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To cite this article: Rachel Tham *et al* 2020 *Environ. Res. Commun.* **2** 065003

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Environmental Research Communications



PAPER

OPEN ACCESS

RECEIVED

10 December 2019

REVISED

8 May 2020

ACCEPTED FOR PUBLICATION

20 May 2020

PUBLISHED

26 June 2020

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Scoping review to understand the potential for public health impacts of transitioning to lower carbon emission technologies and policies

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Keywords: energy transitions, health, HIA, LCAs, review, low-carbon

Abstract

Background: The transformation of the global energy sector from fossil-based fuels to low/non-carbon fuels will reduce environmental pollutant load, which in turn will benefit human health. However, with upscaling of emerging renewable technologies and energy sources, it is important to identify the potential for unintended health impacts, and to understand where the knowledge gaps lie with respect to health. We aimed to identify these gaps by conducting a scoping review. **Methods:** We conducted a systematic search of Medline, Web of Science, PubMed and EMBASE. We used broad search terms to capture literature associated with energy transitioning to low/non-carbon energy sources or related technologies, combined with terms relevant to measuring or estimating health outcomes/impacts associated with environmental exposures. We included original epidemiological studies, reviews, health impact assessments (HIAs), life cycle assessments (LCAs), and modelling studies that examined health impacts. **Results:** The search identified 6933 papers of which 81 original research and review papers were included in the review. The majority of studies were based on modelling scenarios. There were few papers reporting empirical epidemiological studies, either observational or interventional. The principal foci of the studies were: alternative energy scenario modelling; biofuels; wind energy; photovoltaic cells; transport; and building energy efficiency. Within those studies the depth and breadth of the health impact research was limited. **Conclusions:** There is a need to determine the potential for unintended health impacts that may arise from each energy transition scenario, as an adjunct to consideration of environmental and social impacts. Conducting LCAs or HIAs associated with current and emerging transitions, technologies, energy interventions, and policy decisions are likely to be the best methods, currently, for determining the potential for health impacts. Such research needs to be multidisciplinary and iterative to keep abreast of developments in new energy technologies, modelling methods and policy shifts in energy transitions.

Introduction

The current global energy sector is based primarily on fossil-based fuels, namely oil, gas and coal. Fossil fuel combustion has short, medium and long-term impacts on health (Smith *et al* 2013). In the short- to medium-terms, fossil fuel combustion creates air pollution due to the release of particulate matter and gases that have adverse impacts on human respiratory and cardiovascular health (Wu *et al* 2018) and cognitive health (Clifford *et al* 2016). Over the longer term, the contribution of fossil fuels to climate change (Intergovernmental Panel on Climate Change (IPCC (2018))) is predicted to increase health risks associated with more frequent extreme

weather events (heatwaves, droughts, vegetation fires, thunderstorms, floods) (Stott *et al* 2016), increased prevalence of infectious diseases, and changes in environmental exposures (e.g. pollens, fungal spores) (Watts *et al* 2015) and altered agricultural and forestry productivity (Intergovernmental Panel on Climate Change (IPCC (2018))). These impacts, singularly or cumulatively, can threaten economic status and social structures at personal, community and national levels (Watts *et al* 2018).

In the current century, energy transition is understood to be a strategy towards transformation of the global energy sector from fossil-based fuels to a sector that emits zero or minimal carbon, in order to limit the adverse impacts that carbon dioxide and other greenhouse gases have on the climate. There are various conceptual frameworks and varying definitions that have been used to study energy transitions (Sovacool 2016), including those related to technological requirements; political climate and policy cycles; economic impact; environmental, social and behavioural acceptance and willingness by various sectors of society; and also timing. Conceptual frameworks around timing of energy transitions relate to temporal dynamics of the energy shift. These have traditionally often taken decades (shift from oil to gas/coal), but which, with political will, now have the potential to occur more rapidly as technological advancements occur and environmental change necessitates (Sovacool 2016, Roberts *et al* 2018). However, many of those frameworks or definitions do not explicitly include consideration of the potential for direct public health impacts, although some consider the indirect co-benefits of climate change mitigation strategies for public health. In this review, we conceptualise energy transitions as moving from more polluting carbon-based energy sources to lower or non-carbon energy sources while focussing on the public health impacts of energy transition occurring in middle and high-income settings.

Current strategies to reduce carbon emissions include the use of renewable energy sources that do not continue to emit carbon, and energy efficiency measures to reduce energy needs. There has been global action, albeit with varying levels of political commitment across the world, to commit to climate change mitigation policies to reduce the adverse impacts on the environment (Workman *et al* 2018). Climate change mitigation policies may have co-benefits which may include immediate and longer-term population health effects such as reduced chronic diseases, for example, cardiopulmonary and respiratory disease and cancers associated with reduced air pollution, increased physical activity and improved social capital (Workman *et al* 2016, Chang *et al* 2017).

From a public health perspective, actions taken to mitigate climate change are fully supported (Watts *et al* 2018, Beggs *et al* 2019) and studies of the co-benefits to health of reducing greenhouse gas (GHG) emissions have described well the benefits of reduced mortality estimates (Chang *et al* 2017). However, there may be other effects of transitioning between energy sources and technologies that are less well identified and understood. As such, with upscaling of emerging renewable technologies and energy sources, it is equally important to understand whether there may be unintended health consequences of transitioning from one energy source to another. An example is the increased uptake of diesel engine vehicles in Europe which was promoted because of their higher fuel efficiency and lower particulate matter and carbon dioxide (CO₂) emissions (O'Driscoll *et al* 2018). However, an unintended consequence of the shift to diesel engines, was that the change led to increased emissions of nitrogen oxides (NO_x) instead (Beevers *et al* 2012, O'Driscoll *et al* 2018). Now, major cities in Europe are failing to meet nitrogen dioxide (NO₂) standards, predominantly at the roadside (O'Driscoll *et al* 2018, Carslaw *et al* 2019). Concurrently, there has been increasing epidemiological evidence of associations between exposure to NO_x and NO₂ and a range of adverse respiratory outcomes, including premature mortality (WHO Regional Office for Europe 2013). Together this has led to the promulgation of national plans in the UK which aim to reduce population exposure to NO₂ (Department for Environment Food and Rural Affairs and Department of Transport, May 2017). The recent announcement by the UK government to bring forward a ban on the sale of diesel and petrol vehicles from the year 2040 to 2035 will require consideration of feasible vehicle alternatives (Fly 2020). We argue that it is vital that the health impacts of any alternatives are fully considered, and that appropriate testing of emissions occurs prior to widespread implementation.

The public health paradigm is centred around a preventative approach to protecting health. As public health and environmental health practitioners, it is important to understand whether newer energy technologies and transitions being implemented, or in the planning stage by governments and industry, have the potential to adversely impact health. To date, decision making and research in renewable energies, technologies and processes has been rightly and primarily driven by the need for environmental improvement in emissions controls, specifically the need to reduce carbon dioxide (CO₂) emissions, and so it is probable that health consequences of such changes have not been fully explored. It is timely to identify the gaps in knowledge and to identify where potential adverse health impacts may be experienced, alongside the co-benefits.

There are a variety of tools that can be used to study the impacts of energy transitions, including development and implementation of models, health impact assessment (HIA), life cycle assessment (LCA) and epidemiology. While modelling and LCAs have been used to project environmental benefits and impacts, it was unclear to us as health practitioners the extent to which health impacts have been assessed for specific transitions scenarios e.g. transitioning from the use of petrol/gasoline vehicles to electric vehicles. While this scoping review

Table 1. Search terms.

	Terms
Energy transition	energy AND (transition* OR reform* OR future* OR greenhouse gas* OR decarbon* OR fossil fuel* OR alternative OR carbon constrained OR clean OR renewable* OR low carbon OR future* OR solar* OR wind* OR biofuel* OR electricity OR biogas OR ethanol OR diesel OR gasoline OR petrol*)
AND	
Health outcome	health AND (co-benefit* OR externalit* OR impact* OR effect* OR cardiovascular OR cardiorespiratory OR CVD OR respiratory)
Excluding	
NOT	(diet OR biomass OR accident*)

considers the various methods used to date, it was not our intention to evaluate the modelling methods as this was beyond the scope of our review and has been reported recently (Chang *et al* 2017).

The aims of this scoping review were:

- (1) to synthesise the current evidence available on the health impacts of transitioning from traditional fossil-based fuels to other low/non-carbon forms of energy in high- and middle- income countries; and
- (2) to identify current gaps in knowledge on the potential for health impact from energy transitions, processes and technologies.

Methods

As the field of energy transitions is multidisciplinary and broad in its inputs and reach, we used the following criteria to structure the review. The inclusion criteria comprised research which reported empirical and modelling studies, reviews, and HIAs that examined the health co-benefits or impacts in relation to energy transition technologies and processes. As we aimed to include all papers related to health we included ‘health’ as a broad search term as well as specific search terms pertaining to cardiovascular and respiratory disease (table 1).

