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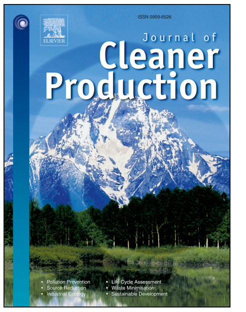

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Carbon Footprint Scenarios for Renewable Electricity in Australia

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Abstract

Despite considerable mitigation efforts, global emissions from the electricity sector continued to grow in recent years. In Australia, the electricity sector is the largest CO_2-emitting industry, contributing 35% of the country's total greenhouse gas emissions. The Australian government targets an 80% reduction of greenhouse gas emissions by 2050 relative to 2010. With a large variety and quantity of renewable energy resources, it is technically feasible and seems indispensable that Australia's electricity sector be largely decarbonised by 2050 in order to achieve this target. In this paper, scenario-based hybrid Life-Cycle Assessment is applied to calculate the economy-wide carbon footprints of seven electricity generation technologies in scenarios with differing renewable electricity penetration. This work is the first to apply a full life-cycle approach to scenario analysis of electricity generation in Australia. The findings are at the higher end of previously reported carbon footprint intensity ranges and above median values. However, even when taking into account indirect emissions along the technologies' life-cycles, the results indicate that the employment of different renewable energy technologies can potentially save a considerable fraction of Australia's greenhouse gas emissions. This makes renewables an essential option for climate change mitigation.

1. Introduction

Despite considerable mitigation efforts, global emissions from the electricity and heating sector continued to grow by more than 3% per year on average between 2000 and 2009 (Bruckner et al. 2014). Australia made a binding commitment to reduce greenhouse gas emissions (GHGE) by at least 5% by 2020 compared to 2000 levels (UNFCCC 2012). Australia's Intended Nationally Determined Contribution to the 2015 Paris Agreement on climate change is an economy-wide target to reduce GHGE by 26 to 28% below 2005 levels by 2030 (DPMC 2015), but commentators have questioned whether this can be achieved with existing and proposed policies (Pears 2015, Vorrath 2015). For 2050, an even more ambitious target of 80% emission reduction is envisaged (DOE 2012). This target was accompanied by the Renewable Energy Target scheme for large-scale electricity generation of 41 TWh/year by 2020 (Diesendorf 2014), reduced in 2015 to 33 TWh/year by 2020 (Parkinson 2015).

Meanwhile, fossil fuels made up 84% of Australia's electricity generation in 2012-13 (BREE 2014a, Table 4.1). Thus, electricity generation is the largest emitting industry in Australia with around 35% of total emissions (ClimateWorks et al. 2014, DOE 2012). Future demand growth is uncertain: some authors forecast that Australia's electricity demand will increase considerably by 143% by 2050 (ClimateWorks et al. 2014), although actual demand for grid electricity has declined each year since 2010 (BREE 2014a, p. 42).

Australia has huge resources of solar, wind and hot rocks (the latter for engineered geothermal power), significant resources of biomass residues and wave power, and modest hydro resources (Geoscience Australia & ABARE 2010). Given the commercial availability of solar and wind technologies, it seems more likely to achieve deep cuts to GHGE in the electricity sector than in other sectors such as agriculture or non-energy, heavy manufacturing industries – sectors in which low carbon options are less abundant (Buckman & Diesendorf 2010). Following this rationale, Elliston et al. (2014) argued that the electricity sector should be virtually completely decarbonised in order to achieve the 80% cut. Hourly computer simulations of the operation of Australia's National Electricity Market show that 100% renewable electricity, based mostly on commercially available technologies, is technically feasible and would be reliable and affordable (Elliston et al. 2013, 2014, AEMO 2013). Simulations in the USA have shown that a large-scale integration of wind, water, and solar energy into the power grid is feasible while maintaining reliability of supply and at low cost (Jacobson et al. 2015). However, even if 100% renewable electricity were achieved, with zero emissions during operation, the economy-wide supply chain emissions of the whole electricity sector would not necessarily be emission-free.

This article investigates how effective the large-scale implementation of renewable energy in Australia is likely to be, including total emissions during the whole life-cycle of different technologies. The two main questions addressed are 'Even if all electricity generation processes are completely carbon free, what are the remaining, indirect GHGE associated with the provision of electricity?' and 'What proportion of the intended 80% emissions reduction by 2050 can be achieved by 100% renewable electricity technologies alone (without reductions in other sectors of the economy)?'. Answering questions such as these sheds light on the interdependencies of industry sectors and their associated emissions and can help making emission reduction strategies more efficient and effective.

In order to answer the questions above, a novel scenario-based approach to hybrid Life-Cycle Assessment (hLCA) is employed in this work to evaluate a range of different renewable electricity scenarios. The focus metric of the analysis is the total carbon footprint (CF) of electricity as a final service product. The CF is an indicator that analyses and quantifies not only direct but also indirect GHGE of a product, process, activity or entity (Gao et al. 2014, Wiedmann & Minx 2008, ISO 2013). It is therefore well suited to identify the indirect (embodied) GHGE of electricity provision, even if all electricity is produced with renewables. The materials and economic sectors that contribute most to the CF of electricity are quantified and alternative options are compared. The scenario outcomes are also compared to a national carbon budget for Australia which represents the total amount of GHGE that can still be emitted (per country) before global warming exceeds 2°C. It is the first time that this hLCA-based scenario approach is being used for the electricity sector and results are presented for Australia.

2. Electricity generation scenarios with embodied emissions

Energy scenario models often ignore embodied emissions of energy technologies. Hertwich et al. (2014) perform the first full life-cycle approach to different electricity generation options at a long-term and global scale. Their underlying global scenarios are the climate-change-mitigation (BLUE Map) and the baseline scenario of the International Energy Agency. The baseline scenario assumes a 22% share of renewables and 57 Gt of energy-related CO_2 emissions globally in 2050. The more optimistic BLUE Map scenario assumes a 48% renewables share and 14 Gt CO_2 emissions. As a result, global GHGE can be reduced by 62% by 2050 relative to the baseline scenario. Similar work has been performed recently by Arvesen & Hertwich (2011), Gibon & Hertwich (2014) and Gibon et al. (2015).

Stamford & Azapagic (2014) apply a life-cycle scenario approach to electricity generation in the UK and extend the time frame to 2070. The study considers different economic, environmental and social impacts and explores 65, 80 and 100% reduction scenarios of electricity-related GHGE. It is found that a high penetration of renewable and nuclear power scores best in terms of GHGE but compromises health and other social concerns and increases material use by a factor of seven.

