower WTs can be derived from their results.

Similarly, Pernkopf [35] stresses the influence of the tower material, and reports specific energy requirements of concrete towers for WTs between 30 and 150 kW ranging between 22% and 38% of those for equivalent steel towers. For a 300 kW

WT, Domrös [30] assumes a concrete tower of twice the mass of a steel tower, but arrives at about 20% of the energy requirement, decreasing the overall energy intensity by about 23% from 0.037 $kWh_{in}kWh_{el}^{-1}$ to 0.028 $kWh_{in}kWh_{el}^{-1}$. If, however, recycling is taken to account, the respective energy intensities are 0.027 $kWh_{in}kWh_{el}^{-1}$ and 0.023 $kWh_{in}kWh_{el}^{-1}$, thus decreasing the advantage of the concrete-tower version to 13% (compare Section 2.5). Finally, Lewin [44] reports a 36% decrease of the CO_2 intensity from 11 to 7 g CO_2-e/kWh_{el} when appraising a concrete instead of a steel tower for a 300 kW WT.

2.5. Influence of production in country of manufacture

A large number of the studies examined in this review demonstrated that the energy intensity of WTs decreased when a site with higher mean wind velocity was appraised. This effect is, however, not surprising, and also already covered by the load factor. There are additional site-specific differences which relate to country-specific energy requirements for the manufacture of components for WTs. The manufacture of a 500 kW German WT in Brazil, for example, requires almost twice as much primary energy as its manufacture in Germany. This increase results mainly from different energy contents of steel, which are in turn due to differences in the steel production route and scrap utilisation between the two countries [49]. Nevertheless, German and Brazilian production are about equal in terms of CO_2, because 95% of Brazilian electricity is generated by hydroelectric plants [58]. Similarly, Grum-Schwensen [38,59] analyses a Danish on-shore farm of six 95-kW Tellus WT manufactured from steel containing 88% scrap and 12% mined ore, and from copper containing 80% scrap and 20% mined ore. The extraordinarily low energy contents for steel of 5 MJ/kg and for copper of 23.8 MJ/kg result in an overall energy intensity of only 0.014 $kWh_{in}kWh_{el}^{-1}$. These figures demonstrate that energy intensities of WT can vary considerably with the country of manufacture.

Finally, the energy required for the international transport of WT components is usually below 5% of the total energy requirement, even for large distances such as between Germany and India [25], and Germany and Brazil [49].

2.6. Influence of recycling and overhaul

Recycling of WT components has been examined in detail in four German studies [21,30,35,60]. According to the authors, the separation of fibre glass, epoxy resin and PVC within rotor blades poses technical problems, so that plastics recycled from rotor blades are of inferior quality, and only useful as filler materials. Kehrbaum [60] suggests that a combined material–thermal recycling in cement production, where the (organic) epoxy resin contributes toward the process heat, while the glass fibres become embedded in the cement, could be more economical in energy terms. A purely thermal recycling of rotor blades in steel furnaces or waste incineration plants could be problematic because of the toxic residuals originating from the chloride contained in the PVC. Domrös [30] concludes that recycling the concrete foundations (and possibly tower) does not significantly affect the energy balance, since transport and processing are energy-intensive, and that the resulting inferior rubble should only be used in construction sites close to the WT location. In contrast, the conventional recycling of steel, copper and aluminum in metal works represents a considerable energy gain.[2] Pernkopf [35] shows for a 30 kW WT that a complete overhaul and reinstallation after the service life, involving the exchange of rotor blades, pitch control, hub, bearings, cogs, hydraulics and cables, requires only about 20% of the total energy requirement, and is therefore in favour of complete recycling from an energy point-of-view. Lifetime extension toward 50 years with overhaul after 25 years is also discussed as to lower generation cost in the case of recent Danish wind parks [61].