Given the need to focus the review on health and public health impacts, we excluded research that related to:

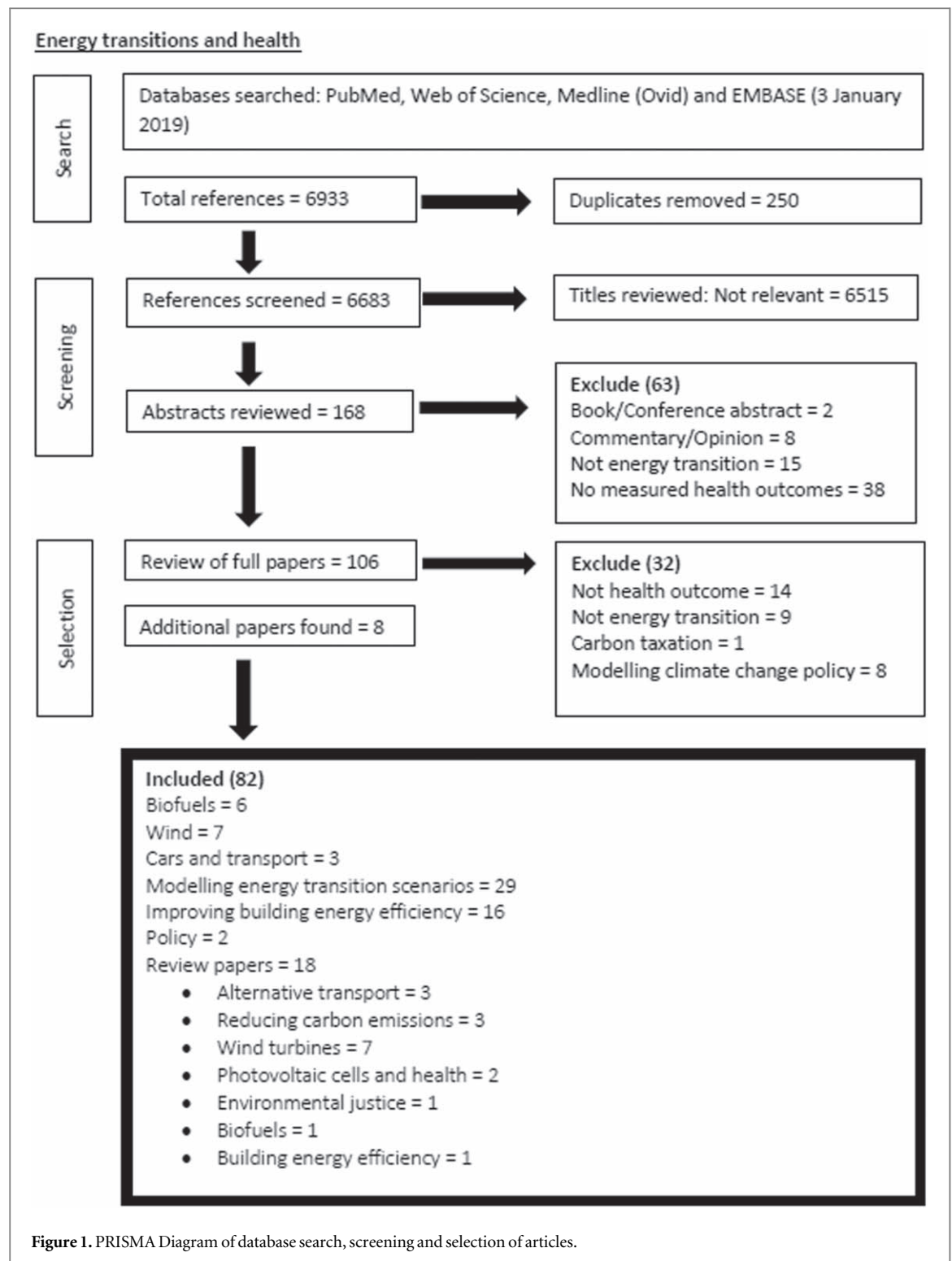
- (1) energy transitions but which did not relate to health outcomes;
- (2) clinical or public health trials that did not relate to energy transition, energy use or alternative energy production;
- (3) modelling of climate change policies that did not relate to transitioning from fossil-based energy sources to other low/non-carbon forms of energy. That is, papers which reported analyses of the health co-benefits of improving air quality through general reductions in GHG emissions or changes to policy and planning, as we were mindful of the substantial literature already in existence (Thompson *et al* 2014, Turnock *et al* 2016, Partanen *et al* 2018);
- (4) changes in building energy use that did not examine impacts on health;
- (5) energy use for indoor cooking or heating using biomass in low income settings;
- (6) economic, social, political, technological and temporal impacts on energy transitions which did not related to health outcomes; and
- (7) studies relating to consumer and societal behaviour, energy security and geo-political science, as we considered these to be outside the scope of the review and are broad, complex disciplinary areas in themselves.

To avoid duplication of included papers we checked the original papers cited in review papers and subsequently excluded them unless they contained relevant findings that were not reported in the reviews.

Search strategy

The literature was searched using bibliographic databases commonly used in the health sciences: Medline, Web of Science, PubMed and EMBASE. No publication date restrictions were imposed but only English language papers were searched and selected.

The search terms used are detailed in table 1.



The abstracts of all identified papers were reviewed for initial inclusion, then full papers were read if inclusion criteria were met. Further hand searching of reference lists from included publications was undertaken. We have reported the results of these papers along with discussion of them in the next section.

Results

Our search, conducted on 28 January 2019, initially identified 6933 papers of which 82 papers were included in our final narrative synthesis (figure 1). Overall, few epidemiological studies, either observational or interventional, were found in the peer-reviewed literature. Of these most were related to wind turbine studies

and building energy efficiency studies. The majority of papers were based on modelling energy and climate change scenarios. We included 18 review papers which had previously synthesised relevant literature.

The included papers covered a diverse and broad range of key topics associated with the health impacts of energy transitioning from fossil-based fuel to low/no carbon energy sources. To facilitate the summary of findings from the range of papers we grouped them according to themes: modelling alternate energy production scenarios, biofuels, wind energy, photovoltaic cells, alternative forms of transport, and improving building energy efficiency.

The included papers comprised studies that modelled scenarios of alternate energy source/production/use and the impact on health ($n = 29$), followed by studies on building energy efficiency ($n = 17$), wind turbines/farms ($n = 14$), transport ($n = 6$), and photovoltaic cells.

Discussion

Modelling alternate energy source/production scenarios

The majority of papers included in this review were modelling studies that compared energy source scenarios and estimated health impacts or benefits. The modelling approaches are summarised in table 2 by geographic location. In the USA, the CMAQ chemical transport model combined with a regulatory standard health impact assessment was reported in the US EPA Benefits Mapping and Analysis Program (Akhtar *et al* 2013, Buonocore *et al* 2016a, Buonocore *et al* 2016b, Abel *et al* 2018b); the Electrical Policy Simulation Tool for Electrical Grid Interventions (EPSTEIN) (Buonocore *et al* 2016a, Buonocore *et al* 2016b); GATOR-GCMOM with the U.S. National Emission Inventory (Jacobson *et al* 2005); and CoBenefits Risk Assessment (COBRA) (McCubbin and Sovacool 2013). In China, the Long-range Energy Alternatives Planning system (LEAPs) (Chen *et al* 2007, Pan *et al* 2007, Xue *et al* 2015, Liu *et al* 2018); the Comparative Risk Assessment Approach (Qin *et al* 2017); and Damage Function Methodology (Partridge and Gamkhar 2012), were reported. Among these studies, the key health outcomes were assessed using economic modelling, for example, premature mortality or avoidable deaths using the 'value of a statistical life' to monetise the savings, and respiratory and/or cardiac hospitalisations and/or symptoms using the metric 'willingness to pay' to monetise the savings.

The modelling studies of fossil-fuel based energy production that was replaced with renewable energy sources (solar, wind, hydro) resulted in reduced levels of air pollutants (particulate matter with aerodynamic diameter of $<2.5\mu\text{m}$ [$\text{PM}_{2.5}$], $<10\mu\text{m}$ [PM_{10}]; CO_2 ; NO_2), with concomitant health benefits being obtained through reduced avoidable deaths and reduced health care costs associated with hospitalisations, emergency department attendances, and loss of time from work/school due to ill-health (Aunan *et al* 1998, Chen *et al* 2007, Pan *et al* 2007, Gilmore *et al* 2010, Haluza *et al* 2012, Partridge and Gamkhar 2012, Akhtar *et al* 2013, McCubbin and Sovacool 2013, Shih and Tseng 2014, Treyer *et al* 2014, Gschwind *et al* 2015, Xue *et al* 2015, AlRafea *et al* 2016, Buonocore *et al* 2016a, Buonocore *et al* 2016b, Wiser *et al* 2016, Castro *et al* 2017, Ramaswami *et al* 2017, Qin *et al* 2017, Abel *et al* 2018a, Liu *et al* 2018, Monforti-Ferrario *et al* 2018, Peng *et al* 2018, Yang *et al* 2018). Two modelling studies examined nuclear power and their results suggested that nuclear energy has the potential to reduce premature deaths when compared to fossil-fuel energy (Rosen 2009, Qvist and Brook 2015) due to reduced air pollution emissions even after accounting for potential radiation health risks. One study modelled the impact of replacing ethanol with gasoline in Brazil and reported that the air pollutants emitted by the ethanol were higher than from gasoline and could potentially have more adverse impacts on long-term health outcomes (Scovronick *et al* 2016). Of these studies, one study used a LCA to model base load power generation using fossil fuel, nuclear, wind, solar and geothermal technologies in Europe. They found that, overall, nuclear and renewable energy and natural gas power generated substantially less human health impacts than hard coal and lignite (fossil-fuels). Fossil fuel combustion and mining (coal, uranium and metal) were reported as generating the highest human health impacts (Treyer *et al* 2014).

Despite the relative consistency of health benefits related to transitioning from fossil-fuel to lower-carbon fuels and other air pollutants, we were unable to pool the results due to the diversity of modelling methods, assumptions, scenarios, geographic locations and evaluation metrics.

Biofuels

Liquid biofuels are the subject of increasing interest as they represent sources of renewable fuels considered to have the potential for reduced GHG emissions and so their use could assist in mitigating climate change, strengthening energy security and contributing to diversified agricultural economies. Liquid biofuels are usually produced by fermenting sugars derived from plants such as corn grain and sugar cane into ethanol; or by processing oil crops such as canola, soybean or palm oil into biodiesel (Scovronick and Wilkinson 2014). Research is currently exploring the viability of 'second-generation' biofuels which include those produced by the conversion of lignocellulosic (plant cell wall) feedstock residues into bioethanol and other renewable liquid

Table 2. Summary of papers that modelled alternate energy scenarios grouped by geographic region: North America, China and Taiwan, Europe, Brazil.