Bush et al. (2014) assess micro-scale wind and solar power systems in the UK considering PV facility degradation due to ageing of the system. Taking into account full life-cycle emissions and UK-specific solar and wind resources, the article concludes that, at current efficiencies, it will not be possible to meet UK's targeted electricity carbon intensity of 50 g CO_2e/kWh by 2030. Thus, efficiencies will need to improve in the future. Scott & Barrett (2015) calculate two UK consumption emission trajectories in a future with a temperature rise by two and four degrees Celsius, respectively. Assuming that the UK meets its 80% reduction goal in 2050 relative to 1990, the authors estimate that, by 2050, UK consumption emissions are 40-260% greater than UK territorial emissions depending on the strength of global emission reduction efforts.

Daly et al. (2015) link a bottom-up energy system optimisation model to an input-output model and find that, by 2050, marginal abatement cost for the mitigation of direct and indirect emissions of UK energy supply are roughly double compared to the mitigation of direct emissions alone. Similar hybridisation of IO- and optimisation models has been performed e.g. by Menten et al. (2015) and García-Gusano (2015) and also exists for sectors other than electricity such as transport (see e.g. Noori et al. 2015).

The many other scenarios for 80-100% renewable electricity (e.g. Mai et al. 2012, Elliston et al. 2012 and others listed in Cochran et al. 2014) only consider direct emissions from power plants but not life-cycle emissions.

3. Methods

As set out in the introduction, the emphasis of this work is on the carbon footprint (or total life-cycle GHGE) of electricity generation. Two fundamental methods have been described in the literature for calculating CFs: bottom-up, based on process analysis (PA), and top-down, based on input-output analysis (IOA, Wiedmann 2009). PA allows for detailed assessments of specific processes with relative precision, due to the possibility of using primary physical data. This makes PA suitable for applications at the product-level scale. However, earlier research has shown that the system boundary using PA can be up to 80% incomplete (Crawford 2005, Lenzen 2000). IOA on the other hand is based on modelling the interdependencies between different economic sectors, which makes system-cut offs unnecessary but comes at the expense of resolution (Minx et al. 2009, Peters 2010).

3.1 Carbon footprint calculations using IO-based hybrid LCA

A full CF calculation requires the inclusion of all globally emitted GHGE that are associated with the production of goods and services for final demand. In this work, the functional units are both one kWh and total annual final demand of electricity consumed in Australia.

Input-output tables (IOTs) were initially formulated by Leontief (1936) and have since become an integral part of most national economic accounts (Miller & Blair 2009, UN 2009). Extending IOTs with environmental interventions by industries allows broad, economy-wide assessments of environmental footprints to be conducted (Ewing et al. 2012, Kitzes 2013, Nagashima et al. 2015).

Following the standard IOA calculus, a decomposition of the total carbon footprint $\boldsymbol{CF_{ij}}$ of a product $\boldsymbol{j}$ showing GHGE originating from industry $\boldsymbol{i}$ can be calculated as shown in (Eq. 1) (see also Wiedmann et al. 2015).

$$\boldsymbol{CF_{ij}} = (\widehat{\boldsymbol{E_i} \times \boldsymbol{x_i}^{-1}})(\boldsymbol{I} - \boldsymbol{A})^{-1}\hat{\boldsymbol{y}}_j \qquad \text{(Eq. 1)}$$

where

- $(\widehat{\boldsymbol{E_i} \times \boldsymbol{x_i}^{-1}})$ is a diagonalised vector of industry emission intensities. $\boldsymbol{E_i}$ is a 1×n row vector of direct industry emissions and $\boldsymbol{x_i}$ is a 1×n row vector of total industry outputs of sector $\boldsymbol{i}$. The hat symbol (^) indicates diagonalisation; × indicates element-wise multiplication.
- $\boldsymbol{I}$ is an n×n identity matrix with ones exclusively on its diagonal and otherwise zeros.
- $\boldsymbol{A}$ is the technology coefficient matrix of the size n×n. Its elements $\boldsymbol{a_{ji}}$ are derived with $\boldsymbol{a_{ji}} = \boldsymbol{x_{ji}}/\boldsymbol{x_i}$ where $\boldsymbol{x_{ji}}$ is the product output of sector $\boldsymbol{j}$ that is used by sector $\boldsymbol{i}$ to realise its own production.
- $\hat{\boldsymbol{y}}_j$ is a diagonalised n×1 column vector of final demand of product $\boldsymbol{j}$.

While both PA and IOA have been used on their own for carbon footprinting, the combination of both in hybrid Life-cycle Assessment (hLCA) has emerged as state-of-the-art method by practitioners and researchers (Suh et al. 2004). Hybrid approaches preserve PA accuracy for crucial processes, while higher upstream processes are covered by IOA, thus combining the strengths of both methods. In this paper, the IO-based hLCA method is applied, which involves disaggregation of industry sectors in the IOT and subsequent augmentation with process data (Malik et al. 2014, Wiedmann et al. 2011).

The first step in the IO-based hLCA method is to convert physical to monetary values for specific process-based inputs. Process data is typically available in physical units (e.g. t/kWh). In order to be entered into an IOT it has to be converted into monetary values. Therefore, each process value is multiplied by the price of the raw material (e.g. AUD/t) and by the total output of the respective electricity industry (e.g. wind) in kWh. Prior to this exercise, price data has to be gathered. As the Australian Bureau of Statistics (ABS) does not publish prices for raw materials and products, they are estimated by dividing the total monetary value of the depicted sector (e.g. cement) by its total physical output in one year. Furthermore, this purchaser's price is converted to basic price using conversion ratios from the ABS (2012, Table 4). A discount of 20% is applied to account for bulk purchases. Moreover, prices are inflation-adjusted and converted from foreign currencies to AUD using the average 2009 exchange rate, as IO-data from 2009 is used.

The second step involves disaggregating electricity columns and rows in the Supply-and-Use Table (SUT) (see section 4.1 for more details on the SUT used). This is to enable an explicit representation of all different types of electricity generation in the model, which is required for accurate calculations (Lindner et al. 2013). The ABS SUT in its original form discerns three electricity sectors (fossil fuels, hydro, non-hydro renewable electricity), which are further broken down into 16 sub-sectors as follows. Fossil fuels are broken down into black coal, black coal carbon capture and storage (CCS), brown coal, direct-injection coal engine, natural gas, natural gas CCS, oil and other fossil fuels. Hydro power (HP) remains as one sector. Non-hydro renewable electricity is broken down into biomass, wind onshore, wind offshore, solar photovoltaic (PV), concentrated solar power (CSP), wave and geothermal. By default, the disaggregated sectors are scaled according to their share in Australia's 2009 electricity mix. These shares are applied to both the Supply and the Use table and to both columns and rows.

In the third step, the monetised process data for all electricity types are inserted into the disaggregated electricity columns in the Use table, replacing some of the original, pure IO-based inputs thus. This specifies the purchases $\boldsymbol{x^*_{ij}}\ \forall\ \boldsymbol{j}$ that each electricity generation sector $\boldsymbol{j}$ makes from other sectors (such as steel; cf. Vendries-Algarin 2014). This leads to updated input vector $\boldsymbol{x^*}$ and technology coefficient matrix $\boldsymbol{A^*}$.

