The Australian Journal of
Agricultural and
Resource Economics

AARES
AUSTRALASIAN AGRICULTURAL & RESOURCE ECONOMICS SOCIETY

Australian Journal of Agricultural and Resource Economics, 64, pp. 575–604

Economic vulnerability and regional implications of a low carbon emissions future*

David A. Fleming-Muñoz, Lavinia Poruschi, Thomas Measham, Jacqui Meyers and Magnus Moglia[†]

Climate change, as well as associated mitigation efforts, will substantially disrupt some economies. Seemingly inevitable market and policy changes will push economies to transition away from reliance on industries with higher carbon emissions and bring transient economic impacts, especially in regions that are currently heavily reliant on such industries. This situation is not unusual in a global context. To underpin better-informed decisions that enable a smoother economic transition to a low-emissions future, we developed a 'latent economic vulnerability to emissions reduction' (LEVER) index, which maps and explores regions that are more likely to be economically impacted from climate change mitigation. Thus, this paper provides an analysis and discussion of the potential regional implications of a future low-emissions economy, with the analysis contextualised for the state of Queensland, Australia. Given this case study, the economic impacts and future of coal-fired power stations, coal mining and renewable energy are discussed. The LEVER index weighs the risk of high carbon economic exposure against the variability in carbon economic resilience from employment in low-emission sectors across local economies. We find that between 3 and 6 per cent of Queensland regions are assessed as having a very high latent economic vulnerability to increased decarbonisation of industrial activities. To promote a smoother transition, these regions will require targeted investments and strategies to enable their transition towards lower carbon-intensive systems, while maximising economic and social outcomes.

Key words: carbon economic exposure, climate change mitigation, coal mining, economic resilience, just energy transitions, thermal coal-fired power stations.

1. Introduction

Climate change will result in economic disruptions caused by climate-driven physical changes (Burke *et al*. 2015; Tol 2018) and through long-term economic transitions associated with mitigation efforts (Schlenker and Auffhammer 2018). These disruptions would necessarily lead to structural

*We are grateful to Erin Fentiman, Tim Capon and Yiheyis Maru for their review and feedback on this work. We also thank Steve Cook, Claire Naughtin and Simon Toze for comments and suggestions on earlier versions of this manuscript. This work was developed as part of a project looking at low-emissions futures for regional Queensland, which received funding from the Queensland Government as part of the Q-Foresight program, an initiative under the multiyear Queensland Government and CSIRO Data61 Strategic Partnership Agreement.

[†]David Fleming-Muñoz (e-mail: david.fleming@csiro.au) is a Senior Research Economist, Lavinia Poruschi is a Research Scientist, Thomas Measham is a Principal Research Scientist, Jacqui Meyers is a Senior Research Scientist and Magnus Moglia is a Principal Research Scientist are with the CSIRO, Ecosciences Precinct, Brisbane, Australia. Magnus Moglia is at the Centre for Urban Transitions, Swinburne University, Melbourne, Australia.

doi: 10.1111/1467-8489.12356

changes in some local and regional economies. As the world transitions away from coal and other fossil fuels, multiple impacts are likely to occur, especially in those local and regional economies that substantially rely on carbon-intensive industries to sustain their activities and livelihoods. A high-level strategic analysis of potential employment impacts of industry changes is useful for developing policies and planning for changes towards carbon-neutral economic systems. In particular, there is a need for an analysis that highlights the importance of relative dependence of individual local economies on carbon-intensive industries. This paper proposes a method to carry out this form of analysis, contextualising the research on regions in the state of Queensland, Australia.

Following the Paris Agreement to limit climate change, several countries have introduced ambitious targets to reduce emissions to ‘net-zero’ (carbon-neutral). For example, France, the UK and New Zealand aim to achieve net-zero emissions by 2050 (Darby 2019). Australia’s target is set at achieving GHG emissions of 26–28 per cent below 2005 levels by 2030 (DEE 2019a). Independent of this national target, most Australian states and territories have also set a net-zero target by 2050 (ClimateWorks 2016).

In Australia, the state of Queensland is responsible for a third of all national emissions, reporting the highest emissions per capita (31 tonnes of CO_2 equivalent per person (CO_2ePP) in 2014), close to double the rate of New South Wales (17 tonnes CO_2ePP) and South Australia (16 tonnes CO_2ePP) (ClimateWorks 2016). At this rate, if Queensland were a country, it would have the fourth largest emissions of greenhouse gases (GHG) per capita in the world (The World Bank 2019; Queensland Government 2018). In acknowledgement of the urgent need to reduce emissions, the Queensland Government is in a process to consider future policies and identify the challenges that the state faces in reducing emissions and creating solutions that support a transition towards a less carbon-intensive economy. This paper contributes to this process and to the efforts of other governments who are aiming to reduce their carbon footprint by analysing the economic implications that future climate change mitigation can bring to different regions.

To achieve this, we conduct two analyses that emphasise transitionary employment outcomes: a regional economic analysis of the most carbon intensive industries – including coal mining – and the renewable energy sector in Queensland, and the development of an index of latent economic vulnerability to emissions reduction (the LEVER index) and its empirical implications for policy.

This paper complements international studies looking at exposure and vulnerability of workers and communities to climate change mitigation efforts (e.g. Markkanen and Anger-Kraavi 2019; Vona 2019), as well as cross-country metrics of climate change vulnerability and resilience (e.g. ND-GAIN 2019). In Australia, almost all studies of the impacts of climate change mitigation focus on national-level/aggregated economic forecasting analyses of emissions reduction targets (see The Australia Institute (2018) for a list of reports), with most conclusions highlighting low negative impacts (Jotzo and Kemp 2015). One exception to national-level studies is Burke *et al.* (2019), who provide a comprehensive regional economic analysis of the employment impacts after coal-fired power station closures across Australia.[1] In this study, we are building on this research by providing a way to define regional economic exposure and resilience to increasing decarbonisation of the economy. To achieve 'just transitions' (Healy and Barry 2017), it is important to identify which, and understand why, some regions will need special attention from government interventions.

By exploring the economic geography of our case study in 2016, the LEVER index provides insights on the relative economic impacts that each region in Queensland could experience as a result of global, national or state efforts to mitigate climate change. That is, the LEVER index captures the relative economic vulnerability of regions due to market or policy pressure that cause a shift towards a low-emissions economy. Hence, the approach proposed here to measure latent regional economic vulnerability to climate change mitigation can be applied beyond the Queensland/Australian context. This regional analysis tool applies to other regions and countries, particularly where data on industry-by-industry employment figures are available.

Importantly, the LEVER index can be useful for highlighting regions that are more exposed to economic disruption as a consequence of emissions reductions and for countries where carbon-intensive industries such as coal mining and coal burning for electricity generation are distributed broadly across multiple regions. For use as an economic policy analysis tool, the index incorporates weights which can be changed to allow adjustment of inputs and study outcomes from alternative policies or market trends. Its design can also be expanded in the future to include sectors that currently do not have regional disaggregated data (such as the renewable energy industry, which case we discuss below) or that will increase their spatial footprint as projects become a reality. In its current form, the LEVER index is a simple metric aimed at providing an initial, but crucial, mapping and exploration process to define and contrast potential economic vulnerability across regions. Its goal is to support a 'climate resilient' and 'just transition' policy design process and is intended for further use by policymakers and researchers.

The remainder of the paper is structured as follows. Section 2 briefly describes the data methods used for the regional analysis and development of the index. Section 3 describes the economic geography context of our case study, outlining the critical characteristics of GHG-intensive industries and the emergence of renewable energy projects. Section 4 describes two regional-level indicators: the 'carbon economic exposure' and the 'carbon economic

[1] Several other regional-level studies have focused on the potential economic impacts or adaptation of communities to weather variability. See Smith *et al.* (2015) for a review and synthesis of this literature.

resilience' indicators. In Section 5, we describe the design of the 'latent economic vulnerability to emissions reduction' (LEVER) index, and in Section 6, we analyse outputs derived from the LEVER index. Finally, Section 7 highlights how the LEVER index can be used in other contexts and provides concluding remarks.

2. Methods and data

Before developing the index, we conducted an analysis of the economic geography of our case study – Queensland (detailed in Section 3). This was done to contextualise the analysis and show why Queensland is a region where the index could provide valuable information. Next, we used the data and analysis generated in the case study to derive the components of the LEVER index (detailed in Section 4). We created two regional indicators using employment data from the Australian Bureau of Statistics (ABS) 2016 Census of Population and Housing (ABS 2019a): the 'carbon economic exposure' and the 'carbon economic resilience' indicators. These two indicators were then used to create the LEVER index.

The analysis and discussion hereafter are based on state-level, SA4-level and SA2-level statistical area data. In Australia, SA4 regions are the largest administrative area below the state level, for which statistical data are available from the Australian Bureau of Statistics (ABS 2016a). Queensland had 18 SA4 regions in 2016. SA2 regions are nested within SA4 regions and are the smallest level for which detailed time-series census data are available. SA2 regions generally have a population range of between 3,000 and 25,000 persons and have an average population of 10,000 persons. Queensland had 530 SA2 regions in 2016 (ABS 2016a). The LEVER index is developed and discussed at the SA2 level. We employ SA2 geographic boundaries for the index because they were designed to 'represent a community that interacts together socially and economically' (ABS 2016b). As such, SA2 regions provide a good spatial representation of local economies in Queensland as they generally encompass at least one or two major towns and have census data publicly available at this scale, enabling detailed regional economic analyses (see Fleming and Measham 2015).

We sourced industry of employment and population size data from the 2016 census (ABS 2019a). To provide context, such as understanding changes over time, census data from the 2006 and 2011 are used in relevant sections. Unless otherwise specified, population and employment data are gathered on a 'place of usual residence' basis. We employ 'place of usual residence' data to avoid the fly-in fly-out or drive-in drive-out bias that 'place of work' data can produce, especially for people employed in mining. GIS analysis was employed to retrieve location variables for SA2 regions. We used ArcGIS® to determine whether an SA2 is coastal and whether they host coal mines or coal-fired power stations. All data sources are referenced in the figures and the text below.