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Alternate energy scenarios –North America: USA and Canada				
Abel <i>et al</i> 2018a, 2018b; Eastern United States (USA)	A security-constrained electricity dispatch model with a best-available, regulatory standard emissions inventory, a detailed, regulatory standard chemical transport model (CMAQ), and a regulatory standard health impacts (EPA Benefits Mapping and Analysis program) and valuation tool. Solar photovoltaic (PV) cells compared to fossil fuel generated electricity. Exposure: PM _{2.5}	Mortality incidence.	On average, with 17% penetration of solar energy, 1424 (95%CI 284-2732) deaths could be avoided—with estimated savings of US\$13.1 billion (95%CI 0.6 to 43.9 billion) in 2015 dollars.	Health impact estimates are based on changes in PM _{2.5} during summer only, therefore impacts may be underestimated.
Akhtar <i>et al</i> 2013; USA	Decision model framework to identify alternative techno-policy futures—assessing air quality, health and climate impacts: 2015, 2020 and 2030. Potential health effects for emission scenarios are estimated using a national per-ton impact factors calculated by the Community Multiscale Air Quality Monitoring System (CMAQ) model as well as the Environmental Benefits Mapping and Analysis Program. Exposure: SO _x , NO _x and carbonaceous aerosol emissions.	Health costs = increase in mortality multiplied by value of a statistical life.	This analysis indicated that emission reductions of aerosols and their precursors under expected USA air quality regulations will lead to significant benefits to human health, yet they will, on net, increase the rate of near-term climate change because reductions in USA emissions of cooling sulphate aerosols will more than offset reductions in warming black carbon aerosols. In the combined scenario where both near-term emission limits were put into place alongside a long-term CO ₂ reduction goal, they found opportunities to improve both human health and climate outcomes beyond the outcomes from a single policy.	Modelling framework may assist USA policymakers to coordinate air quality regulation across short-term and long-term time scales. Application to broader range of air pollutants and aerosols needed.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
AlRafea <i>et al</i> 2016; Southwest Ontario, Canada	Model comparing the use of natural gas (NG) compared to hydrogen enriched natural gas (HENG) in a combined cycle power plant. Exposure: PM _{2.5} , CO, NO ₂ , SO ₂	Health cost	Health costs associated with PM _{2.5} reduced by 3.3% and with NO ₂ reduced by 3.7% when HENG was used compared to NG. The health cost benefit was maximised when hydrogen concentration in HENG was 2.3%, beyond that no additional health benefit was observed.	HENG was not found to be the most economical technology for reducing health costs associated with combined cycle power plant emissions.
Buonocore <i>et al</i> 2016a; USA	Modelling the climate and health benefits of different sizes of offshore wind projects off the coast of Maryland and New Jersey, USA compared to electricity generated by coal or gas using Electrical Policy Simulation Tool for Electrical Grid Interventions (EPSTEIN) model. Air pollution emissions (SO ₂ , CO ₂ and NO _x) modelled from CMAQ.	Health impacts = value of a statistical life (VSL) of US\$7.58 million.	Health benefits varied in order of magnitude with annual benefits ranging from US\$75 million for the smallest installation to \$690 million for the largest. Benefits attributed to reduced SO ₂ followed by reduced CO ₂ and then NO _x . Variability was associated with facility size, geographic location and simulated year (2012 v 2017).	Model does not account for: full life-cycle impacts of fuels; seasonal or temporal variation in power plants cycling up and down and the associated emission; particulate matter emissions and other gases and metals.
Buonocore <i>et al</i> 2016b; USA	Modelling benefits of different energy efficiency and renewable energy choices (wind, solar, peak demand-side management (DSM) and baseload DSM) by displacing the emissions from fossil-fuel based power generators across 24 scenarios (in 6 USA cities) using the Electrical Policy Simulation Tool for Electrical Grid Interventions (EPSTEIN) model. Air pollution emissions (SO ₂ , CO ₂ and NO _x) modelled from CMAQ.	Health impacts = value of a statistical life (VSL) of US\$7.58 million.	Total health benefits varied by a factor of 37 across the 24 scenarios with central estimates varying from US\$5.7 million to US\$210 million, with displaced SO ₂ from coal generally dominating the benefits. Hence quantifying public health benefits may be site specific and vary by the technology.	Model does not account for: full life-cycle impacts of fuels; seasonal or temporal variation in power plants cycling up and down and the associated emission; particulate matter emissions and other gases and metals.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Gilmore <i>et al</i> 2010 USA	Monte Carlo modelling. Comparing the levelised private and social (health) costs of diesel internal combustion engines (ICE) with and without diesel particulate filters (DPF), natural gas ICEs, and microturbines to a new power peaking plant in New York compared with using back-up generators to provide power during periods of peak energy demand.	Willingness to pay (WTP) to avoid adverse health effect (US\$) using Environmental Benefits Mapping and Analysis Program (BenMap). Premature mortality due to O ₃ and PM _{2.5} . VSL = \$7.5 million.	Many generators have air emissions that may be potentially damaging to health. This study found that using backup generators to supply electricity during the periods of peak demand has lower private and social/health costs than a new peaking plant in addition to making electricity supply more reliable and relieving major problems associated with siting new generation and transmission. This analysis uses conservative assumptions throughout that tend to overestimate the health costs.	While uncontrolled diesel ICEs would harm air quality and health, putting controls on these generators and using ultralow sulphur fuel reduces the social costs significantly. Location and maintenance are important considerations.
McCubbin and Sovacool 2013; USA	Modelling natural gas against wind energy in California (Altamont) and Idaho (Sawtooth). Exposure: PM _{2.5} Model: Co-Benefits Risk Assessment Tool: COBRA.	Premature mortality—unit value = US \$8.8 million	Wind farms likely to avoid the following costs associated with premature mortality: Altamont: US\$129 million to US\$1.75 billion. Sawtooth: US\$1.4 million to US\$13.8 million.	High level of ambiguity in some of the models' inputs: emission rates of air pollutants; location and sources of emissions; estimated number of avian deaths associated with colliding with turbine blades compared with those dying due to climate change.
Rosen 2009; Ontario, Canada	Modelling cogeneration of thermal and electrical energy power using coal and uranium in a range of proportions and supplying differing proportions of the residential, commercial and industrial sectors. 1990 Annual and cumulative (20 year) assessments. 6 hypothetical models.	Mortality, morbidity and days of work lost. Method for health impacts not described in the methods.	Modelling indicated that cogeneration of thermal and electrical energy led to reduced air pollutants and associated reduced health costs. However, the measurement and analysis of the health impacts within the scenario modelling was not clear.	Results validated 20 years after the initial case study was undertaken—annual use of gas, liquefied natural gas, coal and petroleum has increased at higher proportions than predicted in the base modelling.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Wiser <i>et al</i> 2016; USA	Electric sector capacity-expansion model for US—ReEDS. 2015–2050 Scenarios: Baseline: No New Solar (NNS) SunShot Vision deployment—solar penetration 14%-by-2030 & 27%-by-2050. Exposure: SO ₂ , NO _x , PM _{2.5}	Premature mortality, emergency department visit for asthma, acute bronchitis, lower and upper respiratory symptoms, lost workdays, asthma exacerbation, hospital admissions for respiratory and cardiovascular, non-fatal heart attacks.	Benefits identified across all health outcomes related to emissions reductions. Prevention of 25,000 to 59,000 premature deaths; 2.5 million lost work days; 2.5 million lost school days; 30,800 hospital admissions for respiratory and cardiovascular conditions.	No evaluation of upstream or downstream impacts such as from heavy metal releases, waste products, land use for power or upstream fuel for production.
Alternate energy scenarios—China, Taiwan				
Chen <i>et al</i> 2007; China	Model: long-range energy alternatives planning system (LEAPs): low carbon energy scenarios on CO ₂ and local air pollutants in Shanghai, China. Multiple scenarios: base case and energy-efficient improvement, expanding natural gas for final sectors, wind electricity generation. Pollutants: PM ₁₀ and SO ₂ .	Health effects: mortality; chronic bronchitis; cardiac and respiratory hospitalization; outpatient visits; acute bronchitis; asthma attack (children and adults). Economic evaluation: value of statistical life; willingness to pay (WTP)	Compared with the base case scenario, implementation of various energy scenarios in Shanghai could prevent 2804 to 8249 and 9870 to 23,100 PM ₁₀ -related avoidable deaths (mid-value) in 2010 and 2020, respectively.	Selection of optimal low-carbon scenarios requires further cost-benefit analysis based on both estimates and other analyses on the implementation cost of the scenarios.
Liu <i>et al</i> 2018; China	Alternate transport scenarios: 1. Business as Usual (BAU) 2. Energy Efficiency Improvement (EEI) 3. Travel Mode Optimization (TMO)—increase clean energy sources for buses, cars 4. Comprehensive Policy (EEI + TMO) Emissions: SO ₂ , NO _x , PM ₁₀ , PM _{2.5}	Unit value (US\$) of: Mortality, respiratory hospital admission, cardiovascular hospital admission, asthma attack, acute bronchitis, chronic bronchitis.	The EEI, TMO and CP scenarios all have positive impacts on health outcomes compared to BAU scenario with reductions in health-related economic costs ranging from 23.9 billion to 572.3 billion USD.	Scope for energy transitions within the transport sector to have significant public health benefits.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Pan <i>et al</i> 2007; China	LEAP Model. Scenarios: Baseline: Business As Usual Scenario 1: Clean Energy Consumption (CEC) (natural gas replacing coal burning) + Industry Structure Transformation (IST) Scenario 2: CEC + IST + Energy Efficiency Program (EEP) Scenario 3: CEC + IST + EEP + - Green Transportation (Natural gas, liquid petroleum gas) Baseline, 2010, 2020, 2030 Exposures: SO ₂ , PM ₁₀	Acute excess deaths, chronic excess deaths, respiratory and cardiovascular hospital admissions, outpatient visits to internal and paediatric departments, emergency room visits, asthma attacks	3 scenarios compared to Baseline: Reductions in PM ₁₀ associated with reduction in acute excess deaths: 2010 = 29-152; 2020 = 30-212; 2030 = 39-287 Reductions in chronic excess deaths 2010 = 340-1811; 2020 = 356-2529; 2030 = 462-3424 Reductions in SO ₂ associated with reduction in acute excess deaths: 2010 = 237-331; 2020 = 285-371; 2030 = 400-554 Best health benefits achieved under Scenario 3 and increase with time. Variations in scale of health benefit depended on health endpoint and scenario.	At the time of the study little epidemiological evidence from the impact of air pollution on health in China was available for estimating the health impacts. The health data used in this analysis was based on epidemiological research from USA and European countries which experiences much lower levels of air pollution. Hence the health benefits associated with changes in air pollutant levels reported here may be underestimated.
Partridge and Gamkhar 2012; China	Modelled health co-benefits using 'Damage function methodology' in China: Transition from coal-powered power stations to ones using wind and small-scale hydro projects. Occupational health risks not included. Only estimated health damage related to PM + secondary sulphites and nitrates (excluding ozone and SO ₂).	Premature mortality (value of statistical life); incident chronic bronchitis, respiratory and cardiovascular (CV) hospitalisations	Preliminary modelling indicated overall reduction in premature mortality, chronic bronchitis and CV and respiratory hospitalisation across all regions of China, but levels varied between regions and types of energy transition. For wind generation, the co-benefit varied between 2.3% and 9.1% of the additional cost compared to a coal-fired power station in the same region	Limited range of co-benefits were included in the model to fully inform a cost-benefit analysis. Authors state their results are subject to considerable uncertainty but provided a preliminary analysis that could inform future research.
Peng <i>et al</i> 2018; China	Modelling coal intensive versus half decarbonized power for electricity production with multiple end-user electrification scenarios in China. Exposure: PM _{2.5}	Avoided deaths	Half decarbonized power supply (~50% coal) for electrification of the transport and/or residential sectors leads to a 14%–16% reduction in carbon emissions compared to BAU, as well as greater air quality and health co-benefits (55,000–69,000 avoided deaths in China annually) than coal intensive electrification.	Modelling was based on annual total emissions and authors suggested that future models should include a finer temporal analysis. Other important air pollutants such as NO _x and O ₃