For Use table rows the default sales structure of the original electricity sector is used, since information that provides more detail on which industries purchase which type of electricity is unavailable (Wiedmann 2011, Vendries-Algarin 2014). For the Supply table it is assumed that each electricity industry only uses one technology and produces one type of electricity. All values at the intersection of electricity industries and corresponding electricity products are hence located on the diagonal. This assumption is not applied to the Use table (as opposed to Vendries-Algarin 2014) as different electricity industries can purchase any type of electricity.

In a final adjustment step, the direct emissions from each electricity sector are adjusted based on available process data, resulting in an adjusted vector of direct industry emissions $\boldsymbol{E^*}$. The updated equation for the CF calculation becomes:

$$\boldsymbol{CF^*_{ij}} = (\widehat{\boldsymbol{E^*_i} \times \boldsymbol{x^*_i}^{-1}})(\boldsymbol{I} - \boldsymbol{A^*})^{-1}\hat{\boldsymbol{y}}_j \qquad \text{(Eq. 2)}$$

The results of (Eq. 2) are total carbon footprints of final demand for each type of electricity, expressed in Mt CO_2e. The relative carbon footprint intensity $\boldsymbol{cf}$ for each electricity product $\boldsymbol{j}$, expressed in g CO_2e/kWh, is then obtained as $\boldsymbol{cf_j} = \boldsymbol{CF_{ij}}\, \boldsymbol{z_j}^{-1}$ where $\boldsymbol{z_j}$ is the actual amount of finally demanded electricity in physical units (ABS 2011).

3.2 Scenario analysis

Consequential LCA (CLCA) allows the inclusion of dynamic effects in LCA and is increasingly applied to evaluate the effects of systemic changes (e.g. Pehnt 2006, Earles & Halog 2011, Plevin et al. 2013). IOA is particularly suitable for CLCA as changes in production recipes can be modelled at an economy-wide level as a consequence of changes in demand. IO-based scenario analysis is applied in this work as a means to include consequential elements into the hLCA method.

The business-as-usual (BAU) scenario (referred to as S1) is based on the default case of CSIRO's e-future web tool (CSIRO 2015), in which electricity demand is forecast to grow from 229 TWh in 2015 to 353 TWh by 2050. The share of renewable electricity in 2050 is 36%. The second scenario (S2) is based on ClimateWorks et al. (2014)[1] who present a scenario that assumes 96% renewable electricity supply combined with a large growth in electricity demand of 143% by 2050 relative to 2010. Scenarios three (S3) and four (S4) are combinations of the former two and represent a worst case and a best case, respectively. S3 projects lower electricity consumption consistent with S1 and a 96% renewable electricity mix and annual average emission reduction compatible with S2. In S4, higher electricity consumption growth, consistent with S2, is assumed and combined with the electricity mix and annual emission reduction rates of S1.

The changes based on these scenarios are introduced as exogenous parameters in the 2009 SUT in five-year intervals, i.e. updated SUTs are produced for the years 2015, 2020, 2025 and so on until 2050. The columns and rows that have been disaggregated and augmented with process data beforehand are scaled up according to the size of each electricity generation technology as defined by the scenarios (see Figure S1 in the SI).

By doing so, the original table is imbalanced in the first place, i.e. total inputs do not equal total outputs anymore. To rebalance the table and thus model endogenously changes in all other sectors of the economy, this work follows the "analytical approach" presented by Malik et al. (2014, p. 86). For each five-year interval $\boldsymbol{t}$ a new total output $\tilde{\boldsymbol{x}}$ and a new supply and use table $\tilde{\boldsymbol{T}}$ is calculated from changed final demand $\tilde{\boldsymbol{y}}$ according to (Eq. 3) and (Eq. 4):

$$\tilde{\boldsymbol{x}}_t = (\boldsymbol{I} - \boldsymbol{A}^*)^{-1}\tilde{\boldsymbol{y}}_t \qquad \text{(Eq. 3)}$$

$$\tilde{\boldsymbol{T}}_t = \boldsymbol{A}^*\hat{\tilde{\boldsymbol{x}}}_t \qquad \text{(Eq. 4)}$$

This approach effectively adjusts inputs of all sectors in the economy in order to match new, scenario-generated, outputs. The implicit assumption in this approach is that the production recipes of sectors do not change, i.e. input proportions remain constant (and so does the technology coefficients matrix $\boldsymbol{A}^*$) except for coefficients in electricity product rows. Only the total levels of inputs are adjusted as a consequence of changes in total sector outputs. New direct GHGE of all industry sectors in the scenario economy can be calculated as in (Eq. 5), based on the assumption that the emissions intensity of industries has not changed over time (industry index $\boldsymbol{i}$ omitted):

[1] Note that ClimateWorks et al. (2014) also consider electricity for transportation, which is not within the scope of this study, however.

$$\widetilde{E_t} = \widetilde{x_t} \times (E^* \times x^{*^{-1}}) \qquad \text{(Eq. 5)}$$

This means that it is not assumed in the scenarios that industries other than electricity production improve their carbon efficiency. It is likely that all industries actually achieve some emission reductions over the long time period considered, however, the assumption of no changes to industrial carbon intensities is taken for two reasons. First, it is not within the scope of this study to find data for and model all industry sectors and second, it allows for impact analysis of electricity in isolation. Further details are given in Wolfram (2015).

In section 5, the CF of finally demanded electricity, direct GHGE of electricity-generating industries and direct GHGE of all industries in Australia are presented.

4. Data

The two main types of data used for this article are input-output data and process data, described in detail below. The combination of these two is typical for state-of-the-art hLCA as described above.

4.1 Input-output data

In this work, an SUT from the Industrial Ecology Virtual Laboratory (IELab) is used, which originates from a national SUT for the accounting year 2008-09 from the Australian Bureau of Statistics (ABS 2012). The IELab is a novel collaborative research platform for data and knowledge sharing, jointly facilitated by nine collaborating Australian institutions (http://ielab.info, Lenzen et al. 2014). The IELab allows for a flexible compilation of multi-regional SUTs with a choice from 1284 product groups and 2214 regions of Australia. A table of intermediate size that represents a compromise of practicality and sufficient detail has been compiled for this study. The tailored SUT with a total of 215 rows and columns in both the Supply and the Use table ensures that those sectors that represent specific process inputs for electricity generation are included in their maximum disaggregation (see Figure S1 and further information in the SI).

To account for international trade, a multi-regional input-output (MRIO) framework is used which overcomes the unrealistic assumption of single-region input-output models that imported goods have the same carbon intensity as goods produced with domestic technology. In this case, the MRIO framework consists of a national SUT for Australia and a Rest-of-the-World (RoW) IOT linked by tables for imports and exports. RoW data is taken from the Eora database (Lenzen et al. 2012, 2013) in its simplified format of 26 economic sectors (see Supporting Information in Wiedmann et al. 2015).