3. Uncertainty of the energy requirement

Within process analyses, the total energy requirement E of WTs is usually calculated from a breakdown of the total mass M into i=1,…,c components of more or less homogenous material content m_i (in kg) or μ_i (in %), specific energy content ε_i (in MJ/kg), and relative energy requirement e_i (in %) according to

$$E = E\sum_{i=1}^{c} e_i = \sum_{i=1}^{c} m_i\varepsilon_i = M\sum_{i=1}^{c}\mu_i\varepsilon_i \quad (5)$$

Assuming that, for any case study, the m_i can be evaluated without uncertainty, and that the ε_i carry stochastic uncertainties $\Delta\varepsilon_i$, the overall relative uncertainty $\Delta E/E$ of the total energy requirement E is

$$\frac{\Delta E}{E} = \frac{\sqrt{\sum_{i=1}^{c}(\mu_i\Delta\varepsilon_i)^2}}{\sum_{i=1}^{c}\mu_i\varepsilon_i} \quad (6)$$

The uncertainty Δe_i in the component's relative energy requirement e_i is

$$\Delta e_i = \Delta\left(\frac{m_i\varepsilon_i}{E}\right) = e_i\times\sqrt{\left(\frac{\Delta\varepsilon_i}{\varepsilon_i}\right)^2 + \left(\frac{\Delta E}{E}\right)^2} \quad (7)$$

[2] An analysis of four steel-tower WTs yielded energy credits of 12.5% of the total energy requirement for a 100% recycling of 500–600 kW plants [60], 20.3% (100%, 30 kW, [35]), 31.9% (75%, 0.3 kW, [30]) and 25.5% (75%, 300 kW, [30]).

Table 2 shows the results of a compilation of the μ_i, ε_i and $\Delta\varepsilon_i$ from a number of studies on propeller-type WTs, and the e_i and Δe_i calculated according to Eqs. (5) and (7). The $\Delta\varepsilon_i$ are the standard deviations of the energy contents ε_i used in these studies.

The concrete foundations and the steel tower are by far the heaviest components, accounting for already 84% of the total mass. However, since the energy content of concrete is about one order of magnitude below that of steel, the concrete foundation accounts for only 10% of the total energy requirement. In terms of energy, steel parts such as the tower and the transmission are most important. A surprisingly large scatter was found for the energy contents ε_i used in those studies, resulting in accordingly large standard deviations of relative energy contents e_i of the components. Inserting the values of $\Delta\varepsilon_i$ in Table 2 into Eq. (6) yields $\Delta E/E \approx 26\%$. The largest error component is the uncertainty of the energy content of steel used for the tower.

In addition to stochastic uncertainties, process analyses carry systematic *truncation errors*, which are caused by the setting of a finite system boundary. Through this system truncation, energy or emissions requirements from upstream production stages are omitted. Pick and Wagner [23], Voorspools et al. [51] and Hartmann [53] found that energy or greenhouse gas intensities for WTs based on a materials breakdown in weight units yielded energy intensities that were lower than intensities based on cost breakdowns and input–output multipliers. This was also observed by Lenzen [12] for solar–thermal power plants. Fig. 1 and the multivariate regression discussed earlier confirm these findings. Lenzen and Dey [62] find a 50% truncation error in a process analysis of the energy content of basic iron and steel products. Considering that basic steel used for the tower accounts for more than 40% of the energy requirement for a typical propeller-type WT (see Table 2), the largest component of the discrepancy between process- and input–output-based intensities may be caused by a systematic error in the energy content of steel used for the tower. Therefore, the curve in Fig. 1 representing the multivariate regression of η_{norm} against P for Me=2 (input–output-based analysis) and Sc=8 (BCDEGMOT) may be regarded as the most comprehensive estimate of the energy intensity, applying maximum analysis depth and maximum analysis breadth.

