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Greenhouse Gas Analysis of Electricity Generation Systems

Christopher Dey and Manfred Lenzen
School of Physics, A28, University of Sydney
NSW 2006
AUSTRALIA
E-mail: cdey@physics.usyd.edu.au

Abstract

All renewable energy systems make some contribution to climate change. This is due to the emission of greenhouse gases from the fossil fuels combusted for their construction, and as back-up energy during their operation. Accurate calculation of greenhouse gas emissions per kilowatt hour of electricity is difficult, but is an important part of policy making and planning. Calculation methodologies and results for different grid-scale electricity generation systems are presented in this paper, with an emphasis on solar thermal systems. Both material inventory and financial-based methods are employed, and the results are compared with other recent studies. For most renewable electricity plants, the emissions have a strong dependence on the capacity factor, back-up fuel, and on the size of the plant. For typical solar thermal plants, the results show that approximately 90 g of CO_2 *equivalent are released per kWh of electricity generated over the lifetime of the plant.*

1. Introduction

The oil crises of the 1970s stimulated the formulation of methods for evaluating complex energy systems. For power plants, the idea is to account for the primary fossil energy needed over the plant's whole service life for its construction, operation, and decommissioning, including the energy embodied in structural elements during their manufacture. A useful quantity is the *net energy requirement* (NER). This is the ratio of the total plant energy requirement to the plant lifetime electricity output. There are numerous studies calculating the NER of electricity generating systems as diverse as biomass, fossil-fuel, geothermal, hydro, nuclear, ocean-thermal, photovoltaic, solar-thermal, tidal, wave, and wind power plants (see for example Mortimer 1991). These studies were meant to assist in decision-making on future energy technologies, but they quickly lost political relevance with the lowering of crude oil prices after the early 1980s.

With growing concerns over climate change, the field of *greenhouse gas analysis* has arisen, in analogy to net energy analysis. Although there is some correlation between energy use and greenhouse gas emissions, there is no direct proportionality between these quantities. This is because firstly, different fuels have different greenhouse gas contents, and secondly, because some emissions are not associated with the combustion of fuels. Therefore, a separate set of data is needed, which enables the calculation of the power plant's lifetime *greenhouse gas cost* (GGC), usually expressed in terms of an equivalent mass of CO_2 emissions per unit of electricity output (kg CO_2-e/kWh$_{el}$). The factor CO_2-e accounts for the different global warming potentials of the various greenhouse gases. There is, however, a much more limited amount of data on embodiments in monetary or material units in greenhouse gas terms than there is in energy terms.

The present paper describes GGCs for various electricity generation technologies. In the following section, different methods for calculating GGCs are appraised, along with their shortcomings. Data sources are discussed in Section 3. Then in Section 4, these methods and data are applied to three types of solar thermal power plants: parabolic trough, central receiver, and parabolic dish. Five different aspects of the plants are examined: (1) the effect of the choice of method on the result for a given plant, (2) the effect of fossil fuel backup on the plant GGC, (3) the effect of energy storage on the plant GGC, (4) economies of scale, and (5) a comparison with recent greenhouse gas analyses of other electricity generating systems.

2. Methodology

Two fundamentally different approaches for greenhouse gas analysis can be employed. In the first method, an inventory of the materials used in the structural elements of the plant is established (in units of tonnes (t), for example). These amounts are multiplied by a *greenhouse gas content*, that is, the greenhouse gas embodiment per unit of mass of the respective material, to obtain the associated emissions. Materials for the operation and the decommissioning are treated in the same way. Moreover, greenhouse gas emissions from direct energy use (such as from the combustion of backup fuel) are added. The sum of all greenhouse gases must finally be divided by the lifetime electricity output of the plant, in order to yield the GGC. This first method is referred to as *materials-based analysis*.