4.2 Process data

Case study power plants are modelled with process data from the latest Ecoinvent 3.1 database (Ecoinvent 2014) and from an LCA study on CSP[2]. The whole life-cycle of power generation from raw material mining to decommissioning is consistently considered. This includes transportation and energy requirements during all life-cycle stages, construction, operation and maintenance of plants, and disposal at the end of life. Recycling is not considered. The impact indicator is IPCC's 2007 global warming potential over 100 years (GWP 100). As a result, unit-based CO_2-equivalent (CO_2e) emissions of 1 kWh of consumed electricity are obtained for each technology.

Different studies show that the location of production can alter the CF of a renewable technology considerably (e.g. Lenzen & Wachsmann 2004, Yue et al. 2014). To better reflect the carbon intensity of Australian electricity, respective adjustments are made by replacing some Ecoinvent data with country-specific process data from AusLCI, an Australian life-cycle database (ALCAS 2011). This is done for both PA and hLCA calculations. For some other input materials own calculations are applied, see SI for more details.

5. Results and discussion

Overall, the results indicate that the employment of different renewable energy technologies can save a considerable fraction of Australia's GHGE, even when taking into account indirect emissions along the technologies' life-cycles.

[2] As CSP data is not directly available in Ecoinvent, mass inputs and impact factors provided by Burkhardt et al. (2011) are used. Burkhardt and colleagues model a hypothetical plant in Dagget, California, USA where climatic conditions are comparable to Geraldton, Western Australia. In both regions annual direct solar insolation is approximately 2700 kWh/m^2.

5.1 Carbon footprint of renewable electricity in Australia

The carbon footprint intensities of different electricity types and their breakdown according to main categories are shown in Figure 1. Results are shown for both PA and hLCA. The PA breakdown shows the CF contributions of materials and processes. Hybrid LCA adds further upstream, economy-wide emissions that are cut off in pure PA, thus increasing the final footprints considerably (see lower part of each twin bar in Figure 1). The breakdown of hLCA results shows the origin of main GHGs from different industries that are emitted along the whole supply chain of power generation.

One striking difference between PA and hLCA results for all technologies is the influence of upstream electricity emissions in hLCA. Generally, the highest contribution in hLCA is due to electricity inputs ranging from 32% for CSP to 62% for run-of-river and reservoir HP. This includes electricity use by *all* processes along the life-cycle, e.g. electricity used in the production of steel, copper, aluminium, plastics, et cetera. While PA data capture this to some degree, hLCA results obviously reflect the extended system boundary and the specific Australian carbon intensities of all industries. Australia's carbon-intensive electricity mix is dominated by coal and gas.

Geothermal electricity has the highest CF intensity for both PA (79.7 g CO_2e/kWh) and hLCA (92.2 g CO_2e/kWh), exceeding the results for all other technologies. Run-of-river hydropower (HP) lies on the other end of the range with a CF intensity of only 5.0 g CO_2e/kWh for PA and 37.2 g CO_2e/kWh for hLCA.

According to the results from PA, cement contributes about half to the GWP of HP (44% for run-of-river, 55% for reservoir). The major contributors to the CF of wind power are steel and iron (about 45%, cf. Wiedmann et al. 2011). For both solar technologies, almost half of the impact potential is due to electricity requirements (40 - 49%). Fossil fuels contribute to more than a third to the CF of geothermal power. The CF intensities from pure PA and the contribution of main material and energy inputs are further detailed in Table S1 in the SI. Results from hLCA show a different breakdown. Generally, the highest contribution is due to electricity inputs ranging from 32% for CSP to 62% for run-off-river and reservoir HP (as mentioned above). Geothermal is the only exception with a contribution of only 14% from electricity. Conversely, the mining sector is the main contributor to the CF of geothermal (68%) while contributing only 5 to 10% to the CF of all other technologies.

Figure 1. Carbon footprint intensities of different types of renewable electricity generation calculated by PA (upper part of the twin bar) and hLCA (lower part of the twin bar). Error bars have been calculated for indicating sensitivity ranges.

An MRIO approach, as applied in this work, allows for taking into account the environmental impact potential of imported goods. These add up to one fifth to the total hLCA-based CFs. Geothermal has the lowest relative impact from imports (7.3%) and reservoir HP the highest (20%). Consistently, imported petroleum, chemical and non-metallic mineral products contribute the most to the imports fraction of the CFs (2.8 - 6.4%).

In general, the results of this article fall within the range of other studies. Compared to an extensive harmonisation and review study by Asdrubali et al. (2015), the findings are at the higher end of reported CF intensity ranges and above median values. This is mainly due to two facts: 1) hLCA is applied and therefore all higher upstream, indirect emissions, are included and 2) by incorporating Australia's economy as a background system, Australia's high carbon intensity of production (in particular electricity production) is taken into account.

5.2 Carbon footprint reductions under the different scenarios

As demonstrated in section 5.1, electricity inputs generally have the highest share in the hLCA-based CF of renewable electricity. This implies that renewable electricity has a lower carbon intensity when the overall electricity mix is less carbon-intensive as well. Therefore, the scenarios analyse to what extent the CF of final demand of renewable electricity can be reduced if the use of fossil fuels is reduced and the share of renewables is increased. It is assumed that the GHGE of the electricity sector are reduced while all other sectors retain their carbon intensity.

As expected, a reduction in CFs is achieved for all case study technologies due to carbon reductions in the electricity sector (Figure 2). Yet the magnitude in the reduction potential differs. The highest CF reductions can be achieved for reservoir HP consistently in all scenarios, ranging from 46% in S4 to 74% in S3 in 2050 relative to 2009[3]. As a result, reservoir HP even arrives at the same

[3] Run-of river HP is no longer considered in this analysis as the share of electricity generation from run-of river power plants is negligible compared to reservoir HP plants.

carbon intensity as wind onshore and wind offshore power by 2050: 9.5 vs. 9.6 vs. 9.5 g CO_2e/kWh, respectively (S3). The lowest reduction is achieved for geothermal power, ranging from 45% (S4) to 64% (S3) which is due to the relatively low contribution of electricity inputs to geothermal's CF.

Figure 2. Changes in CF intensity of different renewable electricity generation technologies due to changes in the energy mix assumed in scenarios (a) S1, (b) S2, (c) S3 and (d) S4 (RHP denotes reservoir hydro power).

In all scenarios, both the direct emissions from power plants as well as total carbon footprints of final demand for electricity (including indirect or supply chain emissions) decrease. However, they do so at different speeds (Figure 3). Direct GHGE are reduced to 3.9 Mt/a by 2050 in the best-case scenario (S3). This equals to a 97% reduction relative to 156 Mt CO_2e in 2009. Under the worst-case scenario, S4, direct GHGE account for 102 Mt in 2050, which represents a 35% reduction.