3. The economic geography of Queensland's GHG-intensive sectors and renewable energy

In designing the LEVER index, we need to understand the specific carbon profile of the industrial activity in the case study regions to analyse the carbon dependence of local economies. In this section, we discuss the two industries that are linked with high emissions coming and sourced from Queensland; electricity generation and coal mining. The former is responsible for a third of all GHG emissions in Queensland, and the latter is the leading export sector in the state's economy. We also discuss, although briefly, aspects of the agricultural and manufacturing sectors in the state, as they also relate to carbon emissions. To complete the picture, an analysis of trends in the power generation of and potential employment in renewable energy projects in the state is also included.

3.1 Employment and the future of coal-fired power stations

While market signals and societal concerns around climate change have increased, coal is still the main method to generate electricity in Australia, and globally. Coal-fired electricity generation stations were responsible for approximately 30 per cent of the total emissions in Queensland in 2016–2017 (47 Mt CO_2e of the state's total emissions of approximately 159 Mt CO_2e; see Table 1). While coal-fired electricity generation made up around 61 per cent of electricity generation across the Australian National Electricity Grid in 2017, in Queensland this share was 71 per cent (DEE 2018). However, in both cases, the share has decreased since 2008–2009 when coal accounted for approximately 75 and 78 per cent of electricity generated in Australia and Queensland, respectively.

The reasons for the decrease in the use of coal for electricity generation in both Australia and Queensland can be explained by multiple factors, including the ageing of the plants and increasing uncertainties over how the externalities from coal-based power generation would be costed in the future (Burke *et al.* 2019). In addition, even though mostly destined to export markets, natural gas sourced 27 per cent in 2014–2015 and 18 per cent in 2016–2017 of the electricity generation in Queensland (DEE 2019b). Finally, and most importantly, technical progress keeps reducing the cost of renewable energy, increasing its competitiveness (see Section 3.4). All this has translated into the absence of new coal-fired power stations in future energy planning (AEMO 2018b; Burke *et al.* 2019). As such, the remaining coal-fired power plants in operation in Queensland will likely cease operations in the medium to long term, before or at their maximum technical lifespan, and without being replaced by similar power plants (Burke *et al.* 2019).

Several options have been proposed to guide the process of decommissioning coal-fired plants across Australia, in particular electricity generation

Table 1 Queensland coal-fired power stations location, capacity, emissions and jobs

Region (SA4 name)	Station name	Capacity (MW)	Age (years)	Emissions (Mt CO_2e/ year)†	Subregion (SA2 name)	SA2 Jobs 2011‡	SA2 Jobs 2016‡
Central Queensland	Gladstone	1,680	34–40	6.44	Callemondah	261	232
Central Queensland	Stanwell	1,460	20–23	7.97	Rockhampton region west	118	224
Wide Bay	Tarong	1,400	30–32	10.71	Nanango	258	225
Darling Downs-Maranoa	Millmerran	851	14	5.41	Millmerran	61	92
Central Queensland	Callide C	810	15	4.92	Banana	82	232
Darling Downs-Maranoa	Kogan Creek	750	9	4.85	Chinchilla	70	91
Central Queensland	Callide B	700	27	4.43	Banana	82	232
Wide Bay	Tarong North	443	14	2.28	Nanango	258	225
Total		8,094	21 (avg.)	47		850	1,096
Closed large stations	Age (year closed)						
Ipswich	Swanbank B	500	42 (2012)	4.13	Ripley	80	8
Mackay-Isaac-Whitsunday	Collinsville	180	14–44 (2012)	1.32	Collinsville	31	3

Note: SA2 data retrieved from ABS (2019a). Capacity and year sourced from Australian Senate (2017) and Burke *et al*. (2019). Capacities, as well as emissions, vary year by year.
†Emission estimates provided here are for 2016–2017 and sourced from the Clean Energy Council (2018a) except for emissions for *Tarong North*, *Yabulu* and the closed stations which are sourced from http://carma.org and are based on estimates for 2009.
‡Jobs in the industry sector 'fossil fuel electricity generation' based on place of work sourced from ABS (2019a). The SA2 of Nanango also has 303–320 jobs in coal mining. The SA2 of Ripley currently has a natural gas power station and a biogas power station in operation. The total number of jobs excludes repeated SA2 values.

capabilities from other sources (Australian Senate 2017). While technical discussions play a major role in deciding how this may proceed (for economic research in this aspect, see Nelson *et al*. 2018), our focus is on the employment impacts that the future decommissioning of coal-fired power stations and

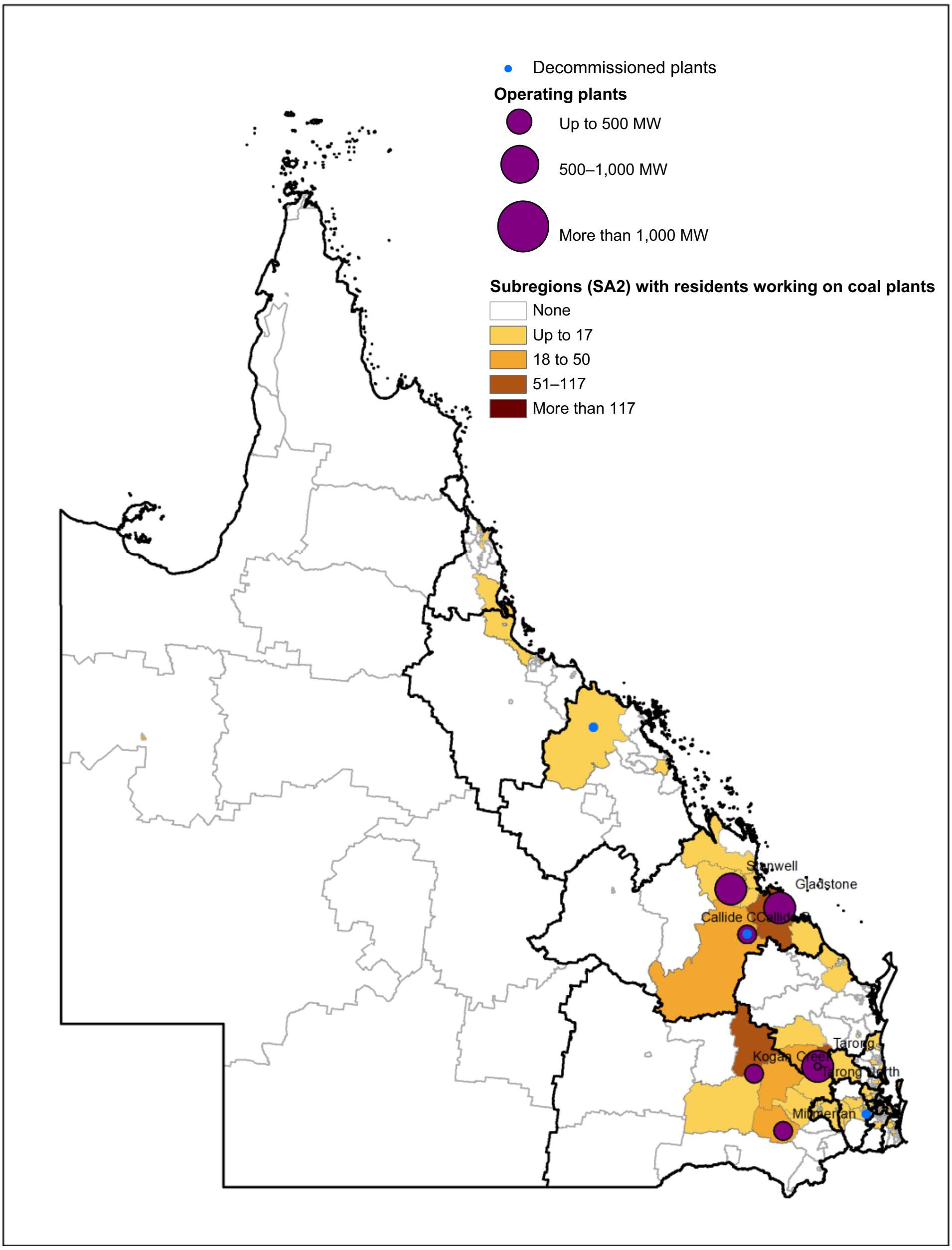

Figure 1 Location of coal-fired power stations and neighbouring SA2 regions.
Source: Own elaboration using data from CER (2019), ABS (2016b), ABS (2019a), Australian Senate (2017) and Burke *et al.* (2019). [Colour figure can be viewed at wileyonlinelibrary.com]

transitions to other electricity generation sources might bring to the functioning of local economies.

3.1.1 Coal-fired power station jobs

The total number of people working directly in coal-fired power stations across Queensland reached approximately 1,096 in 2016 (ABS 2019a) (Table 1), which is < 0.1 per cent of total employment in the state. The data in Table 1 also reflect the impact of the closure of the Swanbank B and Collinsville stations, with employment dropping from 80 and 31 people in 2011 to eight and three people in 2016, respectively. Figure 1 shows the location and employment of these plants.

Aggregating the jobs data to SA4 level, Table 2 shows that Queensland's coal-fired power stations are clustered in the SA4 regions of Darling Downs-Maranoa, Central Queensland and Wide Bay. Notably, the state capital, Brisbane, also has significant employment numbers compared with other regions; however, these are generally people who work at the head offices of electricity companies.

Table 2 also demonstrates the relative importance of coal-fired power stations to the respective regional economies, pointing to the relatively low number and proportion of jobs generated by the electricity generation stations within the SA4 regions that are hosting them.