In the second method, a breakdown similar to the materials inventory is established for the lifetime monetary cost of the plant (in units of Australian Dollars (A$), for example). In this case, the GGC is obtained using *greenhouse gas intensities*, that is, the greenhouse gas embodiment per unit of value. This method is referred to as *cost-based analysis*. It should be mentioned that hybrid techniques employing both material and cost methods are possible, and in some cases can lead to better estimates of NERs and GGCs (eg. Bullard *et al*, 1978, and Van Engelenburg *et al*, 1994).

The materials-based analysis relies on greenhouse gas content data being available for all relevant materials. Data that can be found in the literature is usually obtained from so-called *process analysis*. This is a vertical, bottom-up technique, which considers emissions of particular industrial processes, and includes a limited order of supplying industries, and their corresponding emissions. Process analysis involves accounting for single industrial operations, and is therefore an accurate but tedious undertaking. However, it is specific to a particular type of production, and is only valid for a defined system boundary. The greenhouse gas content of mild steel, for example, varies considerably depending on the country of production, the amount of scrap steel used, or whether or not ore extraction and shipping are included. As a result, a materials-based calculated GGC has a strong dependence on the quality and applicability of the greenhouse gas contents derived from process analyses.

The cost-based analysis employs monetary greenhouse gas intensities which can be obtained from an input-output analysis, a statistical, top-down method, which usually encompasses all industrial dependencies to unlimited order, and for a whole economy (Lenzen, 1998). As a consequence, these intensities are values in terms of broad commodity groups (such as "Fabricated Metal Products" or "Glass and Glass Products" in the Australian input-output tables) and moreover, are averaged over different firms and production processes. An advantage of input-output analysis is that it does not exhibit a case-dependency as is inherent to process analysis, since it deals with aggregates. However, it does not account for peculiarities, such as the option of using steel with a high proportion of recycled scrap. Finally, the input-output matrix calculus is relatively easy to carry out.

This work seeks to make general statements about the GGC of a particular type of solar-thermal power generation to be implemented in Australia, but independent of other particular circumstances such as the origin, transport, and processing of materials. One would therefore choose the cost-based analysis as the appropriate method. However, Australian input-output data show a comparatively high degree of aggregation. This fact results in a considerable uncertainty for the GGC, because a structural element used in a power plant (say, a turbine, or a mirror) might be atypical in its greenhouse gas intensity compared to its allocated input-output category. One way to estimate the accuracy of these results is to compare them to values obtained using materials-based analysis, where, in order to achieve sufficiently general results, average greenhouse gas contents should be used, thus taking into account a range of material production options. Such a comparison is presented in the following section.

It is difficult to estimate the uncertainty associated with the calculation of GGCs. The highest uncertainty in a materials-based calculation is probably the deviation of materials used in the actual power plant from average materials. Greenhouse gas intensities obtained from input-output analysis have uncertainties of around 15%, but again, the highest uncertainties in a cost-based evaluation probably result from aggregation or inappropriate allocation of plant elements into commodity groups (Bullard *et al*, 1978). Another uncertainty is the effect of structural-economic and technological changes. The cost-based GGC given in this work are calculated from only one input-output table, and hence reflect the economic structure and technology of the base year 1992/93 (compare Proops, 1996). Since greenhouse gas contents of fossil fuels are well-known, the GGC will be quite accurate (uncertainty less than 10%), if emissions from fossil fuel combustion dominate indirect greenhouse gas requirements. However, for solar power plants without a fossil backup system, embodied greenhouse gases exceed direct emissions. In this case, the overall uncertainty of GGCs may be in the order of 50%.

3. Data Sources

Reliable breakdowns of electricity generation plant, both as comprehensive material inventories and as full financial costings, are difficult to obtain. Construction of renewable electricity systems is often undertaken by separate contractors, and the coordinating authority will usually not compile a full material inventory of the project. Financial breakdowns are likely to be more detailed, but again, the coordinating authority is unlikely to have access to the full cost breakdowns of the individual contractors. Furthermore, detailed financial information may well be regarded as confidential, and may not be in the public domain. This is the case for some of the plants examined in Norton *et al* (1998). Objective comparisons with their results are difficult, therefore, because we cannot be sure of all of their inputs.