Figure 3. Direct GHG emissions from electricity production and carbon footprints of electricity as a finally demanded product under scenarios S1 to S4.

Note that electricity-related CFs are considerably lower than direct emissions from electricity generation. This is due to the fact that only households consume electricity as a *final* product. All other industrial consumers, such as manufacturing sectors or the commercial or public sector buy electricity as an *intermediate* product. In CF calculations the emissions associated with this intermediate use are allocated to the final product, e.g. emissions from the steel industry are allocated to the purchase of a family car or electricity-related emissions from hospitals are allocated to medical services. Furthermore, the CF emissions of electricity come from many sources, not only the electricity sector. As a consequence, reductions in electricity CFs are lower than reductions in direct GHGE (Figure 3Table 1. Direct GHG emissions of the electricity sector (El.-GHGE), CFs of finally demand electricity in 2050 (El.-CF) and total economy-wide industry emissions in 2009 and in 2050 under scenarios S1 to S4. and Table 1). Even if emissions from electricity are reduced, other sectors might not reduce their emissions. In fact, it is assumed in the scenarios that the carbon intensity of other sectors is not reduced. This way, the influence of the electricity sector to Australia's

80% target can be evaluated in isolation from the potential contributions of other sectors. Under S3, total economy-wide industry emissions decrease from 495 Mt in 2009 to 402 Mt in 2050, which equals a 19% reduction. Conversely, the worst-case scenario, S4, represents a growth of all industry emissions by 2%, because the gains in electricity carbon efficiency are too little and cannot outweigh increased electricity consumption (see Table 1).

Table 1. Direct GHG emissions of the electricity sector (El.-GHGE), CFs of finally demand electricity in 2050 (El.-CF) and total economy-wide industry emissions in 2009 and in 2050 under scenarios S1 to S4.

	Base year 2009	**S1 2050**	**S2 2050**	**S3 2050**	**S4 2050**	**unit**
El.-GHGE in 2050	156	59	8	4	102	Mt CO_2e/a
Reduction 2009-50		-62	-95	-97	-35	%
El.-CF in 2050	47	20	4	2	35	Mt CO_2e/a
Reduction 2009-50		-58	-92	-96	-26	%
Total economy-wide industry emissions	495	459	411	403	505	Mt CO_2e/a
Reduction 2009-50		-7	-17	-19	+2	%

5.3 Considerations on a carbon budget for Australia

The global carbon budget is defined as the maximum amount of GHGE that can be emitted worldwide in order to stay below a global warming of 2°C (Meinshausen et al. 2009). A brief evaluation of Australia's cumulative GHGE between 2013 and 2050 is carried out here to examine whether Australia is likely to keep its national GHGE within a limit that would be in line with global warming not exceeding 2°C. According to Ecofys (2013), Australia can be assigned an (unofficial) carbon budget of 18 Gt, of which two thirds have been already used up between 1990 and 2012 (WWF 2013). That leaves a budget of roughly 6 Gt for the period 2013-2100, assuming that emissions will be zero post-2100. The underlying assumption for these figures is that per-capita GHGE of all countries converge to an equal level at some point in the future (referred to as "convergence point") and then decrease to zero altogether. This principle is called "Contraction & Convergence" and has been established by the Global Commons Institute (GCI 2008, also cf. Renaud & Matthews 2015, Meinshausen et al. 2015).

Under S1, S2 and S4, cumulative economy-wide GHGE (producer perspective) exceed 6 Gt before the end of 2024. Surprisingly, the results indicate that even in the best-case scenario, S3, the budget is already used up early in the year of 2025 (see Figure 4). This clearly shows that emission reductions in the electricity sector alone are by far not sufficient to achieve GHGE levels commensurate with a 2°C warming.

Figure 4. Cumulative direct economy-wide GHGE in relation to the available carbon budget in the scenarios S1 to S4.

Though renewable electricity options have substantially lower CFs compared to fossil fuel options, it is demonstrated that even a strong renewable electricity penetration *on its own* is insufficient to meet Australia's 80% target by 2050, nor to stay within the national carbon budget. Further efforts have to be taken beyond renewable electricity deployment (and electricity efficiency) to reduce Australia's GHGE decisively. This finding is consistent with those of other studies, see e.g. Palmer (2012), Dietz & O'Neill (2013), or BREE (2014b).

However, detailed global and US national scenarios explore the feasibility of providing worldwide energy for all purposes (i.e. electric power, transportation and heating) from renewable *electricity* (Jacobson & Delucchi 2011, Delucchi & Jacobson 2011, Jacobson et al. 2015). In this case, electricity demand would be higher, but providing renewable electricity could substitute for the majority of the GHGE from fossil fuels.

5.4 Sensitivity analysis

To demonstrate the accuracy of the seven renewable electricity CFs, a simple sensitivity analysis of the hLCA model is performed by varying prices by ± 20% (adopted from Wiedmann et al. 2011). The changes in CFs range between ± 3% for run-of-river HP and ± 19% for CSP. The sensitivity ranges are also illustrated with error bars in Figure 1.

The higher sensitivity of solar technologies, especially of CSP, is due to the number of process data inputs in the respective LCI of each electricity type. While the LCI of run-of-river HP has merely 23 input processes from the Ecoinvent database, CSP has 224. The higher the amount of input processes, the more monetary values have to be estimated for the hybridisation process, thus increasing the uncertainties associated with price conversion.

6. Assumptions and limitations

The scenarios applied in this article assume that only the electricity sector is being decarbonised over time whilst other sectors in the economy – most notably heavy industry and transport – are assumed to continue operating with their current carbon intensity. Whilst this might not be the case in reality, the approach allows for a focus on the electricity sector and its potential to lower GHGE *on its own* without changes in other sectors.

In terms of the modelling approach, by comparing results from pure PA to results from hLCA, it is demonstrated that CFs of energy carriers are often underestimated. This emphasises the usefulness of hybrid approaches, however, some limitations inherent to hLCA shall be mentioned explicitly:

1. The usual assumptions and constraints of input-output analysis apply, i.e. homogeneity and non-elasticity of prices as well as proportionality between price and environmental impact (Miller & Blair 2009).

2. Replacing IO data with process data in the SUT is based on the subjective choice of the practitioner and therefore potentially biased. For example, a chosen IO sector *a* might not adequately reflect wind turbine component *b*. Lenzen & Wachsmann (2004) assume a standard error of 50% for the misallocation of input processes and IO categories. The allocation

uncertainty, however, is alleviated in this work by using the highest level of disaggregation available from IELab relevant to the sectors that are important for the processes considered.

3. Temporal boundaries are not necessarily consistent throughout this assessment. The average impact of each technology during its life-cycle is used and assumed equal in every year. In reality, emissions associated to construction will be emitted entirely during the construction phase, i.e. the first years of a facility's lifetime.