Table 2 Number of jobs in fossil fuel-related industries by SA4 regions

	Fossil fuel electricity generation	Gas supply	Coal mining	Oil and gas extraction	Total fossil fuel-related jobs	Total jobs in the SA4	Share of fossil fuel jobs over total SA4 jobs, %
Brisbane†	418	307	2,486	2,696	5,906	720,484	0.82
Cairns	23	13	23	17	77	99,300	0.08
Darling Downs-Maranoa	216	228	551	1,238	2,232	55,949	3.99
Central Queensland	861	103	6,704	609	8,273	96,567	8.57
Gold Coast	18	29	148	41	237	239,262	0.10
Ipswich	43	53	313	39	445	107,899	0.41
Logan-Beaudesert	12	45	16	29	104	94,247	0.11
Mackay-Isaac-Whitsunday	10	10	13,465	251	13,738	80,844	16.99
Moreton Bay†	10	19	39	39	112	115,270	0.20
Queensland Outback	46	–	72	94	215	36,772	0.58
Sunshine Coast	6	33	59	19	114	130,982	0.09
Toowoomba	7	52	46	266	369	64,068	0.58
Townsville	27	16	54	16	113	98,272	0.11
Wide Bay	230	18	363	15	631	91,913	0.69

Note: Data based on place of work.
Source: ABS (2019a).
†Brisbane includes five SA4s and Moreton Bay includes the SA4s of Moreton Bay North and South.

Despite the relatively low employment share that coal-fired power plants generate in hosting SA4 regions, some communities in these areas will become more economically vulnerable when plants shut down. In addition to the direct job losses from the potential closure of coal-fired power stations, indirect job losses would also be expected. These are particularly likely to affect jobs in thermal coal mines that directly supply the power stations and that would have less opportunity (compared to metallurgical coal mines) to sell to international markets.

Other sectors of the regional economy will also be indirectly affected by the loss of employment in coal-fired power stations and coal mines. The local construction industry, for instance, may face reduced demand as a result of lower disposable income in the region, which would flow through to fewer construction jobs.

In terms of overall unemployment rates in the SA4 regions, Burke *et al.* (2019) state that one year before the closures, regions in Australia with closing coal-fired power stations had, on average, a slightly lower unemployment rate than the overall rate for their state. At their time of closing, the unemployment rates were similar to state employment rates. One year after closure, the annual unemployment rate in these regions was, on average, 0.8 percentage points above the state average, and a positive differential (+0.6 percentage points) remained after two years (Burke *et al.* 2019). The effect of closures is not limited to the immediate job losses. In addition, outmigration of former employees leads to a reduction in spillover jobs, which, over time, can lead to further outmigration (Measham *et al.* 2016).

Some jobs in coal-fired power generation may be transferable to other sectors; however, broader employment implications will need to be considered in the design of any future climate change mitigation policy. On the one hand, more jobs may be lost because thermal coal mining employment partially depends on local thermal coal use, so other indirect jobs generated by the sector may disappear. On the other hand, while emerging sectors such as renewable energy generation will absorb some of these workers, the skill set required in the renewable energy industry may not be immediately transferable, or the types of jobs available may not be similar or located in areas near the coal-fired power stations (Louie and Pearce 2016). While the exact number of new jobs in the renewable energy industry is uncertain (see Section 3.4), the sector is expected to grow at the same time as employment in coal-fired power generation is expected to shrink. Other current and future economic activities can also help with this transition, such as the mining of rare earth elements or lithium, and the development of a hydrogen industry.

The job numbers in Table 1 show where the stations and their associated jobs are located, but not necessarily where workers live. Figure 1 shows where people working in the 'fossil fuel electricity generation' sector live, based on 2016 data for SA2 regions (ABS 2019a). Appendix S1 lists the SA2 regions that have a higher dependency on the jobs generated by these stations.

3.2 Coal mining

Coal is the predominant commodity exported from Queensland, and coal mines are a major employer in the state. Queensland's international sales of coal reached approximately A$29 billionin 2016–2017, which was approximately 35 per cent of the state's total value of exports of goods and services in 2016–2017 (DFAT 2019). This very considerable source of revenue for Queensland means that any decline in international or domestic demand for coal will directly and substantially affect Queensland's financial situation – in 2017–2018, royalties from coal reached a historic $3.74 billion (DNRM 2019). The potential loss of exports and the associated revenue is part of a slow trend and is also not within the sphere of influence of local decision-makers, so in this paper, we do not focus on state-level impacts that could emerge because of lower coal royalty revenues. Instead, we focus on local/regional employment impacts associated with a reduced demand for coal.

Nearly all Queensland reserves of coal are black coal, which is less polluting than brown coal when burned (Environment Victoria 2019). In total, Queensland extracted approximately 242 million tonnes (Mt) of black coal in 2015–2016, of which 221 Mt (91 per cent) was exported. Of the exported coal, approximately 160 Mt (72 per cent) was metallurgical and 61 Mt (28 per cent) was thermal coal. Approximately 21 Mt of thermal coal was also extracted and consumed locally (DNRM 2018).

These facts are important for the structure of Queensland's economy and distribution of employment. A point to consider is that regardless of global or local decarbonisation pathways, to this day there is still no economically viable clean alternative to metallurgical coal in many manufacturing processes that require high temperatures, making coal a crucial energy source for smelting metals (Smil 2016). Therefore, global demand for metallurgical coal is likely to remain high in the coming years until viable alternatives emerge. Conversely, thermal coal is burned for electricity generation and is highly substitutable (e.g. by renewable energy). Thus, thermal coal is the primary commodity that will be substantially affected by low-emissions systems in the short to medium term. A strong decarbonisation of the world economy would mean less demand for thermal coal.

3.2.1 Coal mining output versus jobs

The number of coal mining jobs grew by approximately 15,000 people between 1997 and 2016 (Figure 2). The growth in numbers reflects the fast growth trajectory of coal extraction in Queensland, where in the past 20 years, the total tonnes of coal extracted has tripled (Figure 2). These increasing trends in output and production aligned with an increasing international demand for coal that has resulted in a net increase in prices since 2000 (Figure 2). Although prices have fallen during 2018 and 2019, US dollars per metric tonne values in August 2019 were double than those in August 1994. At their peak, prices were four to six times the average of the 1990s (Indexmundi 2018).

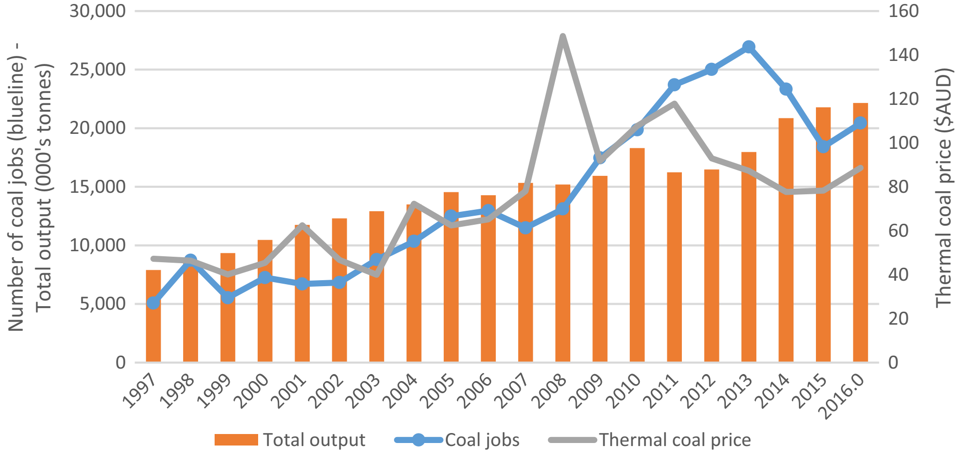

Figure 2 Queensland coal mining outputs, jobs and international thermal coal price. Note: Total outputs (10,000 tons) are from DNRM (2018), jobs from ABS (2017) and thermal coal prices from Indexmundi (2018). Jobs are the average of the quarterly values in each year. [Colour figure can be viewed at wileyonlinelibrary.com]

However, as Figure 2 shows, the change in the number of people employed by the coal mining industry is not perfectly correlated with production. This reflects the resource quality and other factors but is also a consequence of the capital-intensive nature of mining activities.

In 2015–2016, Queensland had 37 open cut mines and 13 underground mines. In addition, a further 21 export coal projects were either under construction or in advanced stages of development (DNRM 2018). These 21 projects are assessed to have at least seven billion tonnes of coal resources that could be extracted and exported – value obtained after summing the lower bound of the estimates provided in Tables 1 and 2 reported in DNRM (2018). If we assume an operational life of 40 years for these future mines and the average ratio output/jobs for the coal mining industry in Queensland in the last 10 years (approximately 9,500 tonnes per miner – derived from the time-series data shown in Figure 2), these mines would be employing around 18,000 people per year in the coming decades. However, this number of jobs could be considerably less if we factor in increasing automation and improved efficiency provided by the adoption of new technologies for mining operations. This last point could importantly reduce the number of workers needed to achieve the same level of output. Appendix S1 discusses more the potential impact that automation can cause to mining jobs.

3.2.2 Coal mining jobs across SA4 regions

While the locations of most coal mining jobs are concentrated in the SA4 regions where coal mines are located, in 2016, 10 per cent of total industry jobs (2,486) were in Brisbane (the largest city in Queensland) (ABS 2019a). Brisbane employment likely reflects people employed in the main offices of these companies and a proportion of long-distance commuter miners. In regional Queensland, as seen in Table 2, the clear majority of coal mining jobs are concentrated in the SA4 regions of Central Queensland and Mackay-Isaac-Whitsunday.

To understand potential job impacts, we differentiate between the locations of jobs in thermal coal versus metallurgical coal. Of the 50 mines listed by DNRM (2018) as operating in Queensland in 2015–2016, only 12 mines were exclusively mining thermal coal.

The distribution of thermal and metallurgic coal mines varies between regions. While the Bowen and Galilee basins in Queensland contain all current and future operating metallurgical coal extraction mines and some thermal coal mines, the 'south basins' of the state (Surat, Ipswich and Clarence Moreton) host only mines that extract thermal coal. Figure 3 shows the area of the south basins, which includes thermal coal mines in the SA4 regions of Darling Downs-Maranoa (with five mines), Wide Bay (with one mine) and Ipswich (with one mine). These seven mines in the 'south basins' area had a total of 1,227 persons employed in 2016. More detailed information on jobs across these SA2 regions is shown in Table A2 in Appendix S1.