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings			Comments																		
Qin <i>et al</i> 2017; China	Modelling of the displacement of coal use in power, industry and households with coal-based synthetic natural gas (SNG) in China. SNG produces less air pollutants such as SO ₂ and PM but has higher CO ₂ emissions. Model—ECLIPSE_V5a_CLE Base case = 2020 Air pollutants: SO ₂ , NO _x , PM ₁₀ , PM _{2.5}	Premature mortality	Deploying all SNG to the residential sector can avoid 32,000 (20,000 to 41,000) air pollution-related premature deaths nationwide in 2020. In contrast, allocating all SNG to the power or industrial sectors barely improves air quality and avoids only 560 (230 to 740) or 3,100 (1,300 to 4,300) premature deaths, respectively. These reductions are approximately 10 to 60 times higher than reductions when SNG used in the industrial and power sectors.			Due to excess CO ₂ emissions from SNG compared to coal, there is a need for an accompanying carbon capture and storage strategy to mitigate effects on climate.																		
Ramaswami <i>et al</i> 2017; China	Social-Ecological-Infrastructural Systems framework. 637 Chinese cities—detailed data on energy supply and heat distribution. Models—Base Case 2010 & two What-If Scenarios + Chinese Five Year Plan (FYP) targets: 1. What-If FYP-Efficiency-plus-Symbiosis 2. What-If FYP-High Efficiency-plus-Symbiosis Pollutants: CO ₂ and PM _{2.5} PM _{2.5} atmospheric modelling for dispersion: AERMOD	Premature deaths	The What-If FYP-Efficiency-plus-Symbiosis compared to Base Case model predicts average premature deaths avoided is 5.6% (25,500 to 57,500) annually. The benefits are highly variable across cities with the mega cities experiencing the greatest reduction in air pollution-related premature deaths (28%). The second model’s results were not reported.			Multiscale model that connects human activities in cities with multi-scale fuel use reductions, PM _{2.5} atmospheric transport models, and health risk assessment.																		
Shih and Tseng 2014; Taiwan	Air Resource Co-benefits model 2010-2030 utilising renewable energy (RE) and energy efficiency improvements (EEI) measures. Lifecycle co-benefits analysis Taiwan Exposure: PM ₁₀ , SO ₂ , NO _x , CO and O ₃	Averted mortality using premature deaths avoided and life table approaches. Value of statistical life (VSL = US\$1.75 million) & Value of statistical life year (VSLY = \$95,000) Averted morbidity = change in attributable proportion of health care cases per year.	<table><tr><th>Outcome</th><th>RE</th><th>EE</th></tr><tr><td>Premature deaths avoided</td><td>69,396</td><td>57,111</td></tr><tr><td>Years of life lost / 100,000 people</td><td>6190</td><td>5140</td></tr><tr><td>Averted mortality US\$ million</td><td>121,444</td><td>99,945</td></tr><tr><td>Averted morbidity</td><td>1405</td><td>1406</td></tr><tr><td>Benefit/cost</td><td>7.9</td><td>2.1</td></tr></table>			Outcome	RE	EE	Premature deaths avoided	69,396	57,111	Years of life lost / 100,000 people	6190	5140	Averted mortality US\$ million	121,444	99,945	Averted morbidity	1405	1406	Benefit/cost	7.9	2.1	Did not include PM _{2.5} in the modelling. Estimation of emissions exposure may differ if the full life cycle of the energy source does not occur within one area.
Outcome	RE	EE																						
Premature deaths avoided	69,396	57,111																						
Years of life lost / 100,000 people	6190	5140																						
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Benefit/cost	7.9	2.1																						

Table 2. (Continued.)

Author, Year; Country	Exposure: PM, toxins, radiation Model, Exposure metric	Health outcome	Findings	Comments
Xue <i>et al</i> 2015; China	PHAGE (Public Health and GHG Emission) model to analyse impact of integrated effects of energy consumption in transport sector in one city in China using the LEAP model. Scenarios: • Business As Usual (BAU) • Integrated (INT) ○ Motor Vehicle Controls (MVC) ○ Fuel Economy Regulations (FER) ○ Promotion of New Energy Vehicles (PNEV) ○ Fuel Tax (FT) ○ Promotion of Biofuels (PB) Exposure: PM _{2.5} , SO ₂ , NO ₂	Economic value of health damage	Public health costs (billions of yuan) in 2025 BAU = 0.49 (0.71 to 1.18) INT = 0.26 (0.24 to 0.64) Public health costs associated with NO ₂ were largest. Greatest public health cost benefit was associated with PM _{2.5} reduction.	Greater air quality and health benefits were gained through reducing the use of motor vehicles and trucks than through biofuels. Biofuels pose other challenges in China: high cost and potential impact on food security.
Yang <i>et al</i> 2018; China	Modelling the displacement of coal-fired power stations with solar energy production in China. Scenarios: • Skewed_Provincial • Balanced_Provincial • Skewed_Regional • Balanced_Regional Exposure modelled by ECLIPSE_v5a_CLE: CO ₂ , SO ₂ , PM _{2.5} , NO ₂	Premature mortality due to chronic obstructive pulmonary disease (COPD), lung cancer, ischaemic heart disease (IHD), ischemic stroke	Balanced_Regional scenario led to greatest health benefit of 10,000 (5000 to 14,000) premature mortalities avoided.	No life cycle assessment of solar panels included in modelling.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Alternate energy scenarios - Europe				
Aunan <i>et al</i> 1998; Hungary	Modelling the health benefits of the National Energy Efficiency Improvement and Energy Conservation Program compared to current status; 20% and 30% reduction scenarios.	Health impacts: Mortality, chronic respiratory symptoms, asthma symptom days, lung cancer cases. Monetised—willingness to pay (WTP) Health benefits from exposure to differing levels of air pollution (NO ₂ and/or PM ₁₀) were modelled: Excess mortality averted; Reduction in infant deaths; Annual symptom-days reduced; Annual respiratory symptoms days reduced.	Health benefits from reduced air pollution (NO ₂ and/or PM ₁₀) were modelled and overall significant public health benefits were reported.	At the time of the study little epidemiological evidence of the impact of air pollution on health in Hungary was available. The health data used in this analysis was based on epidemiological research from other European countries which experiences much lower levels of air pollution. Hence the health benefits in these models may be uncertain.
Castro <i>et al</i> 2017; Switzerland	Health Impact Assessment Modelling 2005 (counterfactual scenario) to 2015 (reference case) Agglomeration Lausanne-Morges (Switzerland): Population = 293,000. Impacts of air pollution calculated using population attributable fractions (PAFs). Monetisation of health impacts. Modelled reduction in PM ₁₀ and NO ₂ Sources were identified from World Health Organization meta-analyses	Health outcomes: premature deaths, hospitalisation days due to CVD, RD; incident cases of bronchitis and asthma attacks in adults; cases of bronchitis and asthma symptom days in children; restricted activity days, working days lost.	Reduction of 3.3ug/m ³ PM ₁₀ suggested prevention of 26 premature deaths, 100 hospitalisation days due to CVD, 110 days due to RD; 30 incident cases of bronchitis and 450 asthma attacks in adults; 150 prevalent cases of bronchitis and 1000 asthma symptom days in children; 47000 restricted activity days, including approx. 11000 working days lost. Assessments based on NO ₂ reduction of 5.6ug/m ³ suggested prevention of 51 premature deaths. The reduction in air pollution between 2005 and 2015 resulted in annual benefits valued at CHF 36 million (PM10) to CHF 49million (NO2).	Need for harmonizing HIA to allow direct comparisons between related or competing policy frameworks.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Gschwind <i>et al</i> 2015; 45 European countries	Health impact assessment of exposure to PM _{2.5} Baseline pathway compared with low carbon scenarios under three air pollution control policies across all European countries.	Loss of life expectancy of population aged older than 30 years. Days of Life Lost (DOLL)	PM _{2.5} concentrations are predicted to be higher under Fixed Emission Factor Policy (6.7ug/m ³) compared to Current Legislation Policy (2.8 ug/m ³) and Maximum Technically Feasible Reduction Policy (1.0 ug/m ³). DOLL ranges from 24 days/person (Norway) and 228 days/person (Belgium and The Netherlands). Greatest reductions in DOLL are reported in the Low Carbon- Maximum Renewable Power/ Maximum Technically Feasible Reduction Policy scenario (34%).	Models included temporal assessment of PM _{2.5} levels instead of annual averages.
Haluza <i>et al</i> 2012; Austria	Health impact assessment Scenario 1: Light fuel oil for domestic heating Scenario 2: Replacement of light fuel oil for domestic heating with natural gas; Scenario 3: Replacement of light fuel oil for domestic heating with natural gas and biomass fuel (wood chips or wood logs). Emissions: PM ₁₀ , NO _x	Mortality—overall, cardiovascular, respiratory. Hospital admissions: respiratory and circulatory	Scenario 2 associated with additional deaths/year: PM ₁₀ = 101; and NO _x = 52 Scenario 3 associated with additional deaths/year: PM ₁₀ = 174; NO _x = 114 Scenario 2 PM ₁₀ associated with additional hospital admissions = 203 Scenario 3 PM ₁₀ associated with additional hospital admissions = 353	Geographic differences in exposure related to local topography. Lack of PM _{2.5} data.
Monforti-Ferrario <i>et al</i> 2018; Europe (Covenant of Mayors)	Modelling the impact of 2713 energy saving measures on 146 cities in 23 European countries on air quality. Energy Saving Measures: ES Renewable Energy Production measures: REP Both: MIX Air quality modelled by SHERPA (Screening for High Emission Reduction Potential on Air) CO ₂ reductions	Premature mortality Years of life gained.	Modelling indicated that the energy saving measures translated to approximately 6596 (95%CI 4356 to 8572) premature deaths avoided and 68,476 (95%CI 45,403 to 89,358) Years of Life Saved.	The findings from this study was limited by the focus only being on energy saving measures and lacking data on other proposed measures which could have different impacts on air pollutants. Annual average emissions were used, and analysis could have been enriched by use of temporal emission data.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Qvist and Brook 2015; Sweden	This paper models the early decommissioning of Sweden's nuclear reactors and the power source is replaced with coal and natural gas, not renewable energy sources.	Potential prevented deaths.	Early decommissioning of the nuclear power plants would lead to the loss of potentially preventing 50,000 to 60,000 energy related deaths.	The phase out of nuclear power needs to be considered but an alternative energy plan should not bring increased risks to public health.
Treyer <i>et al</i> 2014; Europe	Life Cycle Impact Assessments of base load power generation technologies (fossil fuel, nuclear, hydro, wind, solar, geothermal) for 2030. • ReCiPe • IMPACT2002+	Disability Adjusted Life Years (DALY)	Multiple models evaluated. Overall, nuclear and renewable energy and natural gas power generate substantially less human health impacts than hard coal and lignite (fossil-fuels). Fossil fuel combustion, mining (coal, uranium and metal) are the life cycle stages generating highest human health impacts.	Numerous energy technologies compared and contrasted. Methodology assesses the fuel supply chain and the construction, operation and decommissioning of their related power plants. Components included are materials, waste, energy flows, pollutant emissions and land uses. Methodology built on assumptions which have related uncertainties.
Zvingilaite 2011; Denmark	Energy system modelling methodology paper that examines the inclusion of health externalities into the modelling to investigate optimisation of the model.	Health costs	Including health externalities into the planning of energy systems is more economical than paying for resulting damages later. Total health costs decrease approximately 18% and energy system costs reduce by nearly 4% when health externalities are included in the optimisation.	Important to include modelling of health externalities in planning energy transitions systems.