4. The simple sensitivity analysis presented in this work only considers errors made with price conversion. Lenzen & Wachsmann (2004) compile a comprehensive Monte-Carlo sensitivity analysis including various potential error sources. They find uncertainties to be in the order of about 30%.

5. The scenarios used in this assessment do not intend to forecast future developments but simply to explore possible pathways of Australia's electricity market through to 2050. Some additional uncertainty is added by making modifications - albeit very small - to the original scenarios published by CSIRO (2015) and ClimateWorks et al. (2014).

6. A major assumption of Malik et al.'s analytical approach (Malik et al. 2014), which is used in this scenario analysis, is that production recipes (Use table column proportions) of industries do not change over time (only their level of output and sales proportions do). Future work may address probable changes in other important sectors (including their carbon intensity) and thus better capture the real-world situation.

7. Only three GHGs are considered (CH_4, N_2O, CO_2) as well as the compound indicator CO_2e. Other GHGs may be relevant for the electricity network, e.g. SF_6.

8. No environmental impacts other than GHGE are taken into account, though they would have to be under a complete LCA (Hellweg & Milà i Canals 2014) to avoid burden shifting from one environmental impact to another (cf. Stamford & Azapagic 2014) or the 'green vs. green dilemma' (cf. Köppel et al. 2014).

9. An MRIO framework is applied in this work to account for environmental impacts from imported and exported commodities between Australia and RoW. The RoW table used in this work distinguishes only 26 sectors and combines all countries outside of Australia. Ideally, the imports and exports matrices should have the same resolution as the Australian technology matrix (215 sectors in this work). Different country tables instead of just one RoW table may be built in the future to better reflect the real trade situation with different countries. Yet, adding the

aggregated RoW table yields better results than applying the domestic technology assumption within a single-region IO framework.

For further discussion also see Wiedmann et al. (2011). Despite the mentioned limitations, the applied model provides valid, valuable and important information regarding total GHG implications of renewable energy utilisation in Australia.

7. Conclusions

Australia enjoys the benefits of abundant energy resources, both fossil and renewable. Australia's government currently focuses on further exploration and continued large-scale deployment of fossil fuels, and current policy mechanisms to promote large-scale renewable electricity are not ambitious. However, the transition to a low-carbon economy, employing a near-zero-carbon electricity supply is possible, desirable and required if the aim of the Paris Agreement to limit global warming to below 2°C is to be achieved.

This work is the first to apply a full life-cycle approach to scenario analysis of electricity generation in Australia. It presents a consequential hybrid life-cycle analysis that builds on and extends an analytical solution based on input-output analysis. The approach is able to capture carbon emissions embodied in the supply chain of electricity provision as well as the economy-wide effects of changes in technology and demand.

The results indicate that the employment of different renewable energy technologies can save a considerable fraction of Australia's GHGE, even when taking into account indirect emissions along the technology's life-cycle. This makes renewables an essential option for climate change mitigation. However, improvements in the electricity sector alone are not sufficient, neither to reach the stated 80% GHGE target nor to stay within the (unofficial) national carbon budget. According to the depicted scenarios, Australia would become 'carbon-bankrupt' between 2024 and 2025 with no budget left for subsequent years. Further reductions in other carbon-intensive sectors, such as transport, manufacturing or agriculture, combined with a stronger focus on consumption sufficiency, seem therefore necessary.

The modelling approach presented here, and the results obtainable from it, can be used to evaluate specific policy scenarios aimed at decarbonising the economy. Whilst the focus in this study is on the electricity sector, changes in any other industry – be it in technological advances, carbon efficiency improvements or changes in demand for its products – can be modelled with equal rigour.

The current climate change policy of Australia's national government provides (limited) financial incentives for emission reduction activities across the economy. Respective methods set out the rules for estimating emission abatement from different activities and are developed specific to different industries or activities. As of early 2016, methods have been determined for agriculture, energy efficiency, facilities, mining, oil and gas, transport, vegetation management, waste and wastewater. Further methods are in preparation. The hybrid LCA scenario method for sector-specific carbon footprint evaluation employed in this paper can help emission reduction policies in various ways, e.g.:

- by establishing a baseline or benchmark against which newly implemented emission abatement can be ascertained as real and additional
- by helping to set industry or sector specific targets that have to be achieved in order to meet the overall 80% reduction target by 2050, respectively to stay within the (unofficial) carbon budget
- by quantifying the indirect effects on economy-wide emissions as a consequence of reducing emissions in one sector alone
- by 'backcasting' possible decarbonisation pathways for all sectors in the economy, thus helping to devise strategies and prioritise actions.

Further extensions of the demonstrated approach are conceivable, such as the inclusion of more environmental, economic or social indicators or of new technologies. Previous models simulate changes in economic output and employment in an economy if new technology is introduced. Other improvements of such models might include a more detailed representation of inter-regional or international trade flows, a better resolution of industry sectors or improved scenario parameterisation, including the modelling of specific policy changes, economic shocks or even disasters.

The importance of electricity for almost all sectors, such as transportation, buildings, electricity and heat production, industry and other energy purposes is evident. With the increasing uptake of electric vehicles, smart technology usage in homes and industry et cetera, this development will further intensify until 2050. This development demonstrates the necessity of the presented model for current and future technology assessment.