4. Planning and policy applications

The calculation of resource use and pollutant emissions from renewable energy systems such as WTs is important to informed decision making. First, some calculations of emissions from wind power systems are a part of broader analyses of the externalities of energy production and use [46,63], of effects of the internalisation of these external social costs into the accounts of power utilities [64], and of comparative assessments of energy supply options with regard to health risk and environmental damage [6,9,17,18]. Hohmeyer, for example, demonstrated how the market penetration of WTs in Germany and Denmark would be accelerated if all costs of electricity generation to society were taken into consideration [65]. These externality

Table 2
Summary of results from process analyses of horizontal-axis wind turbines [23,25,30,35,36,38,42,43,46,51,54]

Component	Main material	Relative mass (%) μ_t	Energy content (MJ/kg) $\varepsilon_t \pm \Delta\varepsilon_t$	Rel. energy req. (%) $e_i \pm \Delta e_i$
Blades	Glass fibre, epoxy, PVC	2.7	61.8±35.7	8.7±5.5
Hub and mounting	Steel	3.5	36.8±18.5	6.5±3.7
Transmission	Steel	5.2	36.8±18.5	9.7±5.5
Generator	Copper	2.6	86.2±65.5	11.5±9.2
Nacelle cover	Glass fibre	0.3	61.8±35.7	0.9±0.5
Tower	Steel	23.3	36.8±18.5	43.6±24.7
Foundations	Concrete	60.3	3.2±1.9	9.8±6.4
Electrical	Copper	2.1	86.2±65.5	9.4±7.5

analyses suffer already from methodological discrepancies, for example with regard to scope, dose–response relations, and valuation [66], and these discrepancies would only be exacerbated by systematic errors in resource and pollutant inventories.

Second, the consideration of the energy requirement E for the construction of energy supply systems is important for the modelling of plant substitution, source switching and demand growth scenarios (compare analyses of rapidly growing nuclear programs after the oil price shocks [67–69]). It can be shown (see Appendix A) that a system of WTs of unit power rating P, load factor λ, lifetime T and construction time C, which are commissioned at a constant rate κ, generates the power

$$P_a = P\kappa[\lambda(T-C)-\varepsilon_{\text{fossil}}\tau] \quad (8)$$

available for end-users, while recouping the electricity equivalent $\varepsilon_{\text{fossil}}E$ of the primary energy $E=\tau P$ required for its own construction. $\tau\approx0.01$ TJ kW^{-1}=0.336, 2 is the proportionality constant of an approximated linear relationship between the primary energy requirement E of WTs and their power rating P (see regression constant k_1 in Section 2.3).

The effect of introducing the energy requirement E shall be illustrated using the example of the Danish wind industry. In the mid-1990s the total installed wind power capacity in Denmark was about 500 MW [70]. Assuming a load factor of λ=25%, a lifetime of T=20 a, a construction time of C=1 a, and neglecting embodied energy, the projected available wind power in a system with a total capacity of 500 MW, and which is constantly replacing decommissioned capacity is P_a=500 MW×25%=125 MW. According to Eq. (8) (for τ=0), this equates to a commissioning rate of κ=52.6 plants of P=500 kW unit power rating per year. At this commissioning rate, the true available wind power is only P_a=121 MW, because the WTs are to recoup the primary energy required for their own construction.

These differences become more pronounced if a capacity growth program is considered. Fig. 3 shows the result of an iterative computation of the available power P_a (neglecting (E=0) and considering (E>0) embodied energy), as well as the number of plants N_s and N_o, under construction and in operation, for the scenario of implementing an additional capacity of 1000 MW (2000 WTs of 500 kW each) by 2005. This target was set out by the Danish Government in 1996 in order to support the *Energy 2000* plan, which sought to achieve a reduction of CO_2 emissions to 20% below the 1988 level by 2005 (see also [71]).