3.3 Agriculture and manufacturing processes

Agricultural GHG emissions accounted for approximately 12 per cent of the total Queensland emissions in 2016 (Queensland Government 2019). Most of these emissions, approximately 80 per cent, take the form of methane (CH_4) produced from ruminant beef cattle. Cattle grazing is the largest agricultural industry in Queensland, producing just under half of Australia's beef cattle and utilising 78 per cent of the land area of the state (Queensland Primary Industries and Fisheries 2009). It is the fourth largest economic sector in Queensland, directly employing more than 20,000 people (ABS 2019a). These jobs are distributed across most of the regional areas of the state, unlike jobs at coal mines or coal-fired power stations.

Manufacturing contributed another 4 per cent of total Queensland emissions in 2016 (Queensland Government 2019). However, not all sub-sectors in manufacturing are heavy emitters. The Australian Government, under the Clean Energy Regulator (CER), defines a list of manufacturing activities that are considered emissions-intensive and trade-exposed (DEE 2011). Emissions intensity is defined based on weighted-average emissions per million dollars of revenue or per million dollars of added value (revenue less the cost of purchased materials and services) over several years (Queensland Resources Council 2014). In most cases, emissions are counted by the amount of electricity they use in MW/h. Thus, manufacturing activities that could substitute coal-generated electricity with other sources have the capacity to reduce their emissions intensity.

Based on the domain of activity as listed by the CER (DEE 2011), we have aggregated high carbon-intensive manufacturing activities into the following

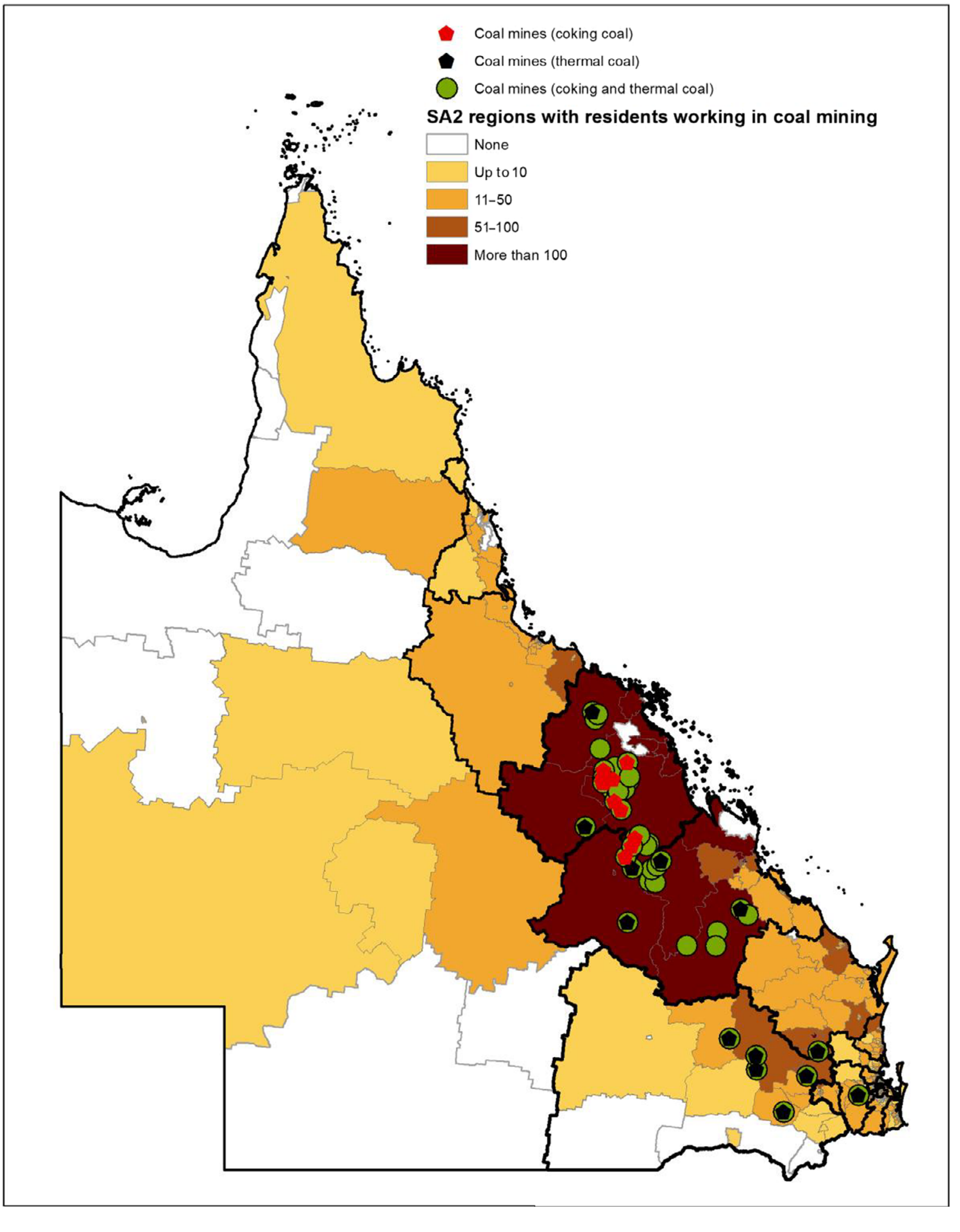

Figure 3 Regions with coal mines and 'place of residence' of coal miners.
Source: Own elaboration based on data from ABS (2016b), ABS (2019a) and Geoscience Australia (2019). [Colour figure can be viewed at wileyonlinelibrary.com]

sub-sectors: pulp, paper and paperboard manufacturing; petroleum and coal product manufacturing; glass and glass product manufacturing; and cement, lime, plaster and concrete. In the following section, we consider the employment generated by these sectors and sub-sectors when aggregating data to construct the carbon economic exposure indicator.

3.4 The growing renewable energy sector

In 2018, Queensland had more new large-scale renewable energy capacity added than any other state in Australia (CER 2019). Changes occurred at a rapid pace; out of the projects in operation, 28 solar and wind farms with a total capacity of approximately 2,158 MW received accreditation under the National Renewable Energy Target (RET) between 2017 and August 2019.[2] Additional landmark projects may shift the centre of power generation in Queensland significantly. For instance, the largest solar farm in the southern hemisphere has planning approval for construction at Bulli Creek in Queensland (2,000 MW).

The changing nature of power generation in Queensland is further underlined by the location of these renewable energy projects. Within 100 km of coal-fired power plants in operation up to the end of 2018, there were around 100 projects over 5 MW capacity, amounting to a total capacity of approximately 14,500 MW, which were either operating (1,542 MW), under construction (944 MW) or were proposed (approximately 12,000 MW). Figure 4 illustrates the approximate location of the largest of these projects. By comparison, coal-fired power generation amounts to about 8,100MW. However, while many projects have already been built, not necessarily all renewable energy projects proposed in Queensland will become a reality and it is hard to predict whether renewable energy capacity will match or overtake fossil fuel generation capacity in the next 5–10 years. For instance, the capacity installed between January and July of 2019 (approximately 550 MW) is around one-third of the capacity installed throughout the calendar year of 2018 (approximately 1,500 MW) (CER 2019). The speed of renewables expansion depends on a combination of multiple factors such as transmission grid limitations, the absence of clear future policy incentives, and challenges to the financial model of large-scale power plants without storage capacity (Macdonald-Smith and Ludlow 2019).

The number of jobs created in the economy from utility-scale renewable power generation will vary considerably from the construction (installation) phase to the operational phase. The technology needed to establish these power plants tends to be made outside of Australia, and the on-site construction tends to be akin to an 'assembly' or 'installation' process. When solar farms are operational, generally few staff are needed to maintain the plant.[3] To better understand the

[2] In policy terms, the national Australian 2020 RET target of installing an additional 6,000 MW, or generating 33,000 MWh, has been reached (CER 2018).

[3] A small number of permanent staff is generally needed on-site for the ongoing technical maintenance of these farms. For example, the Pacific Hydro Solar Farm (max. 500 MW) in Queensland was expecting 240 jobs to be created during installation and 10 jobs in the operational phase (Burdekin Shire Council 2017). Downstream activities such as operations, maintenance, decommissioning and recycling could be more labour-intensive (EY and SolarPower Europe 2017), but the authors are not aware of estimates of actual employment demand at each stage for Australia. Also, it is worth noting that while large-scale solar employment in maintenance is uncertain, it is possible that in the long run, a decentralised market for small systems could employ three times more people than large-scale renewable systems (EY and SolarPower Europe 2017).