Table 2. (Continued.)

Author, Year; Country	Model, Exposure metric	Health outcome	Findings	Comments
Alternate energy scenarios: Brazil				
Scovronick <i>et al</i> 2016; Brazil	Modelling two future scenarios for vehicle fuel use in Brazil: 1. Business As Usual—ethanol production and use follows government predictions 2. Ethanol supply frozen at 2010 levels and fuel demand is met with gasoline. Exposure: PM _{2.5} and O ₃		The population-weighted exposure to PM _{2.5} and O ₃ was 3.0 ug/m ³ and 0.3 ppb lower, respectively, in 2020 in the gasoline scenario compared with the ethanol scenario. The lower exposure to both pollutants in the gasoline scenario would result in the population living 1100 additional life-years in the first year, and if sustained, would increase to 40,000 life-years in year 2020. Without additional measures to limit emissions, increasing the use of ethanol could lead to higher air pollution-related population health burdens.	Numerous assumptions could affect the results: vehicle fleet composition; prevalence of sugar cane burning; changing population demographics as an emerging economy. Biofuels may not be a solution to traffic related air pollution but combinations of improved vehicle technologies, economic incentives and shifts towards mass transit and active travel may be more important for public health.

transport fuels (Tan *et al* 2016) and 'third-generation' liquid biofuels which include those produced from algae (Raheem *et al* 2015). To date, research is progressing into varying fuel stocks for biofuels but the 'second-generation' and 'third-generation' processes have yet to be shown to be commercially viable (Jose and Archanaa 2017).

Since the early 2000's there has been rapid global expansion in the biofuel industry—global biofuel output rose from 38 billion litres in 2005 to 131 billion litres in 2015 (Naylor and Higgins 2018). As it is an industry that is increasing exponentially, it is important that potential health effects are identified, assessed and mitigated. Potential health effects may arise via direct and indirect pathways. An in-depth review of the potential for health impacts of biofuels was conducted in late 2012 (Scovronick and Wilkinson 2014). This review found only five studies which were observational cross-sectional studies or HIA in nature (table 3). The linkages between biofuel production and use, and the pathways of exposure and health outcomes are multiple. The pathways of exposure may be through oral ingestion, inhalation or dermal contact with the fuel, with health effects varying depending on the chemical and the dosage.

There may be marked variability in risks to health associated with occupational exposures such as agricultural activities that can cause injury or disease, exposure to biological and chemical agents used in production and processing of the crops (e.g. herbicides, pesticides, ammonia, sulphuric acid, fungal spores, enzymes, antibiotics, ethanol), or exposure to biodiesel by-products, such as volatile organic compounds. There may also be risks to health through soil and water contamination from crop growing. Biofuel production requires much more water than fossil fuel production per unit of energy produced and, as such, expanded biofuel production may also contribute to local water shortages. The impact of these potential risks may vary depending on the geographic location, local ecology and site-specific legislation and practices (Scovronick and Wilkinson 2014).

A HIA of exposure to fossil fuel/petroleum versus ethanol and biodiesel in biofuel workers indicated that the biofuels emitted fewer carcinogens (Fink and Medved 2013). However, the biofuels emitted more organic respirable compounds, NO_x and ionizing radiation than fossil fuels, and these could have potential health effects. The level of health impact identified in the HIA varied depending on the origin of the biofuel (Fink and Medved 2013). A cross-sectional study of workers in biofuel power plants compared to workers in oil and gas power plants reported that working in a biofuel plant did not seem to entail any greater additional risk for airway diseases compared with working in conventional energy plants (Schlunssen *et al* 2011). However, increased endotoxin and fungal spore exposure appeared to be associated with a higher risk of rhinitis (OR = 3.1, 95%CI 1.1 to 8.8) and asthma symptoms (OR = 8.1, 95%CI 1.5 to 44.4) among the biofuel workers (Schlunssen *et al* 2011). A cross-sectional study of the respiratory function of 39 wood pellet manufacturing workers found a significantly higher prevalence of self-reported nasal symptoms, self-reported breathlessness and asthma exacerbations. However, there was no significant difference in lung function among those who had worked longer in this setting or when compared to the selected controls (men working at a foundry) (Löfstedt *et al* 2017). These findings were limited by the small sample size and the cross-sectional study design as measurements were only taken at one point in time. Furthermore, the statistical methodology and results were not clearly reported. It is unclear if and how these findings might extend to general community exposures to biofuels.

Sugar cane is an identified source of energy for biofuel production. Burning of sugar cane straw is a common practice to enable easier access to the cane and to remove unwanted wildlife from cane fields. These burns are a major source of PM_{2.5} during burning season which can persist for months. Epidemiological studies have reported associations between sugar cane burning and hospitalisations for asthma, hypertension and respiratory conditions among agricultural workers and communities exposed to the dispersed smoke (Scovronick and Wilkinson 2014). Clearly, these effects are similar to those experienced with general biomass burning, which have the potential for respiratory health impacts (Sigsgaard *et al* 2015). Of note, these impacts are likely to occur in and disproportionately affect communities more closely located to crop production and processing, compared with the general population where the fuels are ultimately used.

The beneficial effect, or otherwise, of switching from fossil fuels to biofuels in vehicles is not clear-cut. Studies of lower proportion biodiesel blends appear to show decreased emissions of PM₁₀, hydrocarbons and carbon monoxide, but report increases in NO_x (Scovronick and Wilkinson 2014). The research on air toxin emissions from biofuel production is unclear, with both increased and reduced emissions reported in the studies included in this review. Differing fuel blends may produce PM_{2.5} and PM₁₀ with varying composition, size and structure which may lead to varying health risks related to their toxicity and oxidative stress responses (Betha and Balasubramanian 2013, Scovronick and Wilkinson 2014). A simulated modelling study assessed the impacts of blending 7% and 20% of biodiesel to automotive diesel, in large cities in Brazil, on PM_{2.5} emissions and subsequently on cardiorespiratory morbidity and mortality. The results indicated that 20% biodiesel blends were estimated to reduce morbidity and mortality, however they did not evaluate the potential health effects of NO_x production and the secondary formation of ozone (O₃) (Vormittag *et al* 2018). Air pollution may also occur

Table 3. Summary of papers that examined biofuels—categorised by study type (observational studies and health impact assessments).

Author, year, location, study type, population, sample size	Exposure/Intervention	Outcome	Results	Discussion/Conclusion	Comments (strengths, limitations, other)
Observational studies					
Adar SD <i>et al</i> 2015; USA; before-after adoption of cleaner air technologies and cleaner fuels in school buses (2005–2009), 275 school children (aged 6–12 years)	Cleaner air technologies: diesel oxidation catalysts (DOCs) and crankcase ventilation systems (CCVs) Cleaner fuels: ultralow-sulphur diesel (ULSD) and biodiesel.	In-cabin air pollutants: PM _{2.5} , UFP, BC. Lung function: forced expiratory volume in 1 s (FEV ₁) and forced vital capacity (FVC); Fractional exhaled nitric oxide (FENO).	Lower in-cabin PM _{2.5} was associated with DOCs (–26% 95%CI –42 to –6) and CCVs (–40% 95%CI –48 to –30). Lower in-cabin UFPs were associated with DOCs (–43% 95%CI –53 to –31) and ULSD (–47% 95%CI –58 to –34). Lower FENO in children with asthma was associated with ULSD (–31% 95%CI –39 to –21), DOCs (–12% 95%CI –23 to –0.4), CCVs (–14% 95%CI –24 to –4). Suggestive increases in FEV ₁ among all children were found with ULSD (0.01 L /year 95%CI –0.006 to 0.03) and DOCs (0.01 L /year 95%CI –0.008 to 0.03), with strongest positive effects among children without asthma. No associations with biodiesel.	Adopting specific clean air technologies and fuels can lead to reduced in-vehicle particulate exposures and likely lead to improved respiratory function.	Study obtained repeated measures of in-vehicle air pollutant levels and individual objective measures of respiratory function and airway inflammation. Residual confounding may over-estimate the health effects associated with the cleaner air interventions.
Schlunssen <i>et al</i> 2011. Denmark Cross-sectional study. Workers in 85 heating and combined heating-power plants Total n = 232 (woodchip = 138; straw = 94) + controls n = 107 (oil and gas power plants)	Energy plants using biofuels. Endotoxin Dust	Asthma symptoms Nasal symptoms	Increased endotoxin exposure associated with increased work-related nasal symptoms (OR = 3.1, 95% CI 1.1 to 8.8) and asthma symptoms (OR = 8.1, 95% CI 1.5 to 44.4) Increased dust exposure associated with increased work-related nasal symptoms (OR = 3.2, 95% CI 1.1 to 9.2) and asthma symptoms (OR = 9.4, 95% CI 1.7 to 52.0)	Working on a bio-fuel plant does not seem to entail any greater additional risk for airway diseases compared with working on conventional energy plants, although levels of endotoxin and fungi exposure appear to have an impact on the occurrence of respiratory symptoms among the biofuel workers.	Small sample size resulted in very wide confidence intervals.