Appendix A. Supplementary information

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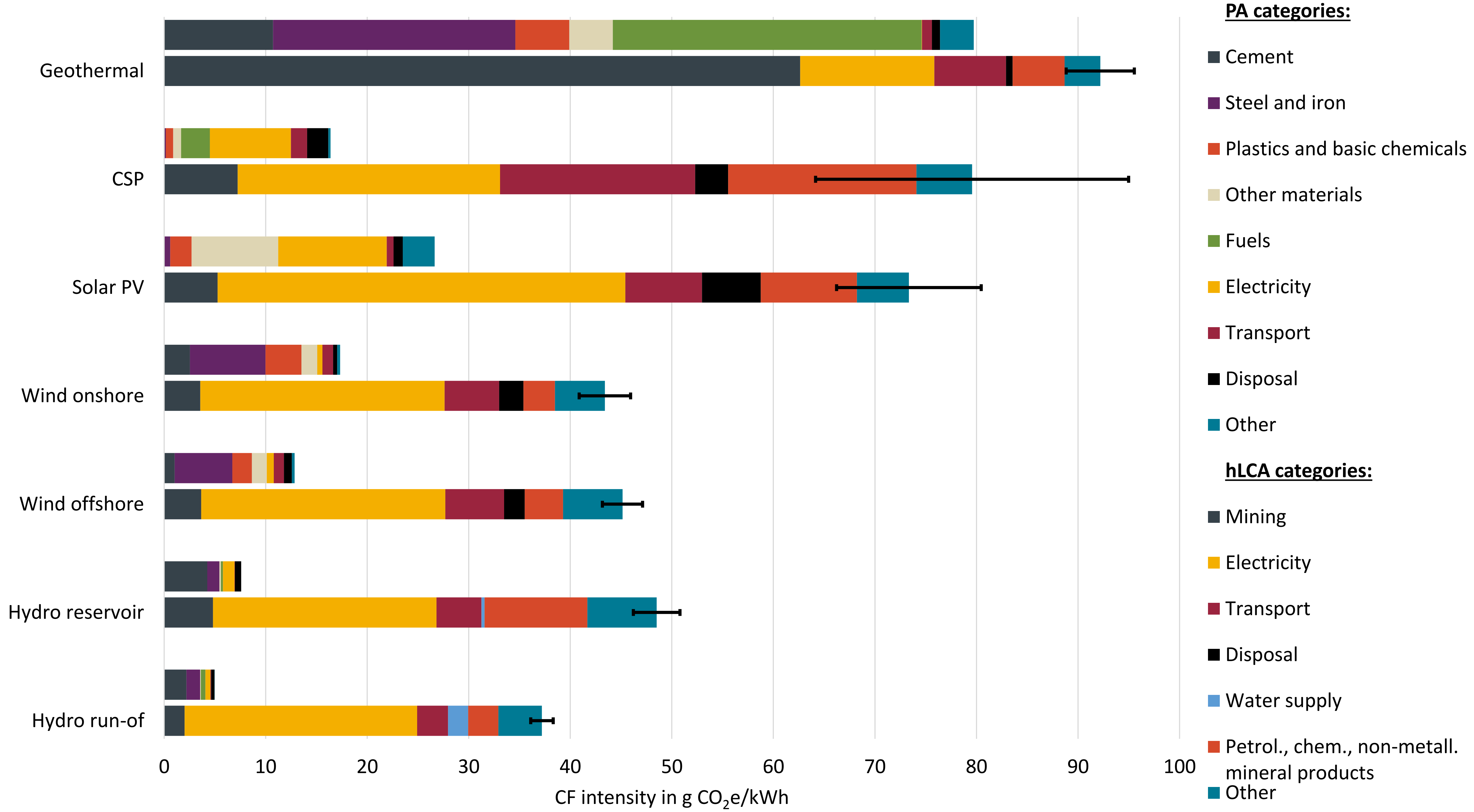
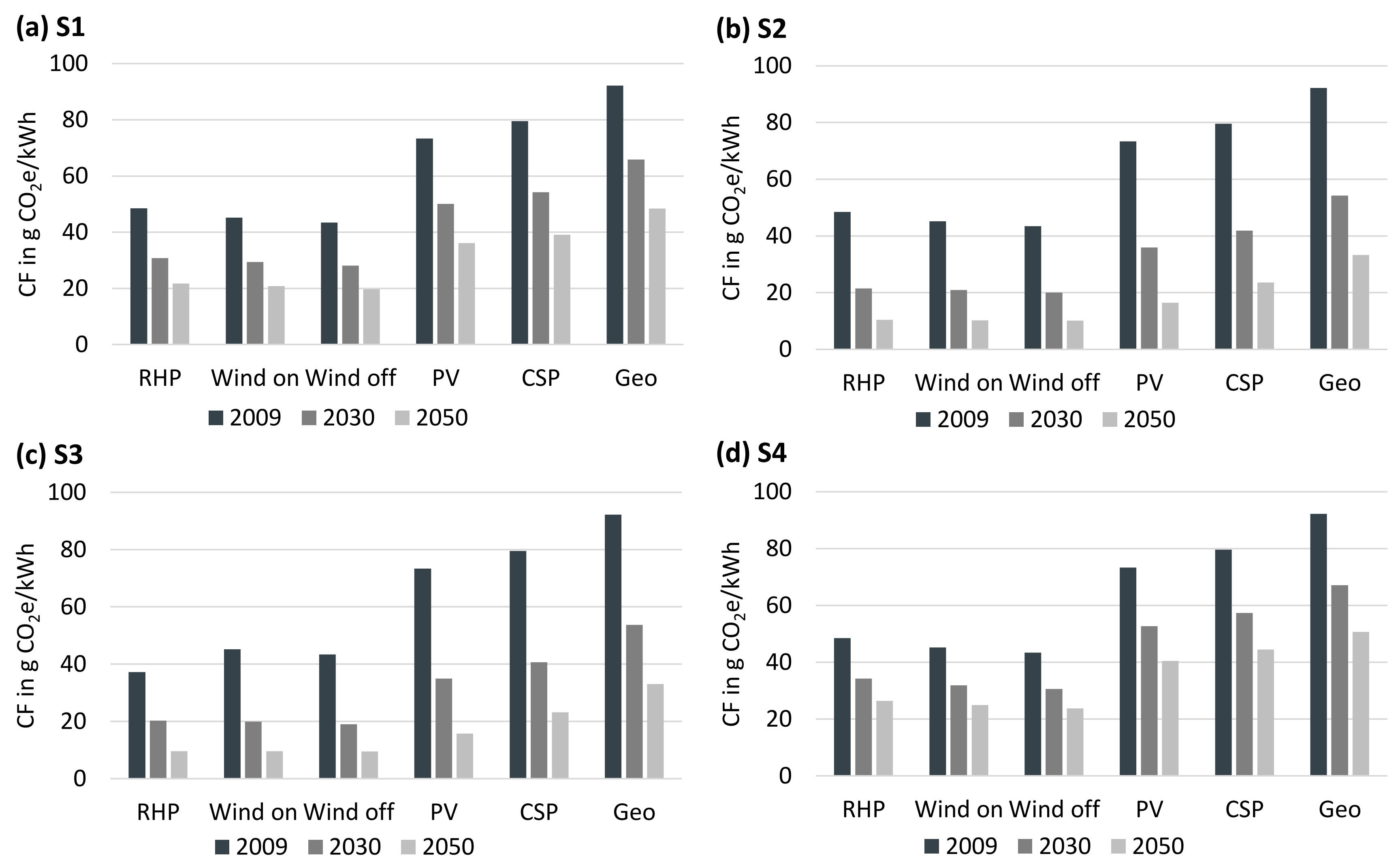
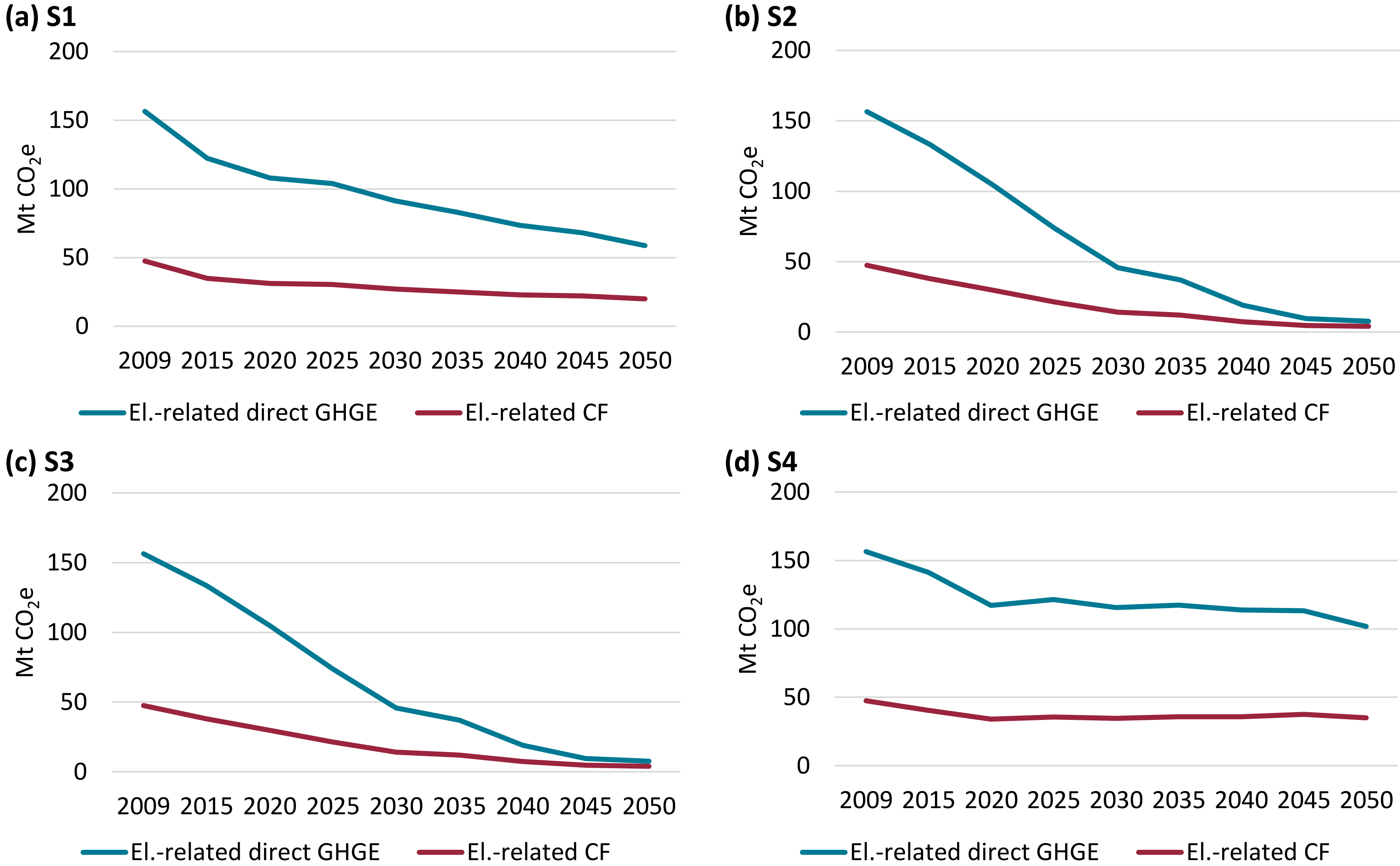
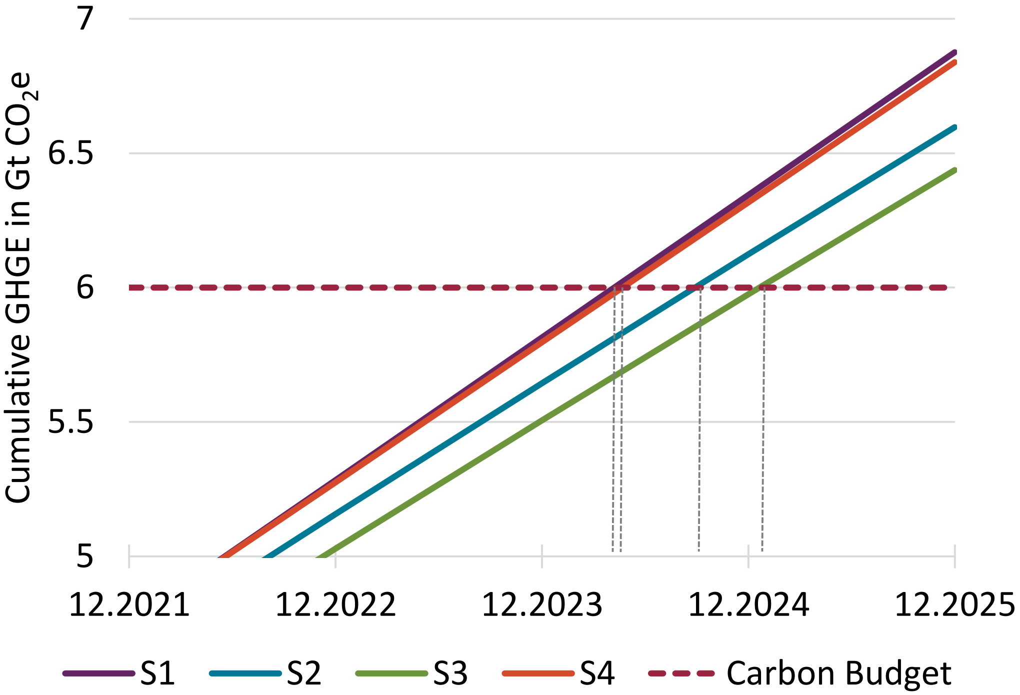