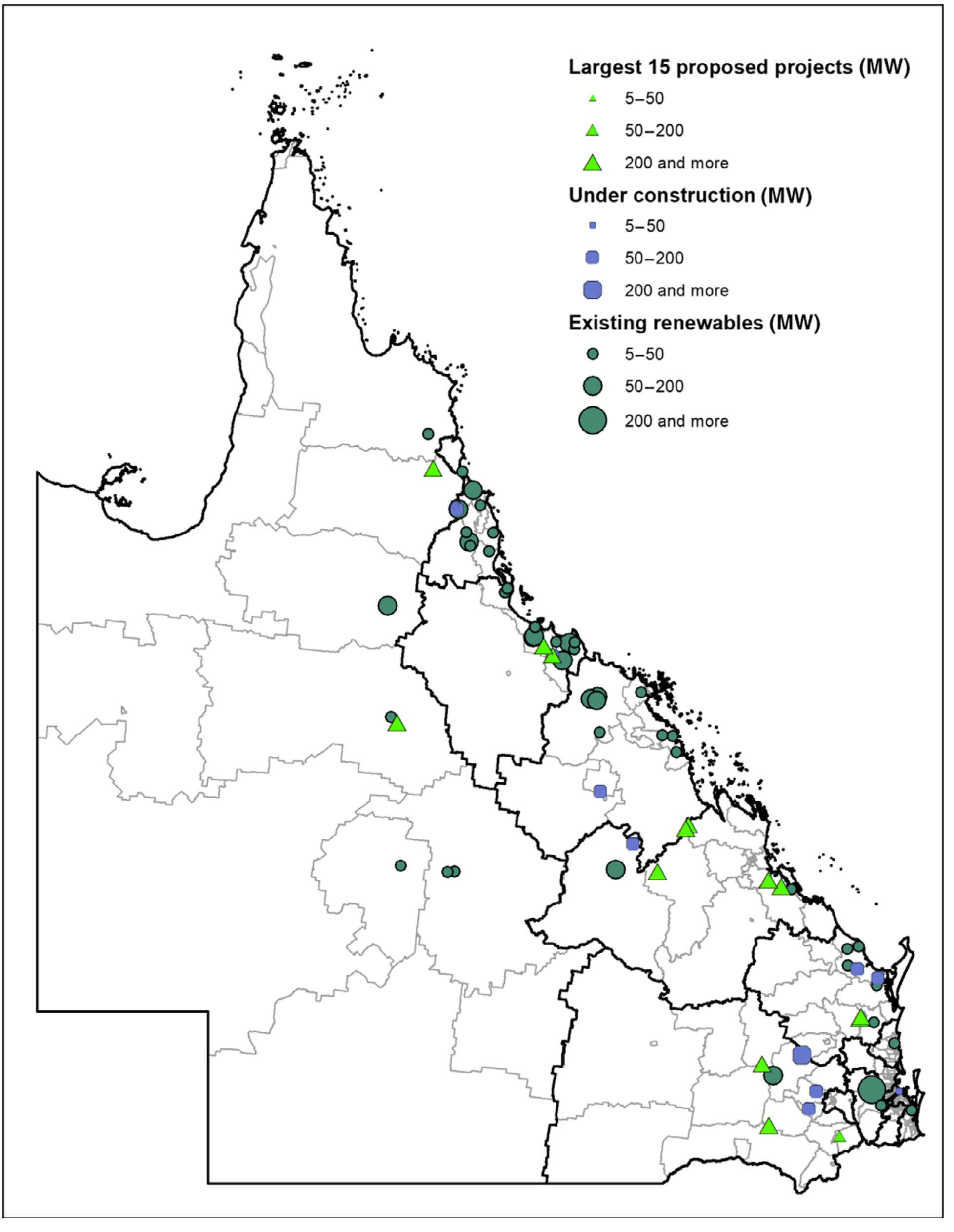

Figure 4 Distribution of renewable energy power stations relative to fossil fuel power plants (December 2018).Notes: Renewable energy projects refer to solar, wind and bioenergy. Renewable energy projects tend to locate near fossil fuel power stations as financial viability for many will depend on their ability to connect to existing transmission lines, so minimise the connections costs. Projects under 5 MW are not displayed. Regions are denoted according to ABS SA2 regions (denoted with grey borders). SA2 regions are nested in SA4 regions (thick borders).
Source: Own elaboration with data from CER (2018), ABS (2016b) and ABS (2016a). [Colour figure can be viewed at wileyonlinelibrary.com]

potential employment outcomes of the solar and renewables boom, we present an estimate of employment factors for large-scale solar energy generation in Queensland in Table 3. Regarding the operational phase of utility-scale solar, the employment factors derived here carry high uncertainty, given they are based on figures cited by project proponents. Nonetheless, past number of jobs in overall renewable energy activity in Queensland oscillated between about 2,700 and 5,600 between 2010 and 2018 (ABS 2019b). Compared to employment numbers in fossil fuel-related industries from the 2016 Census (Table 2), peak employment in renewables in Queensland seems to have surpassed the numbers of jobs in the fossil fuel electricity generation sector or in the oil and gas extraction sector. However, compared with coal mining jobs, peak renewables employment would represent just about a quarter of that figure. Looking into the future, if all the large-scale renewable energy projects proposed in Queensland (and within 100 km of CFPS) at the end of 2018 go ahead, based on the median factors shown in Table 3, the total number of jobs created in the medium term could be as high as 29,000 during the construction phase, with around 725 extra jobs created for ongoing operations.

The current operational large-scale power plant numbers and proposed projects denote a growing industry for Queensland; however, it is still not clear where most of the future renewable workforce will be located – and current workers are not yet captured in Australian census data. It is possible that they are part of the communities where coal-fired power station workers live, or that they are remote contractors travelling from project to project. Given this uncertainty, we refrain from adding the renewable energy generation to the analysis below.

4. Local economic exposure and resilience to carbon emissions reduction

In this section, we compose aggregated regional indices to measure what proportion of local residents directly rely on the economic activity generated by high GHG-intensive, or low GHG-intensive industries. The indicators of 'carbon economic exposure' and 'carbon economic resilience' measure the

Table 3 Employment factors (jobs/MW) for the utility-scale PV solar plants in Australia

	Employment factor [jobs/MW]	
	Construction (installation)	Operation
Mean	2.6	0.073
Median	2.0	0.050
Minimum	0.5	0.017
Maximum	8.2	0.250

Source: Authors' calculations based on the compilation of data from Clean Energy Council (2018b), Queensland Government (2018), Clean Energy Council (2018b), AEMO (2018a) and large-scale solar plant public announcements of employment figures.

total employment share of industries related to carbon emissions within SA2 regions in the state.

4.1 Carbon economic exposure

The 'carbon economic exposure' (CEE) indicator captures the proportion of jobs that depend on carbon-intensive industries. To define this indicator using census data, we estimated the employment share in sectors linked to high GHG emissions for every SA2 region in Queensland in 2016: agriculture (sheep, beef cattle and grain farming; dairy cattle farming); manufacturing (pulp, paper and paperboard manufacturing; petroleum and coal product manufacturing; glass and glass product manufacturing; cement, lime, plaster and concrete manufacturing; primary metal and metal product manufacturing); mining (coal mining; oil and gas extraction); and electricity, gas, water and waste services (fossil fuel electricity generation).

The 'carbon economic exposure' indicator is formed as the sum of the employment shares of all these sectors and sub-sectors. This gives a total share of employment in emissions-intensive activities in each SA2 economy.

Table 5 shows summary statistics of the CEE indicator for the whole of Australia down to SA2 regions in Queensland. As seen, the share of the workforce employed in high-intensive GHG activities is around 2 per cent in the whole Australia and 3 per cent in Queensland. However, these values are larger when looking at the mean of SA2 economies, pointing to the high reliance that some regions have on carbon-exposed economic activities. In this case, the mean of SA2 regions in Queensland has higher (statistically significant) values than the rest of the country, signalling a higher economic dependency than many regions in Queensland have on GHG emissions.

4.2 Carbon economic resilience

The 'carbon economic resilience' (CER) indicator is based on the share of employment of export-oriented low-GHG-intensive sectors across SA2 regions. We define the objective of this indicator as measuring 'resilience' because it captures the capacity of a region to withstand the potential effects of a disruption caused by decarbonisation (Briguglio *et al.*, 2008). The indicator focuses on export-oriented sectors because these are crucial sectors to sustain the economic activity of regional areas, providing primary jobs that can generate job multiplier effects to other sectors (such as construction and local services) in the regional economy (Fleming and Measham 2014). Thus, we do not include jobs in local services or construction sectors because it can be argued that these alone will not bring economic growth to regional economies with low levels of human capital (Kilkenny and Partridge 2009). Undoubtedly, some amenity-rich regions or educational hubs can thrive economically even without primary export-oriented industries or manufacturing, but in most cases, these drivers of growth are hard to establish in most regional areas.

The economic sectors and sub-sectors included in the ‘carbon economic resilience’ indicator are as follows: agriculture (all employment excluding jobs in sheep, beef cattle and grain farming; dairy cattle farming); manufacturing (all employment excluding cement, lime and concrete; petroleum refinery; glass production; pulp and paper manufacturing; primary metal production); mining (all employment excluding coal mining; oil and gas extraction); and tourism. Employment in tourism is associated with accommodation and food services, and arts and recreation; however, the fraction of this workforce sustained by tourism activity will vary considerably across regions. In our analysis, we consider all employment in these sectors for tourism in order to avoid doing arbitrary adjustments. Further research is required to identify the proportion of this workforce sustained by tourism activity apart from that generated by spillovers from sectors linked to the ‘carbon economic exposure’ indicator.

The CER indicator is calculated as the sum of employment shares across these sectors and sub-sectors. This gives the total share of people employed in low GHG-intensive export-oriented sectors over the total labour force of the local SA2 economy. Table 5 shows summary statistics of the CER indicator. The share of employment in resilient activities in the state of Queensland matches that of the whole of Australia. However, the mean and standard distribution of the CER indicators across SA2 regions differ between regions, with Queensland showing lower levels than the rest of Australia.

In addition to the existing CER of communities and regions, changes towards low-emissions systems can bring economic opportunities to regions in Queensland. For example, there are employment and other opportunities around renewable energy generation and the extraction of minerals linked to ‘clean technology’, such as lithium, cobalt and rare earth minerals that are increasingly in demand. We did not include these sectors in the ‘carbon economic resilience’ indicator design as regionally disaggregated data are not available for renewable energy generation and because opportunities (as in the case of rare earth minerals, for instance) still need to become reality on the ground. While these omissions can skew the index towards presenting a less resilient economy, we opted for a more conservative approach instead of making unverifiable claims with regard to specific regional employment numbers. Adding additional elements to the index based on regionally disaggregated data for renewables will form the subject of future research.

5. The LEVER index: Contrasting regional economic vulnerability to climate change mitigation

To enable the analysis of potential economic impacts of the transition towards low-emissions economic activities on regional economies, we developed an index that captures the relative local level of carbon dependency on employment: the ‘latent economic vulnerability to emissions reduction’ (LEVER) index. The index pegs the role of a carbon-intensive set of industries against lower carbon emissions sectors across regions/areas of the local economy.