Table 3. (Continued.)

Author, year, location, study type, population, sample size	Exposure/Intervention	Outcome	Results	Discussion/Conclusion	Comments (strengths, limitations, other)
Questionnaire, spirometry, methacholine provocation, skin prick tests			Straw-workers appeared to be at higher risk compared to woodchip workers. Non-smokers appeared to be at higher risk.	Within this sample, lung function not adversely affected. Preventive precautions should be taken in energy plants using biofuel to keep the bioaerosol exposure as low as possible	
Löfstedt <i>et al</i> 2017 Sweden Cross-sectional study. 39 men (mean age = 38 years (range 21–63 years) working in wood pellet production in six plants. Control group: Foundry workers (n = 118). Questionnaire, medical examination, spirometry, nasal peak expiratory flow, IgE blood test.	Personal exposure to wood dust and monoterpenes.	Lung function: FEV ₁ , FVC, FEV ₁ /FVC (FEV%) Nasal PEF.	No significant difference in lung function between the exposed workers and the controls; nor between workers who had undertaken the current tasks for less than 5 years or ≥5 years. Peak exposures to dust and monoterpenes were not associated with acute effects on lung function. No changes in nasal PEF between work and leisure time.	Authors imply that exposure to monoterpenes or dust during production of wood pellets was not an occupational risk to health.	Interpretation of results are limited due to methodological issues. Small sample assessed at one point in time only. Results of regression analysis were not reported. No adjustment for potential confounders or investigation of potential interactions.
Health impact assessment					
Fink and Medved 2013; No specific location; Health impact assessment (HIA)	Biofuels (e.g. sugar beet bioethanol, soybean biodiesel, sugarcane bioethanol) are potential substitutes for fossil fuels in transportation.	Effect of biofuel production on workers: 1. Carcinogens 2. Respirable compounds 3. Ionizing radiation 4. UV-B radiation Outcome = DALYS	Production of fossil fuel/petrol emits more carcinogens than sugar beet ethanol, sugar cane and rapeseed biodiesel. Higher health impacts from organic respirable compounds emitted during biofuel production compared to fossil fuels. Sugar beet ethanol and soybean biodiesel affects human health less with inorganic respirable compounds	HIA of selected first- generation biofuels shows some advantages with regards to less carcinogenic compounds and non-ionizing radiation. Majority of health effects in production of liquid biofuels comes from organic and inorganic respirable compounds, but level of effect	Modelling methodology not clear.

Table 3. (Continued.)

Author, year, location, study type, population, sample size	Exposure/Intervention	Outcome	Results	Discussion/Conclusion	Comments (strengths, limitations, other)
			than fossil diesel or petrol, but not so for sugarcane ethanol. Production of sugar cane and sugar beet ethanol and rapeseed biodiesel emit more ionizing radiation than fossil diesel. Rapeseed and soybean biodiesel shown to have less effect on increased UV-B radiation than other biofuels or fossil fuels.	varies depending on the origin of biofuel. Alternative biofuels and ethanol derived from renewable organic sources may have some human health impacts.	
Miraglia 2007. Sao Paolo, Brazil. Simulation economic evaluation (cost-benefit) and epidemiological analysis	Using an additive to provide a stabilized ethanol/diesel blend in the bus and truck fleet to reduce harmful emissions (PM ₁₀ , NO ₂ , CO)	Morbidity: Hospital admissions - paediatric (PRHA) and elderly (ERHA); daily ED visits for CVD (EICDERV). Mortality: late foetal deaths (FETAL), all-cause elderly mortality (ETM), elderly respiratory disease (ERM), elderly cardiovascular (ECVDM). Health data obtained from other studies	Avertable events (% reduction) PRHA (PM ₁₀) 230 (3.4%) ERHA (PM ₁₀) 56 (3.4%) EICDERV (CO) 41 (1.7%) FETAL (NO ₂) 11 (0.7%) ETM (PM ₁₀) 309 (3.4%) ERM (PM ₁₀) 85 (3.4%) ECVDM (CO) 37 (1.7%) Health valuation estimates for averted morbidity and mortality ~ USD 178 million/year (1999)	Implementation of an ethanol/diesel blend can be expected to reduce adverse health events by 0.7 to 3.4%. The projected health benefits include: decrease in hospital admissions, emergency room visits, work absenteeism, and mortality.	Lack of official statistics of health impacts at the primary health care level to assess less acute benefits. Social and economic impacts modelled alongside health impacts.
Vormittag et al 2018 Brazil (São Paolo] and Rio de Janeiro). Simulation modelling to estimate impact of addition of biodiesel to diesel for automotive use over the period 2011 to 2025.	Emission of fine particulate matter (PM _{2.5}) from biodiesel additions to standard diesel: Baseline = 5% (B5) Scenarios = 7% (B7) and 20% (B20)	Hospitalisations for conditions associated with PM _{2.5} exposure: respiratory, cardiocerebrovascular diseases and lung cancer. Mortality.	Increasing to B7 over the study period—estimated 2143 fewer deaths and 4594 fewer hospitalisations. Increasing to B20 over the study period—estimated 13,031 fewer deaths and 28,170 fewer hospitalisations.	This simulated study indicates that the introduction of biodiesel to the vehicle fleet throughout large Brazilian cities could reduce PM _{2.5} related morbidity and mortality and associated health costs.	This study did not evaluate the potential health impacts of other secondary air pollutants associated with biodiesel such as NOx, ozone on health. Project funded by a biodiesel producers' association.

at other stages of the biofuel life-cycle, and the benefits and adverse impacts may be differentially experienced across geographic regions, suggesting potential spatial variation in health impact.

These findings indicate the scarcity of health data related to biofuel production, handling, use, disposal and variation by location. This highlights the need for HIAs to include the LCA of the range of biofuels in order to better understand the potential for health impacts, both adverse and beneficial.

Wind energy

The most health-related research in the energy transitions/renewable energy field was evident for wind turbine and wind farm operations. The driving force for this research has been community concern over the alleged health effects experienced by some people living near wind farms. The key aspects of wind farms that are complained about are noise, shadow flicker from turbine blades, electromagnetic radiation and infrasound (inaudible sound). Alleged health effects that have been investigated include sleep disturbance, insomnia, headache, tinnitus, nausea, tachycardia, problems with concentration and memory, panic episodes, and photo-induced epilepsy (Knopper and Ollson 2011, Jeffery and Krogh 2014).

Systematic reviews conducted up to 2015, of the health impacts of exposure to wind turbines/farms, found that there is no consistent evidence that wind farms cause adverse health effects. However, the reviews concluded that higher quality studies are warranted, especially for those people living close to wind farms (i.e. within 1500 metres) (Australasian Cochrane Centre and Monash Centre for Occupational and Environmental Health 2015, Merlin *et al* 2015, National Health and Medical Research Council 2015). Our literature search found seven new studies of exposure to wind turbines/farms and health effects since 2015 (Feder *et al* 2015, Jalali *et al* 2016a, Jalali *et al* 2016b, Klaboe and Sundfor 2016, Kageyama *et al* 2016, Botelho *et al* 2017, Clark and Botterill 2018) (table 4). The overall findings from these papers did not shed alternative findings to the systematic reviews reported previously. The evidence over whether wind turbine farms are associated with negative health effects is still hotly contested. Overall, this most recent research has indicated that stronger adverse health effects were associated with negative attitudes towards wind turbines including concerns regarding property devaluation, visual impacts and noise sensitivity. Two government funded studies on the health impacts associated with exposure to wind turbine noise or infrasound are currently underway in Australia (<https://windfarmstudy.com/?/home> [Accessed 25 September 2019]) These include both laboratory-based control studies and field studies of controlled exposures. They are due to report their findings in 2021–22.

Photovoltaic cells (solar panels)

In simplified terms, solar power is a form of renewable energy that is produced via photovoltaic (PV) cells which absorb photons from the sun's rays to excite the electrons in the PV cells resulting in electricity production. This electricity can then be used to supply renewable energy as single semi-conductor cells (e.g. solar powered calculators, and watches) or assembled and encapsulated into solar panels. Solar panel technology is improving, and the technology is becoming increasingly accessible to populations across the world. This electricity production results in reduced gas and particulate emissions compared to electricity produced from fossil-fuels, such as coal (Abel *et al* 2018a). A number of studies have modelled GHG emissions and air pollution levels, and extrapolated that decreased emissions were likely to lead to reduced health impacts (Siler-Evans *et al* 2013, Wiser *et al* 2016, Abel *et al* 2018b). Despite the rapid improvements being made to PV cells and the uptake in use for electricity production, we found few papers that specifically examined the impacts of PV cells/panels on human health.