Our assessment starts in 1998, where we set t=0, the number of operating plants N_o=1000, and the available power $P_a(E>0)$=121 MW, instead of $P_a(E=0)$=125 MW. The commissioning rate is, as in the static example above, κ=52.6 a^{-1} and, because the construction time is C=1 a, there are N_c=52.6 plants being constructed at any time. The acceleration of the capacity growth program is α=109 a^{-2} (see Appendix A). The simulations show that after 1 1/2 years the available power has decreased to $P_a(E>0)$=117 MW, with power taken up for the sake of building new wind turbines. By 2004 (t=6 a), the capacity growth program is at its maximum rate, and about 650 plants are under construction. The available power at this stage is $P_a(E>0)$=257 MW, but it would be $P_a(E=0)$=296 MW if embodied energy was neglected. Hence, the true available power is 39 MW or 13% below its projected value. Only

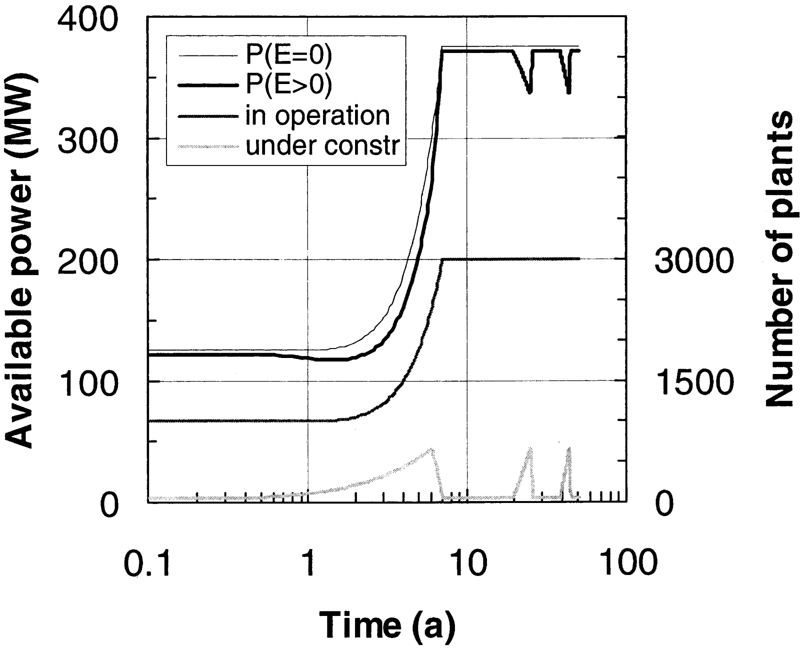

Fig. 3. Available power P_a (assuming both E=0 and E>0, that is, neglecting and considering embodied energy), and number of plants N_s and N_o under construction and in operation, for the scenario of implementing an additional capacity of 1000 MW (2000 WTs of 500 kW each) in Denmark between 1998 and 2005.

by 2005 (t=7 a), after the completion of 2000 plants, does the true available power $P_a(E>0)$=371 MW approach the projected available power $P_a(E=0)$=375 MW. At this stage, once again N_c=52.6 plants are being constructed at any time, in order to substitute decommisioned plants built at $t<0$. Note that in order to maintain a capacity of 1500 MW or 3000 WTs, this construction program has to be repeated every 20 years, with associated power decreases of up to 13%, since all plants have to be substituted after their service life.

Finally, the measures of energy intensity, energy payback time and recouping of energy investments are applicable as indicators for sustainability. The concept of sustainability considers the (energy) needs of future generations and claims that future generations should have at least the same possibilities for satisfying their needs as the present generation on earth. Despite the positive attitude to the sustainability concept, there is a lack of generally approved indicators for sustainability. The concepts of energy intensity and energy payback time (based on the life-cycle paradigm) as well as the recouping of energy investments are operational and easy to interpret from a sustainability point of view. Both concepts focus on how much energy is used today in order to obtain energy tomorrow.