The aim of the LEVER index is to provide a mapping and exploratory analysis to allow policymakers and analysts to examine which regions, under different climate change mitigation pathways, may require support to enable a just and smooth transition. The analysis points to the regions that would require higher levels of support to avoid economic stress and unfavourable employment outcomes. To achieve this, the LEVER index is formed by the ratio of the two indicators described in the previous section:

$$\text{Lever index} = \frac{\text{Carbon economic exposure}}{\text{Carbon economic resilience}}$$

By using the ratio of these two indicators, the LEVER index contrasts the relative importance of high-emitting to low-emitting activities in the local economy. Its construct means that it is a relative index that can be used to contrast the potential economic vulnerability to decarbonisation of a region compared to other regions or the same region over time (provided the index is updated periodically). Thus, the LEVER index does not provide an explicit threshold to define the vulnerability of a region by itself. However, in the case of a LEVER index above 1, the local economy is showing that the number of jobs dependent on GHG emissions-intensive activities outweighs the number of jobs provided by less carbon-intensive export-oriented sectors, which points to a very high economic vulnerability to future low-emissions economic activity. This does not mean, though, that only regions with a LEVER index greater than one will be highly vulnerable. The aim of the index is to contrast regions for policy prioritisation rather than to provide an absolute vulnerability threshold.

A critical consideration in the construction of the LEVER index is that all sectors represent similar exposure to (or independence from, in the case of resilience) GHG emissions, which is not necessarily the case. To consider this potential distortion, the LEVER can be constructed with weights applied to different sectors. These weights can differentiate the relative importance of emissions on job activity. For instance, weighting can differentiate employment in coal-fired power stations (linked to more emissions per worker) from employment in ruminant agriculture (linked to lower emissions per worker). By using weights, the LEVER index allows for flexibility of its use to more accurately study how regions are exposed to different potential interventions under the heterogeneous structures of local and regional economies.

The weights can be adjusted to align with chosen criteria. For instance, they can be established after stakeholder consultation regarding future scenarios for low-emissions targets, estimating the relative amount of emissions that different sectors produce to the added value of the economy, the amount of indirect employment generated, or the industry potential for

Table 4 Sectoral employment and respective weights used in the LEVER weighted index in this paper

Carbon economic exposure		Carbon economic resilience	
Sector/activity	Weight	Sector/activity	Weight
Manufacturing (pulp, paper and paperboard manufacturing; petroleum and coal product manufacturing; glass and glass product manufacturing; cement, lime, plaster and concrete)	10	Manufacturing, excluding sectors in 'Carbon Economic Exposure'	25
Agriculture (sheep, beef cattle and grain farming; dairy cattle farming)	10	Agriculture, excluding sectors in 'Carbon Economic Exposure'	15
Oil and gas extraction	10	Mining, excluding coal mining and oil and gas extraction	30
Coal mining (all)	10	Tourism (accommodation and food services and arts and recreation)	10
Thermal coal mining jobs (employment in thermal coal mining regions outside the Bowen Basin)†	20	Tourism in coastal regions†	20
Electricity generation from fossil fuels (all, gas, oil and coal generators)	10		
Coal-fired power station jobs (employment linked to coal power plants)†	30		

Note: All values are set to one for the unweighted LEVER index (except for † weights). Weights applied here are not intended as an absolute benchmark but as a starting point for research.
†Denotes additional weights (see description in text) based on location, which are set to zero for the unweighted index.

emissions substitutability.[4] In this paper, we establish weights, as shown in Table 4, which are a qualitative interpretation by the authors of this article based on the discussion in the previous sections. The weights we assign here are not crucial as they are not intended as a benchmark, but rather as a starting point for research and to contrast with results that arise from the unweighted index.[5]

In addition to the weighting by sectors shown in Table 4, we also include three geographic weights to capture spatial aspects in the LEVER weighted index:

- Thermal coal mining jobs: This weight aims to capture the higher vulnerability that thermal coal can bring to hosting regions, in contrast to metallurgical (coking) coal. As discussed above, thermal coal is more likely to see its demand decline in the near future compared with

[4] This last point is relevant because the Clean Energy Regulator considers the amount of electricity consumed by industry for their emissions-intensive classification. If the electricity currently sourced from coal-fired power plants can increasingly be replaced by electricity sourced from renewables, then the emissions substitutability will be high.

[5] In the online supplementary material, we provide an Excel file where we developed a tool where weights can be changed by the user. A change in the weights changes the LEVER index value for a region.

metallurgical coal, which implies that thermal coal mines are more likely to be affected by climate change mitigation efforts than coking coal mines. To address this, we included a weighting to the coal mining employment of regions located within 50 km of thermal coal mines across the southern basins of Queensland. We excluded regions in the Bowen Basin because this basin hosts all the coking coal mines in the state.

- Coal-fired power station jobs: Similar to the thermal coal mining job weight, we applied a weight to electricity generation employment for regions within 20 km of coal-fired power stations. The activity of these plants could benefit from lower international demand for thermal coal in the future, as cheaper coal would mean cheaper electricity generation in these plants. However, the large GHG emissions these plants generate, a third of all emissions of Queensland, means they could be a direct target of low-emissions policies including early decommissioning in coming years. Given this, we added extra weight to these regions as well.[6]
- Tourism in coastal regions: Given that coastal regions have a higher comparative advantage for tourism activity in Australia, we added extra weight to these regions to reinforce the economic importance of tourism in these regions compared with inland regional areas.

6. Application and results from the LEVER index

Table 5 presents summary statistics of the unweighted LEVER index for all SA2 regions in Queensland, as well as for the rest of Australia. National-level and state-level mean, median and standard deviation values are also included. The mean LEVER value for Queensland's SA2 regions is 0.251, which is 54 per cent larger (and statistically different) than the mean value in the rest of the SA2 regions of Australia (0.163). In contrast, the CEE of Queensland regions is 33 per cent larger than that of the average region in the rest of the country (0.04 and 0.03, respectively). Moreover, the coefficient of variation of the LEVER index is higher than that of the CEE as well. These larger differences point to the usefulness that the LEVER index can have from a statistical point of view; it captures larger differences between regions in Queensland and the rest of the country and higher variation across regions within the state. Capturing this difference and variability can allow policy planners to better contrast the economic vulnerability of regions, considering their dependency and resilience to emissions, as mitigation continues imposing challenges to future industrial activity.

[6] The decision to use a 50 km radial distance for coal mining and 20 km distance for coal-fired power stations was made by the researchers based on the nature of employment in these respective sectors. In contrast to power stations, mining is characterised by long-distance commuting. Although these numbers are not a perfect reflection of what might be happening in reality (for instance, the commuting of miners in southern basins could be much higher), they illustrate the regions that would be more exposed to the economic activity of these sectors.

Table 5 Summary statistics of the CEE and CER indicators and the LEVER index

	Australia	Australia, excluding QLD	Queensland (QLD)	SA2s whole Australia (n = 1,730)†			SA2 regions in Queensland (n = 519)†		
				Mean	Median	SD	Mean	Median	SD
CEE (carbon economic exposure)	0.021	0.019	0.029	0.030	0.011	0.058	0.039	0.014	0.072
CER (carbon economic resilience)	0.157	0.157	0.157	0.167	0.152	0.076	0.159	0.149	0.056
LEVER (latent economic vulnerability to emissions reduction) index	0.135	0.122	0.187	0.163	0.067	0.340	0.251	0.096	0.493

†SA2s with employment data in the 2016 Census after removing the SA2s of 'Eungella Hinterland' (Queensland) and Ettrema (NSW) that report a CER of zero. Values correspond to the unweighted LEVER index.

Figure 5 shows the spatial distribution of the LEVER index within Queensland. The unweighted index results show that 6.2 per cent of Queensland's SA2 regions present a very high LEVER index (values over 1). The SA2 regions with the highest LEVER are mostly located in Central Queensland (11 regions) and Queensland Outback (8 regions), regions mainly characterised by large coal mining and beef cattle production. In contrast, the SA2 regions with the lowest LEVER are mostly located in the Gold Coast and Cairns areas. This particular result is the effect of the relatively higher importance of the tourism sector in these regions.

By comparison, results from the weighted LEVER index show that 3.7 per cent of the state's SA2 regions present a very high economic vulnerability to industry transformation associated with a shift towards lower GHG emissions. This decline in the number of very highly vulnerable regions is mainly caused by the lower weight given to ruminant-based agricultural employment, which decreases the carbon economic exposure of many inland regions. The SA2 regions with the highest LEVER after applying weights are Broadsound-Nebo and Clermont (located in the SA4 of Mackay-Isaac-Whitsunday), Croydon (SA4 Outback) and Banana (SA4 Central Queensland). In contrast, the SA2 with the lowest LEVER is Port Douglas in the SA4 of Cairns, followed by the three SA2 regions in the Gold Coast SA4 and one Brisbane suburb.

Results also show that 18 per cent of the SA2 regions in the state increase their LEVER when weights are included in the analysis. The SA2 regions that increase their economic vulnerability the most when weighted are include Broadsound-Nebo and Clermont (in the SA4 of Mackay-Isaac-Whitsunday) and Biloela and Mount Morgan (in the SA4 of Central Queensland). These are regions with a high presence of coal mining and coal-fired power station employment. In contrast, the SA2s that most reduce their vulnerability when weights are applied are the Northern Highlands in the Queensland Outback SA4 and Roma in the SA4 of Darling Downs-Maranoa, although in these two cases the LEVER value remains above one. In practical terms for policy analysis, this means that including weights is recommended for industries where carbon dependency is relatively hard to shift away from, for example, coal extraction.

Table 6 presents the SA2 regions in Queensland with the highest economic vulnerability to GHG mitigation, including values for both unweighted and weighted LEVER indexes. The SA2 regions reporting the largest change between weighted and unweighted indexes are also presented, indicating regions that become more vulnerable if weights (in this case, those reported in Table 4) are applied to the data.