The life cycle of solar PV panels, incorporating their production to end-of-life, raises potential health and environmental issues. The structure and design of PV cells, panels and modules vary depending on their application. In general, there are four broad families of PV cells/modules (ranked from most expensive and efficient to the least efficient): (1) mono-crystalline silicon—single silicon crystal cut into wafers approximately 0.2mm thick; (2) poly-crystalline/multi-crystalline silicon—cells containing many small silicon crystals; (3) thin film—crystalline cells cut into wafers of 2µm thick (layers of this film containing amorphous silicon, cadmium telluride (CdTe), copper indium selenide (CIS) or copper gallium selenide (CIGS) are placed on glass forming a panel similar to polycrystalline modules; these use less material and are cheaper but are also less efficient), and; (4) multi-junction panels comprised of indium gallium phosphide (InGaP), gallium arsenide (GaAs) or indium gallium arsenide and germanium cells (InGaAsGe) (Bakhiyi *et al* 2014). The production of PV cells involves exposure to a range of heavy metals, chemicals, acids, bases, gases and solvents (for example: aluminium, arsenic, asbestos, cadmium, carbon tetrachloride, copper, hexavalent chromium, hydrofluoric acid, lead, ammonia, argon gas, hydrochloric acid, methane, silane gas, tellurium and nitrogen trifluoride), which may have non-carcinogenic and carcinogenic health effects (Aman *et al* 2015). Silver is used in PV cell manufacture and is considered a relatively valuable metal (Kuczyńska-Łażewska *et al* 2018), and so there is the risk that increased PV cell production to meet rising global demand will place undue pressure on existing silver resources.

Table 4. Summary of papers that examined the impact of wind energy since 2014.

Area, Author, Year, study type, population, sample size	Exposure/Intervention	Outcome	Results	Discussion/Conclusion	Comments
Clark and Botterill 2018. Discursive psychological assessment of how people talk about the health effects of wind farms - conversation analysis. n = 16	Wind farms on landholders' properties.	Participants: opponents, wind farm hosts and 'fence-sitters'.	The 'facts' about whether wind farms cause negative health effects are contested.	Found that stake in windfarm, interest and legitimacy are particularly relevant for the competing descriptions about the 'facts' of wind turbine health effects.	Purposively selected participants. No objective health measures.
Botelho <i>et al</i> 2017 Portugal Cross-sectional survey Community with 53 wind turbines in a wind farm. n = 80 (29 consider retrofitting their homes; 51 do not consider retrofitting their homes)	Direct measurement of sound pressure levels in 4 villages.	Questionnaire: response to the environment, perception of wind turbine noise, implementation of sound mitigation measures on houses.	Key findings: exposure to wind turbine sounds significantly impairs individual wellbeing via the strong effect it has on their decision to spend resources in retrofitting their houses to minimise perceived sound. This is independent of reported annoyance.	More objective data needed to assess the impact of wind turbine noise on individual health or well-being. Compensation may be needed to allay retrofitting costs.	No objective health measures.
Klaboe and Sundfor 2016: 13(8). Norway. Cross-sectional survey Socio-acoustic study post installation. Wind farm (31 turbines) that affects 179 dwellings within 2km radius (n = 90).	Noise measurements	Questionnaire. Annoyance rather than health effects examined.	Response rate = 38% Noise annoyance depends strongly on separate non-acoustic factors: visual and aesthetic factors.	Economic compensation did not appear to act as an effect modifier.	Response bias
Kageyama <i>et al</i> 2016 Japan Socio-acoustic study Cross-sectional study. Rural areas. 34 sites near wind turbines (n=747) and 16 matched control sites (n=332) without wind turbines.	Noise measurements in seven locations within 1km of nearest wind turbine, excluding road traffic noise.	Questionnaire—interview—sleep, mental health, health symptoms, noise annoyance, attitudes towards wind turbines.	No association between noise exposure levels with poor physical/ mental health was found. Significant association between outdoor wind turbine noise exposure and self-reported insomnia (41-45dB OR = 7.93 95%CI 1.57-40.07) (>46dB OR = 6.61 95%CI 0.84—52.31) Insomnia symptoms seemed to be affected by personal features expressed as noise sensitivity and the feeling of visual annoyance with wind turbines.	Sensitivity to environmental stimuli should be considered in future field studies.	Wide confidence intervals. Small sample, especially control group, therefore limited representativeness. Method of noise measurement not provided.

Table 4. (Continued.)

Area, Author, Year, study type, population, sample size	Exposure/Intervention	Outcome	Results	Discussion/Conclusion	Comments
Jalali <i>et al</i> 2016a, 2016b. Ontario, Canada Prospective cohort established before installation of wind turbines. Assessing residents within 2 km of wind turbines. n (pre) = 50 n (post) = 37	Noise exposure assessment conducted indoors.	Validated sleep questionnaire: sleep disturbances.	30% response rate. Participants reported poorer sleep quality if they had negative attitudes to wind turbines, concerns regarding property devaluation, and visual impacts. Associations between noise exposure and sleep parameters were not calculated as the number of participants was too small (n=3).	Role of psychosocial factors are important—they may lead to the development of health complaints in those living near wind farms. Self-reported sleep may be associated with indirect effects of visual and attitudinal cues or concerns regarding property devaluation.	Small sample is a major limitation.
Jalali <i>et al</i> 2016a, 2016b Ontario, Canada. Prospective cohort of 16 adults living within 1 km and in view of a wind turbine.	Before and after installation of wind turbines.	Polysomnography to assess sleep quality Assessed sleep parameters at two time points.	Results from polysomnography showed that sleep parameters were not significantly changed after exposure. However, reported sleep qualities were significantly ($p = 0.008$) worsened after exposure. Noise levels in participants' bedroom did not change between before and after wind turbine installation.	This study cautiously suggests that there are no major changes in the sleep of participants who live near new industrial wind turbines in their community.	Lack of control group, with regard to the exposure levels and wind speed, and with other possible sources of variation that might affect results.
Feder <i>et al</i> 2015 Prince Edward Island, Ontario, Canada Cross-sectional study n = 1236 residents in communities with wind turbine farms.	Outdoor noise levels collected.	Assessment of quality of life (QOL): Interviewer-delivered WHOQoL-BREF: Physical, Psychological, Social and Environmental domains.	Wind turbine noise levels were not found to be related to scores on the Physical, Psychological, Social or Environment domains, or to rated QOL and Satisfaction with Health questions. Hearing wind turbines for less than one year (compared to not at all and greater than one year) was associated with improved scores on the Psychological domain ($p=0.01$). Lower scores on both the Physical and Environment domains ($p=0.02$ and $p=0.04$), were observed among participants reporting high visual annoyance toward wind turbines. Personal benefit from having wind turbines in the area was related to higher scores on the Physical domain ($p=0.04$).	Results do not support an association between wind turbine noise levels and decreased QoL using the WHOQOL tool.	Reporting bias.

The electricity generated by the PV cells/panels needs to be initially stored in a battery group so that it can be supplied as needed, hence rapid expansion of the PV system requires expansion of battery production and disposal. These batteries contain lead and acid which, if not managed properly, can adversely impact on the environment and human health.

Some gaps in LCAs of PV panels have been identified. For example, during the production phase the quantification of emissions of fluorinated-gases and other by-products needs to be undertaken, and reporting of data on specific air emissions and liquid/solid effluents needs to be improved. During the PV operational phase there is uncertainty over: toxic emissions in the event of a fire; the level of potential for toxic rainwater to leach into home water supplies, stormwater or land surface run-off; the longevity of the solar panels; and the risks to PV cells during extreme weather events. During end-of-life processing, the toxic potential of PV cell waste in landfill or incineration needs to be quantified in relation to potential contribution to soil contamination and air pollution. Other considerations during this phase include the impacts of decommissioning, dismantling, and transporting the PV panels for disposal and the associated electricity demand (Aman *et al* 2015). Similarly, there is a need to examine the potential health and environmental impacts of batteries and the prospects for recycling of the batteries (Xu *et al* 2018).

These findings indicate the need for life-cycle HIA of PV systems to better understand potential health and environmental impacts, both adverse and beneficial, across the production, operation, end-of-life, disposal (including take-back) and recycling of PV cells and batteries (Xu *et al* 2018). Such HIAs need to determine the likelihood and magnitude of risk to enable appropriate risk management procedures to be implemented across the industry.

Electric and hydrogen fuel-cell vehicles

As of 2017 there were more than 2 million electric vehicles in service globally with electric vehicles representing an increasing proportion of new car sales (Wilberforce *et al* 2017, Requia *et al* 2018). Electric vehicles are regarded as a key technological development to support sustainable transportation and mitigate the impacts of climate change through reduced GHG emissions. An expected co-benefit of reduced traffic-related air pollution from electric vehicles compared to internal combustion engines using fossil fuels or biofuels is improved public health outcomes (Navas-Anguita *et al* 2018) (table 5).

However, these environmental and health co-benefits will only be realised if the source of electricity used to power the electric vehicles derives from low/no carbon renewable energy sources (Jacobson *et al* 2005). Where the infrastructure used to power electric vehicles relies on conventional fossil fuel combustion, e.g. coal based power stations, then inequity of benefits can occur when there is an unequal burden of polluting by-products in areas where benefits of electrified vehicles are not experienced (Ji *et al* 2015). For example, electricity generating plants may be located in areas where populations are less likely to be able to afford or use electric vehicles. These areas are at greater risk of being exposed to higher levels of air pollutants. Technically, electric vehicles may have net benefits if charged with gas- or renewable energy-powered electricity and those power plants are located far away from people. With increasing use of electric vehicles, we need to consider the location and sources of electricity production and emissions produced, in order to maximise distributional fairness of impacts. Transitioning from passenger vehicles to active transport (walking, cycling) and reducing the numbers of vehicles on the road have been shown to have beneficial health impacts associated with reduced air pollution, increased physical activity, and reduced environmental noise (Perez *et al* 2015, Xia *et al* 2015) (table 5).

Although tailpipe emissions from fossil-fuelled internal combustion engines will be reduced in electric vehicles, other emissions such as particulate matter from tyre and brake wear and roadway dust dispersion remain, and these have the potential to impact on health.

Much research and development is being undertaken to design cost-effective electric car rechargeable batteries to store more energy and lengthen the distances and travelling times (Grey and Tarascon 2016). This form of technology offers great potential for electrification of mass transport systems (Borén *et al* 2017). As with solar panels there is a need to investigate the life-cycle HIAs of battery use.

Building energy efficiency

The aims of improving residential energy efficiency stem from the desire to reduce energy consumption, reduce the demand for fossil-fuels, alleviate financial hardship on households and reduce thermal impacts on health. Several review papers have examined the complex relationship between improving residential energy efficiency and health outcomes (Maidment *et al* 2014, Willand *et al* 2015, Willand *et al* 2017).