The interpretation of the energy intensity indicator is straightforward: The lower the intensity the higher is the trade off between present energy use and future energy needs. Moreover, a criterion for unsustainability can be defined as energy devices having energy intensity $\eta_{norm}>\varepsilon_{foss}{}^{-1}$. In terms of the energy payback time $t_{payback}=\eta_{norm}\times T\times\varepsilon_{foss}$, this criterion reads $t_{payback}<T$. Similarly, the concept of recouping energy investments is an indicator of sustainability: The higher the energy investments the lower is the power available for end-use. The criterion for unsustainability can be derived from Eq. (8) as $\varepsilon_{foss}\times\tau<\lambda(T-C)$.[3]

In using the concepts of energy intensity, energy payback time and energy investment as indicators for sustainablility, it is relevant to distinguish between renewable energy inputs and input of fossil fuels. Once renewables form a significant part of a national power generation system, these have to be taken into account by either replacing ε_{foss} with the average conversion efficiency of the future system, or by subtracting renewables from the total energy input inherent in η_{norm}, $t_{payback}$, and τ. The unsustainability criteria then become less stringent.

5. Conclusions

Despite the fact that most modern WTs differ little over a wide range of power ratings with regard to their material consistency, there is a relatively large variation in energy and CO_2 intensities. Even after normalisation with respect to lifetime and load factor, energy intensities span more than one order of magnitude from 0.014 to 0.15 $kWh_{in}kWh_{el}{}^{-1}$. This *range* reflects economies of scale, with small WTs of 1 kW requiring about three times more life-cycle energy per unit power than large WTs of 1 MW. The *scatter* of normalised energy intensities is mainly due to discrepancies in (1) values for the energy content of materials, (2) the analysis scope, or breadth, and (3) the methodology, or analysis depth. Apart from these procedural parameters, it appears that the normalised energy intensity is influenced by (4) the country of manufacture, (5) recycling or overhaul of components after the service life, and (6) the choice of concrete or steel for the tower. In addition to the above parameters, the CO_2 intensity varies according to the fuel mix in the country of manufacture.

At present, studies show that the differences between the means of energy and CO_2 intensities of some renewable energy technologies are smaller than the deviations from these means for each single technology. This uncertainty poses a problem for decision-making towards minimising externalities of energy supply, if more than one technology option is available for capacity development. Furthermore, government programs involving large transitions from fossil to renewable energy, or large capacity growth programs, should take into account the energy requirement for the construction of plants, when for example stringent emission targets or power demands have to be met during the transition or growth. It is therefore essential that the energy requirements for renewable energy supply systems are calculated in a

[3] Considering Eq. (2) and $\tau=E/P$, the criterion $\eta_{norm}<\varepsilon_{foss}{}^{-1}$ can be expressed as $\varepsilon_{foss}\times\tau<\lambda T$. This is equivalent to the energy investment criterion $\varepsilon_{foss}\times\tau<\lambda(T-C)$ for construction time C=0.

standard but comprehensive way, at maximum breadth an depth. First, it should be aimed at eliminating methodological discrepancies (1–3 above), so that all upstream and downstream effects on pollution and resource use of different systems can be compared. Second, hybrid life-cycle techniques combining process and input–output analysis should be applied in order to achieve system completeness while dispensing with the problem of selecting of a boundary for the production system [72–76].

Finally, it should be noted that the energy requirement is—at least for short-term and local considerations—not a crucial factor for the design and implementation of WTs. This is because (embodied) energy cost do not form a significant part of their monetary inputs [77]. At present, capacity development, even when carried out primarily for environmental motives, is mainly determined by profitability [78,79] and noise and visual impacts on residents living in the vicinity of the installation [71,80,81]. Nevertheless, in the long term and on a global scale—especially from a sustainability point of view—the energy requirement of WTs and other renewable energy technologies will be considered, if those technologies are to replace a considerable part of the present fossil power plant stock.