7. Implications and conclusion

Climate change and the associated long-term industry transformations associated with shifts towards lower emissions will disrupt economies. These 'disruptions' are likely to lead to structural changes in some local and

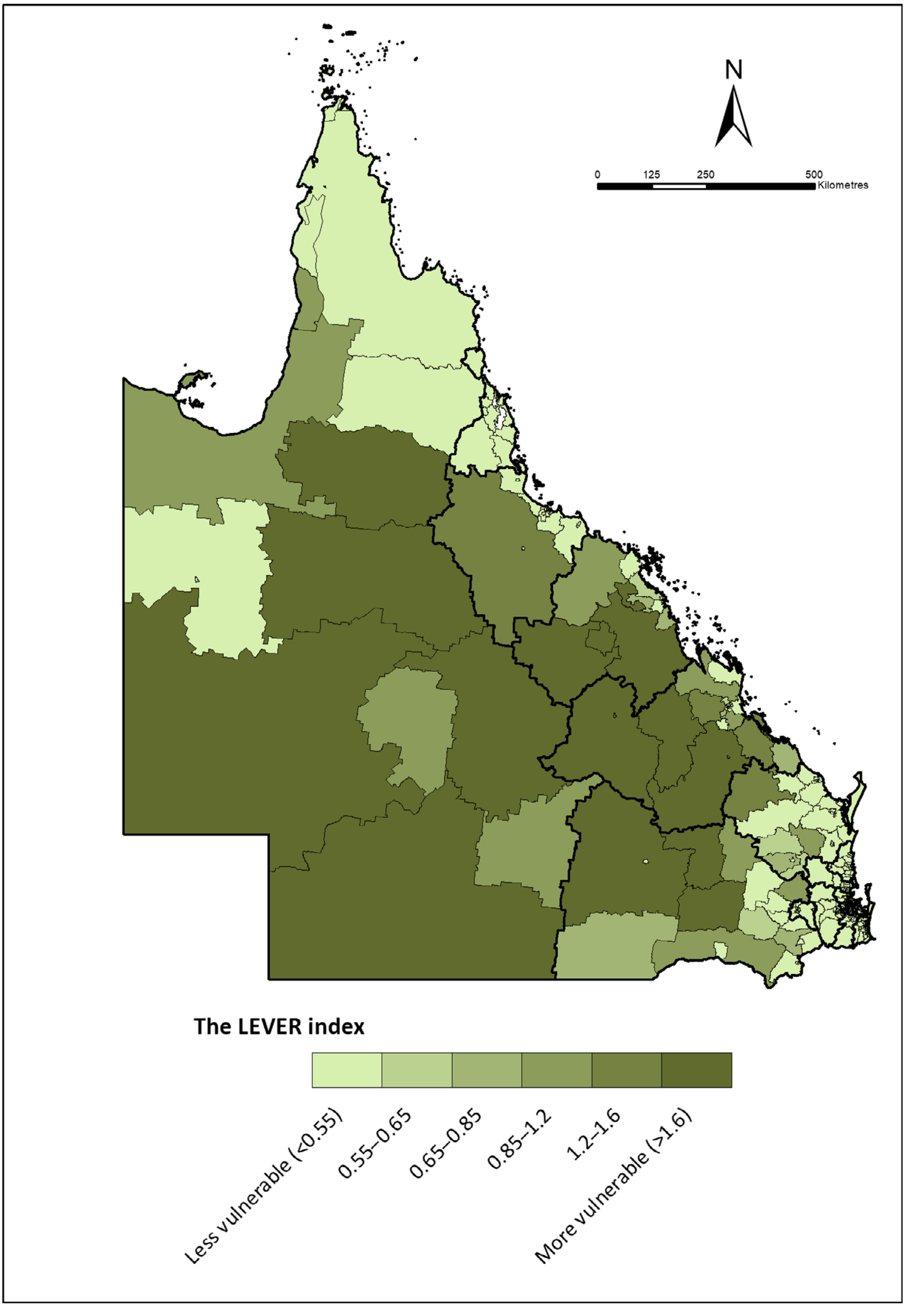

Figure 5 The latent economic vulnerability to emissions reduction (LEVER) index. Regions are denoted according to SA2 regions (denoted with grey borders). SA2 regions are nested in SA4 regions (thick borders). [Colour figure can be viewed at wileyonlinelibrary.com]

Table 6 Top eight SA2s with the highest unweighted and weighted LEVER indexes and the highest change in score between unweighted and weighted versions

SA4 region	SA2 region	Unweighted LEVER	SA4 region	SA2 region	Weighted LEVER	SA4 region	SA2 region	LEVER change (weighted - unweighted)
Mackay-Isaac-Whitsunday	Broadsound-Nebo	3.869	Mackay-Isaac-Whitsunday	Broadsound-Nebo	6.453	Mackay-Isaac-Whitsunday	Broadsound-Nebo	2.584
Queensland Outback	Croydon-Etheridge	3.423	Mackay-Isaac-Whitsunday	Clermont	3.220	Central Queensland	Biloela	0.635
Central Queensland	Central Highlands-East	3.400	Queensland Outback	Croydon-Etheridge	2.752	Mackay-Isaac-Whitsunday	Clermont	0.491
Queensland Outback	Barcaldine-Blackall	3.024	Central Queensland	Banana	2.494	Central Queensland	Mount Morgan	0.259
Darling Downs-Maranoa	Roma Region	2.847	Central Queensland	Central Highlands-West	2.261	Central Queensland	Central Highlands-West	0.205
Queensland Outback	Northern Highlands	2.821	Central Queensland	Central Highlands-East	2.250	Wide Bay	Kingaroy	0.193
Mackay-Isaac-Whitsunday	Clermont	2.728	Queensland Outback	Barcaldine-Blackall	2.188	Wide Bay	Nanango	0.089
Mackay-Isaac-Whitsunday	Moranbah	2.706	Queensland Outback	Far Central West	2.004	Brisbane-west	Chelmer – Graceville	0.083

Source: Own elaboration based on data from ABS (2019a). To replicate results, please use Excel tool available in the Appendix S1 of this paper.

regional economies. As the world transitions away from coal and other fossil fuels, impacts are likely to occur, especially in those local and regional economies that substantially rely on carbon-intensive sectors to sustain their activities and livelihoods. To develop policies and plan for changes towards carbon-neutral economic systems, analysis of potential employment effects from climate change mitigation is needed to be able to support a just and smooth transition for communities. This paper proposes a method to carry out this form of analysis and discusses its output in the context of a case study, the state of Queensland in Australia. The paper proposes a 'carbon economic exposure' (CEE) indicator, a 'carbon economic resilience' (CER) indicator and a 'latent economic vulnerability to emissions reduction' (LEVER) index for regional economies. By developing the indicators and the index, we aim to provide a simple but informative method to map and analyse which regional areas could be more economically vulnerable to a shift away from high-emissions industries.

The CEE indicator captures the relative importance of the local workforce employed in coal mining, coal-fired power stations, cattle agriculture and some particularly GHG-intensive manufacturing processes. The CER captures the relative importance of the local workforce employed by low GHG-intensive export-oriented industry activities (tourism, non-coal mining, non-cattle agriculture and low GHG-intensive manufacturing). The LEVER index is given by the ratio of these indicators (CEE/CER), capturing, in relative terms, local economies that might be more affected as a consequence of mitigation efforts. The analysis we provide with the LEVER index helps to dissect which local economies may struggle and which may cope better with a low-carbon-emissions future.

Regarding the LEVER construction and the results discussed, five points need to be considered when interpreting and using the estimates. First, the LEVER index does not capture some of the opportunities that transition to low-emissions systems can bring to regional economies, many of which can support local economic resilience. In this design of the index, we are not capturing, among other things, the growing expansion of renewable energy projects (discussed in Section 3.4) or other emerging sectors including the potential for new mining to feed the fourth industrial revolution. These variables can be added as more regional disaggregated data become available – official statistics on renewable energy jobs is only available at the state level (ABS 2019b) – and projects materialise. Second, to capture economic resilience, we focused on export-oriented industries that are located in regions with natural comparative advantages, such as climate or resource endowments. These industries generate regional and rural economic activity to support population growth and jobs in other areas, such as services and construction. If these export-oriented industries start reducing their demand for labour (for instance, because of automation or decline of market power), it is possible that residents will move to areas more favourable to the emergence of alternative economic sectors and start-ups. Such areas would tend to be in high amenity (e.g. coastal towns) or densely populated areas (e.g. large regional towns and cities). Third, the LEVER index is a static metric; that is, it only captures a snapshot in time (in our analysis, the Census night of 2016). However, it can be estimated for other years (if data are available) to capture changes over time. Fourth, the weights used in the LEVER index in this paper are an initial exploratory assessment and not a benchmark. As noted before, the weights can be adjusted to reflect the relative importance of different sectors to GHG emissions or a particular policy focus. Fifth, a final and important point is that, as any indicator using proportions (shares), the LEVER index does not identify potential vulnerability differences between regions with large populations and those with small workforces. Thus, two very different regions (one with a large workforce and one with a small one, for instance) can have a similar LEVER index value. Given this, the scale of regional employment numbers (as we show in Table 2, and Tables A1 and A2 in Appendix S1) also needs to be assessed in order to provide complementary insights to the LEVER index metric.

The LEVER index is first and foremost a policy analysis tool, developed to support strategies to enable just and smooth transitions for communities. It is intended for use by policymakers and researchers. Future development of the index can include additional sectors that contribute to the resilience of regional economies, such as the scale of employment in renewable energy generation and emerging alternative export-oriented industries as data become available and projects start materialising. This could be done with the policy goal of identifying which industries potentially increase local economic resilience in the low-carbon transition process to the greatest extent. Future applications and tests of the tool could involve an application to other case studies, including other states in Australia. The LEVER index is a stepping stone contributing to the analysis of potential economic impacts of the transition towards low-emissions economic activities in local economies across the world.

References

ABS (2016a). *Digital boundaries*. Australian Bureau of Statistics. Available from URL: https://www.abs.gov.au/websitedbs/D3310114.nsf/home/Digital+Boundaries [accessed 4 April 2019].