Geothermal
CSP
Solar PV
Wind onshore
Wind offshore
Hydro reservoir
Hydro run-of
0
10
20
30
40
50
60
70
80
90
100
CF intensity in g CO_2e/kWh
PA categories:
Cement
Steel and iron
Plastics and basic chemicals
Other materials
Fuels
Electricity
Transport
Disposal
Other
hLCA categories:
Mining
Electricity
Transport
Disposal
Water supply
Petrol., chem., non-metall. mineral products
Other



(a) S1
(b) S2
(c) S3
(d) S4
100
80
60
40
20
0
CF in g CO_2e/kWh
RHP
Wind on
Wind off
PV
CSP
Geo
2009
2030
2050


(a) S1
(b) S2
(c) S3
(d) S4
Mt CO_2e
0
50
100
150
200
2009
2015
2020
2025
2030
2035
2040
2045
2050
El.-related direct GHGE
El.-related CF



Cumulative GHGE in Gt CO_2e
7
6.5
6
5.5
5
12.2021
12.2022
12.2023
12.2024
12.2025
S1
S2
S3
S4
Carbon Budget

Highlights

- Carbon footprints of seven renewable electricity technologies are calculated.
- A new hybrid input-output framework is used: Industrial Ecology Virtual Laboratory.
- A life-cycle approach to scenario analysis of electricity generation is applied.
- Findings are at the higher end of previously reported carbon footprint intensities.
- Renewable energy technologies can help reduce Australia's greenhouse gas emissions.