Cost and material breakdowns were obtained from various literature sources, which are identified along with the results in the following section. As far as possible, cost estimates using a discount rate of between 8% and 10% were chosen and costs for different base years were corrected for inflation. All calculations are valid for a plant location with an insolation between 2300 kWh m^{-2} a^{-1} and 2700 kWh m^{-2} a^{-1}. A service life of 25 years was assumed for all plants.

While monetary greenhouse gas intensities are readily available from an Australian input-output study (Lenzen, 1998), there are hardly any comprehensive data on the greenhouse gas content of materials produced in Australia. Moreover, data from other studies show large variations with respect to the conceptual boundary, the base year, or the whether they include greenhouse gases other than CO_2. Hence, a judgment has to be made on the choice of a sufficiently typical value of greenhouse gas content. Some of these values were estimated from energy contents (for example in Chapman, 1975; Berry *et al*, 1975; Boustead and Hancock, 1979; Frantz and Cambel, 1981; Roberts, 1982; Lund and Kangas, 1983; Hofstetter, 1992; Yasukawa *et al*, 1993; Van Engelenburg *et al*, 1994; Nishimura *et al*, 1996), which were converted into greenhouse gas contents by multiplication with the ratio of monetary greenhouse gas and energy intensities of the producing industry. All energy/greenhouse gas contents and intensities are listed in Table 1. Intensities include requirements from imports and capital investment.

Table 1. Energy/greenhouse gas contents and intensities of materials used in the present analysis. Figures marked with '*' refer to net tonne kilometres of freight.

Material	Energy content (MJ/kg)	Greenhouse gas content (kg CO_2-e/kg)	Energy intensity (MJ/AU$)	Greenhouse gas intensity (kg CO_2-e/AU$)
Aluminium, from ore in the ground	250	23.1	37.9	3.5
Business services			5.7	0.6
Cement, from raw materials	8	1.0	25.3	3.2
Ceramic products			21.0	1.8
Concrete, from raw materials	1.3	0.16	22.8	2.8
Concrete, reinforced, from raw	2.5	0.31	22.8	2.8
Construction work			12.3	1.3
Copper sheet, from ore in the ground	150	13.9	13.1	1.3
Electrical equipment			10.0	1.0
Electronic equipment	436	41.6	9.6	0.9
Fiberglass	11	1.1	12.6	1.3
Films, plastic, from polymer resin	41	4.2	12.6	1.3
Glass, from raw materials in the ground	25	2.0	13.9	1.2
Glue, from raw materials	78	8.3	8.3	0.9
Gravel, from raw materials in the	0.1	0.02	23.1	3.4
Insurance			5.6	0.6
Lead, from ore in the ground	51	4.7	37.9	3.5
Lime, from limestone in the ground	10	1.2	25.3	3.2
Marketing and business management			5.7	0.6
Paints	20	2.0	14.8	1.5
Polyethylene, from crude oil	74	7.6	12.6	1.3
Polystyrene foam, from crude oil	140	14.5	12.6	1.3
Polyurethane, from crude oil	190	15.6	12.6	1.3
Property services			6.0	0.6
PVC, from crude oil	74	7.6	12.6	1.3
Repairs, mechanical			7.6	0.8
Repairs, other			7.5	0.8
Rock	1.0	0.15	23.1	3.4
Rubber, from crude oil	130	13.4	10.3	1.1
Salt	11	1.7	23.1	3.4
Sand, dry, from sand in the ground	0.3	0.05	23.1	3.4
Scientific research			5.6	0.6
Steel, finished products, from ore in	40	3.6	44.5	4.0
Steel, stainless, from ore in the ground	68	6.4	44.5	4.0
Technical services			5.6	0.6
Tinplate, from raw materials	55	5.1	13.1	1.3
Transport, air	*65.1	*5.40	24.5	2.1
Transport, rail	*0.9	*0.08	29.9	2.7
Transport, road	*1.7	*0.13	17.5	1.4
Transport, water	*0.4	*0.03	23.5	2.0
Water supply			10.3	1.2
Waste disposal and landfill	0.4	0.06	5.5	0.8
Wood board, from standing timber	18	2.7	11.2	1.5
Wood poles, from standing timber	13	1.9	11.2	1.5
Zinc sheet, from ore in the ground	90	8.3	13.1	1.3