ABS (2016b). *1270.0.55.001 Australian Statistical Geography Standard (ASGS): Volume 1 – Main Structure and Greater Capital City Statistical Areas*, July 2016. Australian Bureau of Statistics. Available from URL: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1270.0.55.001~July%202016~Main%20Features~Statistical%20Area%20Level%202%20(SA2)~10014 [accessed 4 April 2019].

ABS (2017). *Time series workbook*. *Table 05*. *Employed persons by State, Territory and Industry division of main job (ANZSIC)*. Available from URL: https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/6291.0.55.003Aug%202018?OpenDocument [accessed 4 April 2019].

ABS (2019a). *Table builder census data*. Australian Bureau of Statistics. Available from URL: https://www.abs.gov.au/websitedbs/censushome.nsf/home/tablebuilder [accessed 4 April 2019].

ABS (2019b). *4631.0 Employment in Renewable Energy Activities, Australia*. Australian Bureau of Statistics, Canberra. Available from URL: https://www.abs.gov.au/ausstats/abs@.nsf/mf/4631.0 [accessed 30 April 2019].

AEMO (2018a). *Generation information*. Australian Energy Market Operator. Available from URL: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information [accessed 10 April 2019].

AEMO (2018b). *Power system requirements*. Australian Energy Market Operator Limited. Available from URL: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf [accessed 1 September 2019].

Australian Senate (2017). *Retirement of Coal Fired Power Stations: Final Report*. Environment and Communications References Committee, Commonwealth of Australia.

Briguglio, L., Cordina, G., Farrugia, N. and Vella, S. (2008). *Economic vulnerability and resilience*. United Nations University Research Paper No. 2008/55. Helsinki, Finland.

Burdekin Shire Council (2017). *Council approved Pacific Hydro solar farm*. Available from URL: https://www.burdekin.qld.gov.au/2017/archived/council-approves-pacific-hydro-solar-farm/#gsc.tab=0 [accessed 7 July 2019].

Burke, M., Hsiang, S. and Miguel, E. (2015). Global non-linear effect of temperature on economic production, *Nature* 527, 235–239.

Burke, P., Best, R. and Jotzo, F. (2019). Closures of coal-fired power stations in Australia: Local unemployment effects, *Australian Journal of Agricultural and Resource Economics* 63, 142–165.

CER (2018). *2020 Large-scale Renewable Energy Target capacity achieved*. Available from URL: http://www.cleanenergyregulator.gov.au/About/Pages/News%20and%20updates/NewsItem.aspx?ListId=19b4efbb-6f5d-4637-94c4-121c1f96fcfe&ItemId=683 [accessed 5 September 2019].

CER (2019). *Large-scale Renewable Energy Target supply data*. Available from URL: http://www.cleanenergyregulator.gov.au/RET/Pages/About%20the%20Renewable%20Energy%20Target/How%20the%20scheme%20works/Large-scale-Renewable-Energy-Target-Supply-Data.aspx [accessed 17 July 2019].

Clean Energy Council (2018a). *Clean Energy Australia Report 2018*. Available from URL: https://www.cleanenergycouncil.org.au/resources/resources-hub/clean-energy-australia-report [accessed 7 August 2019].

Clean Energy Council (2018b). *Jobs and investment in large-scale renewables*. Available from URL: http://www.cleanenergycouncil.org.au/policy-advocacy/jobs-and-investment.html [accessed 17 July 2019].

ClimateWorks (2016). *Queensland can achieve net zero emissions by 2050. Executive summary*. ClimateWorks Australia, Melbourne, Australia. Available from URL: https://www.qld.gov.au/__data/assets/pdf_file/0028/68365/cwa-exec-summary-qld-net-zero-emissions-2050.pdf [accessed 1 September 2019].

Darby, M. (2019). *Which countries have a net zero carbon goal? Climate Home News*. Available from URL: https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal/ [accessed 21 August 2019].

DEE (2011). *Emissions-intensive trade-exposed activity boundaries*. Department of the Environment and Energy, Australian Government. Available from URL: https://www.environment.gov.au/system/files/resources/b293571f-2c64-46ea-be1e-ee7b07d1766a/files/eite-activity-boundaries.pdf [accessed 30 January 2019].

DEE (2018). *Australian Energy Update 2018*. Department of the Environment and Energy, Australian Government. Available from URL: https://www.energy.gov.au/publications/australian-energy-update-2018 [accessed 3 April 2019].

DEE (2019a). *Australia's 2030 climate change target*. Department of the Environment and Energy, Australian Government. Available from URL: https://www.environment.gov.au/climate-change/publications/factsheet-australias-2030-climate-change-target [accessed 9 August 2019].

DEE (2019b). *Australian Energy Statistics, Table O – Australian electricity generation, by fuel type, physical units*. Department of the Environment and Energy, Australian Government.
DFAT (2019). *Trade and Investments data, information and publications – Queensland fact sheet*. Department of Foreign Affairs and Trade, Australian Government. Available from URL: https://dfat.gov.au/trade/resources/Documents/qld.pdf [accessed 3 September 2019].
DNRM (2018). *Queensland coal – mines and advanced projects. Department of Natural Resources and Mines, Queensland Government*. Available from URL: http://www.ohsa.com.au/wp-content/uploads/2017/08/Queensland-Coal-Mines-and-Advanced-Projects-Updated-July-2017.pdf [accessed 11 July 2019].
DNRM (2019). *Natural Resources Inventory – metallurgical coal*. Department of Natural Resources and Mines, Queensland Government. Available from URL: https://inventory.dnrme.qld.gov.au/geological?p1=coalmetal&p2 [accessed 1 September 2019].
Environment Victoria (2019). *The problem with brown coal*. Available from URL: https://environmentvictoria.org.au/our-campaigns/safe-climate/problem-brown-coal/ [accessed 6 August 2019].
EY and SolarPower Europe (2017). *Solar PV Jobs & Value Added in Europe*. Available from URL: http://www.solarpowereurope.org/solar-pv-jobs-value-added-in-europe/ [accessed 4 April 2019].
Fleming, D. and Measham, T. (2014). Local job multipliers of mining, *Resources Policy* 41, 9–15.
Fleming, D. and Measham, T. (2015). Local economic impacts of an unconventional energy boom: the coal seam gas industry in Australia, *Australian Journal of Agricultural and Resource Economics* 59, 78–94.
Geoscience Australia (2019). *Australian atlas of mineral resources, mines and processing centres*. Available from URL: http://www.australianminesatlas.gov.au/mapping/downloads.html [accessed 3 April 2019].
Healy, N. and Barry, J. (2017). Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition", *Energy Policy* 108, 451–459.
Indexmundi (2018). *Australian Thermal Coal Monthly Price*. Available from URL: https://www.indexmundi.com/commodities/?commodity=coal-australian&months=300 [accessed 1 September 2019].
Jotzo, F. and Kemp, L. (2015). *Australia can cut emissions deeply and the cost is low*. Centre for Climate Economics and Policy, ANU for WWF-Australia. Available from URL: https://www.wwf.org.au/ArticleDocuments/353/pub-australia-can-cut-emissions-deeply-and-the-cost-is-low-21apr15.pdf.aspx [accessed 11 June 2019].
Kilkenny, M. and Partridge, M. (2009). Exports sectors and rural development, *American Journal of Agricultural Economics* 91, 910–929.
Louie, E. and Pearce, J. (2016). Retraining investment for U.S. transition from coal to solar photovoltaic employment, *Energy Economics* 57, 295–302.
Macdonald-Smith, A. and Ludlow, M. (2019). *Electricity prices hit minus $1000 in Queensland*. Available from URL: https://www.afr.com/companies/energy/electricity-prices-hit-minus-1000-in-qld-20190904-p52nup [accessed 1 October 2019].
Markkanen, S. and Anger-Kraavi, A. (2019). Social impacts of climate change mitigation policies and their implications for inequality, *Climate Policy* 19, 827–844.
Measham, T., Fleming, D. and Schandl, H. (2016). A conceptual model of the socioeconomic impacts of unconventional fossil fuel extraction, *Global Environmental Change* 36, 101–110.
ND-GAIN (2019). *ND-GAIN Country Index. Notre Dame Global Adaptation Initiative*. Available from URL: https://gain.nd.edu/our-work/country-index/ [accessed 2 September 2019].
Nelson, T., Orton, F. and Chappel, T. (2018). Decarbonisation and wholesale electricity market design, *Australian Journal of Agricultural and Resource Economics* 62, 654–675.
Queensland Government (2018). *Population growth highlights and trends, Queensland*. Available from URL: http://www.qgso.qld.gov.au/products/reports/pop-growth-highlights-trends-qld/pop-growth-highlights-trends-qld-2018-edn.pdf [accessed 8 July 2019].

Queensland Government (2019). *Total annual greenhouse gas emissions*. Available from URL: https://www.stateoftheenvironment.des.qld.gov.au/pollution/greenhouse-gas-emissions/total-annual-greenhouse-gas-emissions [accessed 1 August 2019].
Queensland Resources Council (2014). Available from URL: https://www.qrc.org.au/wp-content/uploads/2016/07/2a.MCA_report_SFS_Econ-3.pdf [accessed 1 July 2019].
Schlenker, W. and Auffhammer, M. (2018). The cost of a warming climate, *Nature* 557, 489–499.
Smil, V. (2016). Examining energy transitions: A dozen insights based on performance, *Energy Research & Social Science* 22, 194–197.
The Australia Institute (2018). *Letter to the Department of the Senate*. Available from URL: https://www.aph.gov.au/DocumentStore.ashx?xml:id = a87614e0-8f5e-4b3f-80ce-9d614e100ec8 [accessed 8 July 2019].
The World Bank (2019). *CO_2 emissions (metric tons per capita)*. Available from URL: https://data.worldbank.org/indicator/en.atm.co2e.pc?most_recent_value_desc = true [accessed 1 September 2019].
Tol, R. (2018). The economic impacts of climate change, *Review of Environmental Economics and Policy* 12, 4–25.
Vona, F. (2019). Job losses and political acceptability of climate policies: why the 'job-killing' argument is so persistent and how to overturn it, *Climate Policy* 19, 524–532.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Fossil fuel extraction and power station regional data.