Appendix A

In the following, the available output of a system of wind power plants of unit power rating P, load factor λ, lifetime T and construction time C, is calculated under the assumption that these plants operate in a predominantly fossil power domain, and that the electricity equivalent $\varepsilon_{\text{fossil}}E$ of the primary energy requirement E for the construction of the plants is being recouped by the system. This concept is referred to as *renewable breeders* [82].

Energy shall not be discounted (see [83,84]). $\varepsilon_{\text{fossil}}$ is the mean conversion efficiency of thermal electricity generation. Let N_d, N_s, and N_f be the number of plants being decommissioned, and where construction is started and finished, respectively. The number of finished plants per unit of time at time t must be equal to the number of started plants per unit time at time $t-C$:

$$\frac{\partial N_f}{\partial t}(t) = \frac{\partial N_s}{\partial t}(t-C) \tag{A1}$$

A similar relationship exists between the number of decommissioned and started plants:

$$\frac{\partial N_d}{\partial t}(t) = \frac{\partial N_s}{\partial t}(t-T) \tag{A2}$$

For the number of plants N_c under construction and N_o operating we find

$$\frac{\partial N_c}{\partial t}(t) = \frac{\partial N_s}{\partial t}(t) - \frac{\partial N_s}{\partial t}(t-C) \text{ and } \frac{\partial N_o}{\partial t}(t) = \frac{\partial N_s}{\partial t}(t-C) - \frac{\partial N_s}{\partial t}(t-T), \tag{A3}$$

so that

$$N_c(t) = \int_0^t [\frac{\partial N_s}{\partial t}(t) - \frac{\partial N_s}{\partial t}(t-C)]dt + N_c(t=0) \tag{A4}$$

and

$$N_o(t) = \int_0^t [\frac{\partial N_s}{\partial t}(t-C) - \frac{\partial N_s}{\partial t}(t-T)]dt + N_o(t=0) \tag{A5}$$

.

The power available for consumption is then

$$P_a(t) = P\lambda N_o(t) - \frac{\varepsilon_{fossil}E}{C}N_c(t) = P[\lambda N_o(t) - \frac{\varepsilon_{fossil}\tau}{C}N_c(t)], \tag{A6}$$

where τ is the proportionality constant in an approximated linear relationship between the primary energy requirement E of plants and their power rating P (see Section 2.3). Note that the energy requirements for operation and decommissioning are neglected.

For a scenario where phased-out plants are constantly being substituted at a rate $\partial N_s/\partial t=\kappa$ starting at time t=0, we find

$$N_c(t) = \begin{cases} \kappa t & 0<t<C \\ \kappa C & t>C \end{cases} \text{ and } N_o(t) = \begin{cases} 0 & 0<t<C \\ \kappa(t-C) & C<t<T \\ \kappa(T-C) & t>T \end{cases} \tag{A7}$$

and for the available power

$$P_a(t) = \begin{cases} -P\kappa\frac{\varepsilon_{\mathrm{fossil}}\tau}{C}t & 0<t<C \\ P\kappa[\lambda(t-C)-\varepsilon_{\mathrm{fossil}}\tau] & C<t<T \\ P\kappa[\lambda(T-C)-\varepsilon_{\mathrm{fossil}}\tau] & t>T \end{cases} \tag{A8}$$

For an accelerated scenario with capacity growth $\partial N_s/\partial t=\alpha t$ starting at time t=0 the available power is

$$P_a = \begin{cases} -P\alpha\dfrac{\varepsilon_{\mathrm{fossil}}\tau t^2}{C\quad 2} & 0<t<C \\ P\alpha[\lambda\dfrac{(t-C)^2}{2}-\varepsilon_{\mathrm{fossil}}\tau(t-\dfrac{C}{2})] & C<t<T \\ P\alpha[\lambda(T-C)(t-\dfrac{T+C}{2})-\varepsilon_{\mathrm{fossil}}\tau(t-\dfrac{C}{2})] & t>T \end{cases} \tag{A9}$$

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