4. Results

The three solar-thermal power technologies considered in this work are parabolic trough (PT), central receiver (CR), and parabolic dish (PD). Their principles and characteristics are described in detail elsewhere (Trieb *et al*, 1997; Mancini *et al*, 1994; Schlaich, 1994; Pacific Power, 1994; for PTs: Pilkington, 1996; for CRs: Radosevich and Skinrood, 1989; Kolb *et al*, 1991; and for PDs: Hagen and Kaneff, 1991, and Kaneff, 1991).

4.1. Comparison of GGC Calculation Methods

Firstly, the results of both materials- and cost-based analyses for the Solar Two CR and the Australian National University (ANU) 334 m^2 PD are compared. The Solar Two CR is an advanced version of the Solar One CR, retrofitted with a molten salt storage system, which is able to supply the heat needed for six hours of electricity generation at full load (Kolb *et al*, 1991). A 100 MW_{el} conceptual utility delivering 340 GWh_{el} per year was appraised for the calculation of the GGC. A monetary cost breakdown can be found in Kolb (1998), while a materials inventory is given by Vant-Hull (1991). Table 2 summarises the findings of both cost- and materials-based greenhouse gas analyses of the plant, excluding operation and decommissioning. In addition, the cost-based GGC and NER calculated for the same plant by Kreith *et al* (1990) are given.

Table 2. A comparison of cost- and materials-based GGC and NER results for a 100 MW Solar Two CR.

	Greenhouse gases (kt CO_2-e)			Energy (TJ_{th})		
Structural element	cost-based	Materials-based	Cost-based, Kreith *et al*	cost-based	Materials-based	cost-based, Kreith *et al*
Tower, receiver, foundations, and site work	49	40	50	491	389	547
Heliostat field	142	132	148	1493	1364	1621
Salt transport and storage	35	33	59	355	244	642
Steam generator, pipes, and power block	93	84	80	942	847	767
GGC (g CO_2-e/kWh_{el})	37.6	34.7	31.3			
NER (kWh_{th}/kWh_{el})				0.107	0.095	0.085

It can be seen that the embodiments of greenhouse gases and energy obtained from the materials- and cost-based methods are in reasonable agreement. Discrepancies between embodiments obtained in this work and by Kreith *et al* are surprisingly low, given the fact that these authors use US intensities for 1977, which are corrected for technology improvement by an average percentage. The GGCs and NERs calculated from the sum of embodiments of all structural elements are in good agreement. The figures calculated by Kreith *et al* are slightly lower, which is due to the fact that their input-output analysis only considers CO_2 and also excludes requirements from imports and capital investment.

A 100 MW_{el} commercial ANU PD unit utilises 948 of 334m^2 dishes (Kaneff, 1991), achieving an annual output of 234 GWh_{el} without storage. The total system cost are 1990A$ 136 million, while the main materials are steel tubes (948x10 t), concrete (948x10 m^3), other steel products (948x4 t), fibreglass (948x1.6 t), glass (948x0.8 t), and polystyrene foam (948x0.4 t). The cost-based analysis yields a NER of 0.059 kWh_{th}/kWh_{el} and GGC of 21.1 g CO_2-e/kWh_{el}, which cover only the solar field.

The respective values from a materials-based analysis are 0.047 kWh_{th}/kWh_{el} and 16.2 g CO_2-e/kWh_{el}. In both of these cases, the materials-based analysis yields the lower GGC and NER. This is due to the boundary limitations inherent in available greenhouse gas and energy content data, that is, some requirements of higher order were not covered by the corresponding process analysis (see Lenzen and Dey, 2000).

4.2. Fossil Fuel Backup and Hybrid Solar/Combined Cycle Plants

The *capacity factor* of a power plant is defined as the ratio of the annual electricity output to the output power rating multiplied by one year. The operation of solar receivers is limited to daylight periods, resulting in power plant capacity factors of around 20%. The plant operation period, and hence the capacity factor can be increased by installing either a fossil-fuelled backup or a heat storage system, or by hybridisation with a fossil plant. The effect of fossil fuel backup or hybridisation on the plant GGC can be illustrated with the Solar Electricity Generating Systems (SEGS), PTs developed by Luz International Ltd. Figure 1(a) shows GGCs calculated from cost data in (Pilkington, 1996) for various conceptual SEGS and integrated solar/combined cycle systems (ISCCS) with either natural gas (NG) or fuel oil (FO) backup, and optional storage. For comparison, values for some fossil-only power plants are added. The GGCs increase with increasing capacity factor. SEGS with fuel oil backup exhibit slightly higher emissions than identical systems with additional storage. ISCCS with natural gas backup have higher GGCs than SEGS with natural gas backup, because the solar capacity factor of ISCCS is quite low at around 10%, compared with 25% for SEGS.

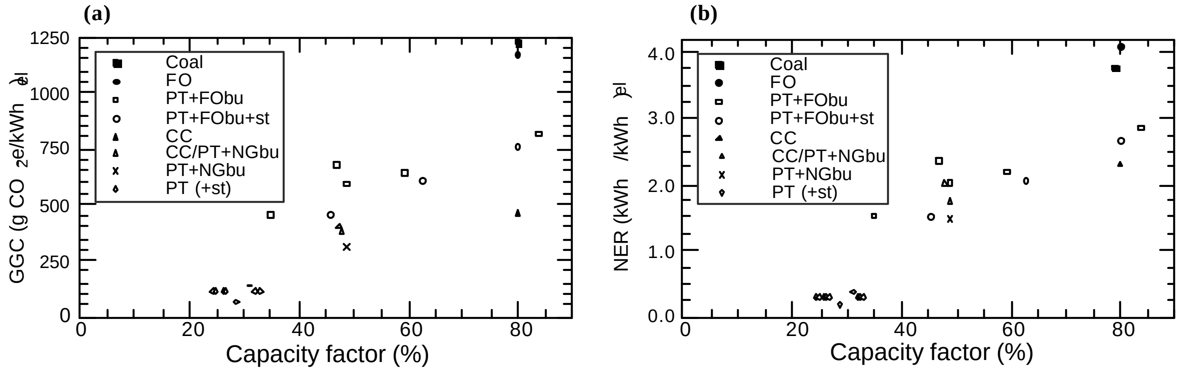

Figure 1. (a) Shows cost based GGC versus capacity factor for solar-thermal power plants using parabolic troughs (PT), and optional fuel oil (FO) or natural gas (NG) backup (bu), or storage (st). The graph also refers to hybrid solar/combined cycle (CC) plants. (b) Shows similar results for cost-based NERs.

The results in Figure 1(a) can be surprisingly well-described by an approximate relation between the GGC of the solar components of the plant GGC_{sol}, the GGC of the fossil components of the plant GGC_{fos}, and the emissions from back-up fuel use. This last quantity can be further described using solar and total capacity factors, the greenhouse gas content of the fuel, and the backup system efficiency. Details are given in Lenzen (1999). For SEGS plants, this breakup gives GGC_{sol} of 108 g CO_2-e/kWh_{el}, $GGC_{fos,FO}$ of 32 g CO_2-e/kWh_{el}, $GGC_{fos,CC}$ = 29 g CO_2-e/kWh_{el}. Therefore the embodied greenhouse gas emissions of the solar plant is approximately a factor of 3.5 greater than that of the fossil backup system. However, and most importantly, the greenhouse gases emitted due to the combustion of backup fuels dominate by far the GGC incurred by the construction of the plant in all cases.

A graph similar to Fig. 1(a) can be drawn for the NER, shown in Fig. 1(b). These NER results can be approximated in a similar manner to the results in Fig. 1(a), with NER_{sol} = 0.3 kWh_{th}/kWh_{el}, $NER_{fos,FO}$

= 0.09 kWh_{th}/kWh_{el}, and $NER_{fos,CC}$ = 0.08 kWh_{th}/kWh_{el} (see Lenzen, 1999). The NER of ISCCS is comparable to that of fuel oil backed-up SEGS, and the NER of natural gas backed-up SEGS is below that of both ISCCS and fuel oil backed-up SEGS. Once again, direct energy requirements from the fossil backup dominate the indirect requirements from the plant construction.

4.3. Energy Storage and Economies of Scale

In solar-thermal power plants, heat obtained from the receiver may be stored for night-time electricity generation. Storage systems have been devised employing media such as air, rock, salt or sodium (see Castro *et al*, 1991, Winter *et al*, 1991 and Brown *et al*, 1992). Figure 3 shows the cost-based GGC and NER of various conceptual plants operating at capacity factors between 15% and 65%. For plants without a fossil-fuelled backup system, GGC (in g CO_2-e/kWh_{el}) ≈ 100·NER (in MJ_{th}/kWh_{el}). The examples include 30 MW Phoebus CRs, 100 MW and 200 MW Solar Two CRs, and other studies (Winter *et al*, 1991; Kolb 1998), as well as SEGS PTs with ratings between 50 MW and 160 MW (Pilkington, 1996). It can be seen that, in general, the GGC and the NER decrease with increasing capacity factor, that is with increasing storage size. This means that additional capacity in the form of heat storage, and an oversized solar field can be installed at lower marginal greenhouse gas and energy cost than the base solar capacity itself. The results are therefore replotted in Fig. 4 as a function of the output rating. This figure shows that there are significant economies of scale in the GGC and NER of parabolic trough and central receiver plants. Especially small CRs show a considerable decrease in both GGC and NER with increasing output rating. Economies of scale are less discernible for larger plants. These effects should not be as strong for parabolic dish plants, due to their modular structure.

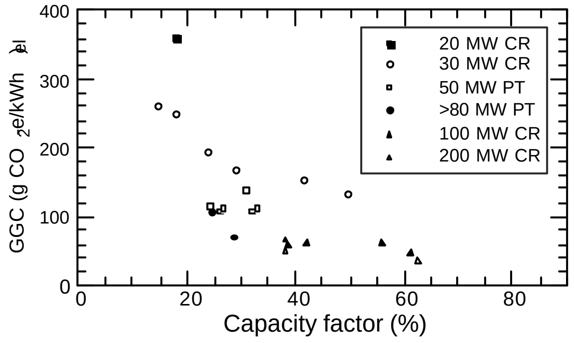

Figure 2. Cost-based GGCs and NERs versus capacity factor for solar-only PT and CR plants with optional storage.

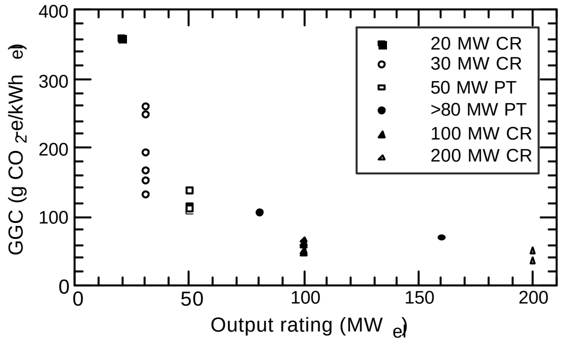

Figure 3. Results from Fig. 3 replotted against plant size.

4.4. Comparison with Other Studies

For a Solar Two CR plant, a comparison of the present work with that of Kreith *et al* (1990) was given in Table 2. Vant-Hull (1991) also looked at this system and obtained results of 12.5 g CO_2/kWh_{el} and 0.045 kWh_{th}/kWh_{el}. These results are more than a factor of two lower than the values given in Tab. 2. A reason for this discrepancy is that Vant-Hull analyses a plant equipped with stretched-membrane heliostats, and assumes energy contents of carbon and stainless steel to be 22.5 MJ/kg and 26.3 MJ/kg, respectively. These values differ considerably from those used in this work, which are 45 MJ/kg and 68 MJ/kg. The NER values quoted from the literature for a 100 MW CR range from 0.05 to 0.16, and are thus lower than the values calculated in this work. However, it could not be established whether these figures include operation and decommissioning, and which assumptions were made about the plant location and lifetime.

Norton *et al* (1998) present CO_2 cost of solar thermal technologies calculated from material contents. Their results are listed in Tab. 3 along with the results from the present study. Norton *et al* assume several different energy contents for processes, depending on the degree of recycling, and the efficiency of the process. Some of the figures given by Norton *et al* for typical material processing are about 20% lower than average values used in this study. Overall, these lower energy contents contribute to making the GGCs of Norton *et al* slightly lower (< 20%) than those calculated here. According to Norton *et al*, GGCs for future plants are projected to be a factor of 4-5 lower than those of present plants.

Table 3. A comparison of materials-based GGCs for three solar thermal electricity technologies.

	GGC - this study	**GGC - Norton *et al* (1998)**		
Technology	Typical process	Typical process	Efficient process	Future process
Central receiver	60	48	21	10
Parabolic trough	90	80	30	20
Parabolic dish	60	58	24	15

Weinrebe *et al* (1998) calculate materials-based GGC for Phoebus CR and SEGS PT plants of 25 g CO_2-e/kWh$_{el}$ and 17 g CO_2-e/kWh$_{el}$, respectively. These values are considerably lower than those calculated in this study. This discrepancy is mainly due to the very low greenhouse gas contents of materials used by these authors (steel: 1.6 kg CO_2/kg, stainless steel: 1.97 kg CO_2/kg, glass: 1.0 kg CO_2/kg, reinforced concrete: 0.18 kg CO_2/kg, copper: 5.08 kg CO_2/kg). If the greenhouse gas contents from Tab. 1 are used, values of 36 g CO_2-e/kWh$_{el}$ and 42 g CO_2-e/kWh$_{el}$ result. These are still below cost-based estimates of around 90 g CO_2-e/kWh$_{el}$, which indicates a discrepancy in the underlying data on plant materials and costs, which at this stage cannot be explained, due to a lack of more detailed information.

The results of other studies investigating GGC of electricity generating systems are summarised in Table 4. The GGC of renewable energy technologies are subject to large variations, which reflects the uncertainty of the underlying analysis as well as the sensitivity of the results with regard to the plant location and to the system boundary, as well as the parameters chosen in the respective study. It is worth noting that the GGC is not a perfect figure of merit for comparing electricity generation systems since it fails to include temporal effects of the emissions. That is, it does not distinguish between emissions which occur mostly early in the life of a plant (as in the case of most renewable plants), and those which occur more evenly over the lifetime of the plant (fossil-dominated plants). Finally, issues such as the dispatchability of generation are not included. A better assessment should take into account the ability of plants to adjust their output to a given demand profile

Table 4. A comparison of GGC values (kg CO_2-e/kWh$_{el}$) for different electricity generation technologies. Values marked with an * are CO_2 only figures.

Technology	Capacity factor (%)	Output (MW)	Lifetime (y)	GGC	Reference	Method
Fossil						
Fossil, Aust. national system	79	23700	-	1224	Lenzen, 1998	I-O
Coal	75	1000	30	1033	Uchiyama, 1996	hybrid
Integrated gasifier combined cycle	80	540	40	*857	Proops *et al*, 1996	I-O
Oil	75	1000	30	692	Uchiyama, 1996	hybrid
Liquefied natural gas	75	1000	30	679	Uchiyama, 1996	hybrid
Liquefied natural gas CC	75	1000	30	543	Yasukawa *et al*, 1993	hybrid
Combined cycle gas turbine	80	340	30	*490	Proops *et al*, 1996	I-O
Fuel cell cogeneration	75	5.0	30	418	Uchiyama, 1996	hybrid
Geothermal						
Standard utility, Japan	60	10	30	*41	Yasukawa *et al*, 1993	hybrid
Double-flash type	60	55	30	23	Uchiyama, 1996	hybrid
Hydro						
Standard utility, Japan	45	10	30	*26	Yasukawa *et al*, 1993	hybrid
250 m head, Japan	45	10	30	18	Uchiyama, 1996	hybrid
PV						
Monocrystalline "Solar grade Si"	13	1.0	30	*151	Yasukawa *et al*, 1993	hybrid
Polycrystalline modules	15	1.0	30	127	Uchiyama, 1996	hybrid
Monocrystalline modules	11	1.5	20	*150	Schaefer and Hagedorn, 1992	mat
Amorphous modules	11	1.5	20	*100	Schaefer and Hagedorn, 1992	mat
Polycrystalline modules	23	1.5	20	*50	Schaefer and Hagedorn, 1992	mat
Amorphous modules	23	1.5	20	*50	Schaefer and Hagedorn, 1992	mat
PV, scaled up to utility size	16	2000	30	*95	Proops *et al*, 1996	I-O
EPRI single-axis design study	21	97	30	*29	Kreith *et al*, 1990	I-O
Solar thermal						
Solar pond	-	-	-	6	Norton *et al*, 1998	mat
Wind						
Upwind propeller, ∅ 30 m	28	1.0	30	*34	Yasukawa *et al*, 1993	hybrid
Unspecified UK utility	29	6.6	20	*104	Proops *et al*, 1996	I-O
Downwind propeller	20	0.1	30	125	Uchiyama, 1996	hybrid

5. Conclusion and Future Developments

The contribution of solar-thermal electricity generation to climate change can be assessed by calculating greenhouse gas costs (GGC) incurred during the provision of services and production of materials needed for the construction and operation of solar power plants. Both process and input-output analysis are able to yield GGC of solar-only plants with an uncertainty of about 25%, at a moderate level of input data detail. The uncertainty of the GGC for hybrid systems decreases with increasing fossil share. The GGC of utility-size solar-only parabolic trough, central receiver and parabolic dish plants range from 30 g CO_2-e/kWh$_{el}$ to 120 g CO_2-e/kWh$_{el}$. Furthermore, GGC vary with plant size and, most importantly, depend on whether a fossil-fuelled backup or a heat storage system is chosen in order to increase the plant's capacity factor. Comparisons with other renewable electricity generation technologies must be judged with care, because of differences in the assessment boundary and methodology, as well in the power plant's location, lifetime, capacity factor, dispatchability, and other characteristics.

The embodied energy and greenhouse gas data and methodology presented constitute a further design constraint in the planning of future sustainable electricity generation capacity. Our intention is to combine the embodied energy and greenhouse gas model with the performance and financial models of renewable plants. Once this integration has been completed, the relative energy, emissions, and monetary costs of various design decisions may be evaluated. Ultimately, such a process would also include temporal effects of greenhouse gas emissions to give an overall figure of effective radiative forcing for a given electrical output.

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