The papers included in this review are grouped into study type and summarised in table 6. A meta-analysis of 33 building energy intervention studies (installing insulation, central heating, double glazing of windows) that included approximately 33,000 resident participants found that, on average, the interventions led to small but significant improvements in self- or parent-reported health status (Maidment *et al* 2014). However, only four

studies collected objective measures of health outcomes, for example, lung function tests, blood tests, medical examination, or blood pressure. Overall, it appears that programs that addressed known problems, such as dampness, cold, or insulation from cold or heat, had more impact than those that addressed broader energy efficiency aspects (e.g. the desire to reduce energy consumption overall). Positive health effects were reported in studies of children; studies of children, adults and older people with poorer health status; and studies of people living on low-incomes. Larger health effects were seen in urban areas however this effect may be biased by the use of objective health testing in these settings or the increased exposure to outdoor air pollution which the interventions provided some protection from.

Other reviews of residential energy efficiency interventions explored the contextual influence on health outcomes (Willand *et al* 2015, Willand *et al* 2017). The key messages from these reviews were that residents' expectations influenced their overall satisfaction with the interventions. In addition, cultural practices around heating of homes such as providing excessive ventilation, resulted in reduced indoor temperatures, despite the attempt to improve indoor warmth. Furthermore, economic deprivation and mastery of technology continued to impede acceptance of energy efficient interventions and energy efficiency.

A number of multi-disciplinary housing studies reported that working in partnership with communities and government agencies to retrofit insulation and install more effective heating has led to significant improvements in health and wellbeing, especially in low-income housing of vulnerable people (Breyse *et al* 2011, Howden-Chapman *et al* 2011, Garland *et al* 2013, Grey *et al* 2017). Some studies also suggested that improving energy efficiency in the home, by reducing air leakage and airflow, may have deleterious health effects because of increased potential for growth of microorganisms such as mould, fungi, house dust mites and bacteria. It is recommended that ventilation measures for health protection and the potential variation in the impact of home energy efficiency strategies be considered in the intervention design of any household energy efficiency program (Gens *et al* 2014). Importantly, research has shown that there is a need for tailored policy approaches in different locations and climates, rather than simply adopting universally rolled out strategies (Shrubsole *et al* 2015).

Implications and conclusions

The field of energy transitions is broad, complex and developing rapidly as governments and industries globally move to adopt policies and targets to achieve a reduction in carbon emissions. We consider this scoping review to be a first step in highlighting potential health impacts of specific energy transition processes and technologies that might otherwise not be fully explored in the literature from a public health impact perspective. Our literature search indicated that, to date, it appears that the depth and breadth of the health impact research is very limited, especially in comparison to research on climate or energy return on investment. It is possible that our search did not produce all relevant papers as we did not include specific health-related search terms such as mortality, morbidity and cancer, amongst others. However, given that the search identified 6933 abstracts for screening, including abstracts with these terms, we are of the opinion that, in all likelihood, our review was successful in identifying the majority of relevant papers.

Research that examines health impacts of energy transitions needs to be multidisciplinary and continually evolving to keep up with the technological developments and policy shifts. From a public health perspective, we strongly support measures to facilitate the transitioning of carbon-based energy use to lower and non-carbon energy sources, as there are quantified health benefits of reduced airborne pollutant emissions from this transition. However, we also acknowledge the need to determine the potential for unintended adverse health impacts arising from the adoption of new measures and technologies.

Our search terms captured a broad range of literature related to energy transitioning, but the depth of research identified and reviewed was limited in some areas given that the search focussed on the health impacts of energy transitions. To better understand the depth of research in each energy transition area, additional individual systematic reviews would need to be undertaken. However, in-depth reviews on each energy theme were beyond the scope of this review. This review did however identify up-to-date in-depth literature reviews which informed some of our findings.

Epidemiological studies examining the health effects associated with a range of energy transition forms were scant. This is perhaps not surprising, given the difficulty in conducting well designed epidemiological studies within this domain. Health impacts were most commonly derived from modelling studies that utilised existing prevalence data for a range of health conditions which were expected to be affected by the environmental exposure/s being examined. The key modelling studies that analysed health co-benefits examined changes in air pollution levels associated with climate change policies, increasing energy demands, and altered vehicle emissions.

We anticipate that this review might subsequently lead to the need for more targeted research to fully explore the impacts on health arising from specific technological or policy changes related to transitioning between

Table 5. Summary of papers examining the impact of alternative transport options to petroleum/gasoline vehicles.

Author, Year, Location, study type	Exposure/Intervention	Outcomes	Findings	Discussion/Conclusion
Navas-Anguita <i>et al</i> 2018. Spain. Energy systems modelling and life cycle assessment.	Scenarios of electric vehicle (EV) penetration into the Spanish transport sector over 30 years (2020, 2030, 2040, 2050). 4 models: 1. Business as usual 2. Low penetration 3. Medium penetration 4. High penetration.	Human health impacts - DALYs	Coal-fired power plants are the most damaging power generation technology in terms of health, so partial avoidance gives rise to favourable reduction in DALYs. However, the withdrawal of fossil-based power generation (natural gas, cogeneration) have less significant impact. There was an overall trend in increasing DALYs for all 3 scenarios after then avoidance of coal-powered generation is no longer happening.	Increased electricity demand in Spain likely to be met by onshore and offshore wind power—this would lead to slight increase in annual life cycle impacts of the power generation sector. High market penetration of 20 million EVs by 2050 could be 0.25 DALYs. This minor impact is likely to be offset by high environmental benefits due to the avoidance of fossil fuel use in the transport sectors- predicted net annual savings of 4-9 DALYs.
Perez <i>et al</i> 2015. Basel, Switzerland. Modelling transport development plans with vehicle reductions.	Modelling the extent to which alternate local transport development plans can contribute to climate change mitigation in Basel, Switzerland. Four modelling scenarios: 1. 'Decided policies' (DP) 2. 'Z9' Reduce traffic by 4% on inner roads 3. 'p10' Reduce traffic by 10% on inner roads 4. 'p50'—expanding p10 with assumption that 50% of private car fleet will be based on electric vehicles Exposure: PM _{2.5} ; elemental carbon (EC); noise (Lden and Lnight); cycling and walking.	Outcomes: All-cause mortality (PM _{2.5} ; EC; cycling; walking) CV mortality (PM _{2.5} ; noise) Lung cancer mortality (PM _{2.5}) Restricted activity days (PM _{2.5}) High annoyance (noise) Highly sleep disturbed (noise) Primary Impact metric: Difference per year in number of premature deaths and morbidity cases due to each policy scenario compared to reference level—using population attributable fraction and life table methodologies. Secondary impact metric: DALY/1000 inhabitants.	DP: PM _{2.5} 38% decrease; EC 66% decrease. Additional reduction in other models was very small. Considerably less change (<2%) in Lden and Lnight for any scenarios considered. DP: 3% (65) reduction in natural deaths. In general, the benefits of noise reduction on mortality (1%), annoyance (3%-4%) and sleep quality (1%) were limited. Comparative analysis shows that reduced near-road traffic in all the models provides the largest health benefit (−3.7 DALYs/1000 population). Noise reduction from electro-mobility contributes to reducing impacts on wellbeing: annoyance (p50 = −0.46) and sleep disturbance (DP=−0.22).	This modelling suggested that currently planned approaches 'DP' will bring relatively large air pollution health benefits, principally due to reduction in tail pipe emissions. The more ambitious hypothesized scenarios considering large penetration of electric cars in the city in the year 2020 did not contribute considerably to increased health benefits from noise reduction and that an increase in population exposure to noise and related negative health impacts is even predicted under the DP scenarios. Despite moderate benefits of air pollution reduction, this study indicates that noise reduction has the largest health effectiveness ratio when the energy production is principally from renewable energy. Limitations: uncertainties are not quantified, not all assumptions are validated.

Table 5. (Continued.)

Author, Year, Location, study type	Exposure/Intervention	Outcomes	Findings	Discussion/Conclusion
Xia <i>et al</i> 2015. Adelaide, Australia. Health impact assessment	Replacing the use of passenger vehicles with cycling and public transport from baseline (2010) to future (2030) [passenger vehicle reductions versus business as usual BUA]. Comparative Risk Assessment Approach (5% and 10% reduction in passenger vehicles). Exposure = PM _{2.5}	Explored the effect on health outcomes (deaths, disability adjusted life years—DALYs) by replacing the proportion of vehicle kilometres travelled by passenger vehicles with public transport and cycling. The health impacts calculated as population attributable fractions (PAFs) for short-term and long-term PM _{2.5} exposures were estimated.	Modelled a range of scenarios. All models resulted in reduced PM _{2.5} and CO ₂ emissions. PAFs for short-term and long-term PM _{2.5} exposures were estimated to decrease, in line with reduced PM _{2.5} . The total burden of disease prevented from air pollution reduction was estimated to be 39 DALYs in both 'Increased Cycling scenarios', and varied from 52 to 98 DALYs in the 'Increased Public Transport' scenarios. The most substantial health benefits came from the reductions in disease burden associated with ischaemic heart disease and stroke.	The largest health benefits would occur when increased public transport and cycling are combined, which is estimated to result in a 55% reduction of total disease burden attributed to physical inactivity.

Table 6. Summary of papers examining building energy efficiency interventions, grouped by study design (meta-analysis, epidemiological studies, modelling studies).

Area, Author, Year, Title	Exposure/Intervention	Outcomes	Results	Discussion/Conclusion	Comments
Meta-analysis of epidemiological studies assessing direct health effects					
Maidment <i>et al</i> 2014. Meta-analysis of 36 studies (1997 to 2009). Europe, USA, New Zealand and Japan 33,376 participants	Range of interventions targeting improving energy efficiency and indoor warmth.	Direct effects on health. Measures of general health; mental health; wellbeing; subjective and objective measures of cardiovascular and respiratory conditions.	Average effect of household energy efficiency intervention on residents' health was positive, albeit, small (0.08 95% CI −0.01 to 0.18). Effect sizes in primary studies ranged from −0.43 (negative health benefits) to +1.41 (positive health benefits). Effects sizes were highly heterogeneous and multiple moderators identified were: single versus multiple interventions; specific vulnerable groups (children, elderly and people living on low-income); urban versus rural location; broad tools assessing general health versus specific medical conditions; self-report versus objective measures of health; study design: case control versus cross-sectional versus randomised controlled trial; recency of publication.	The health and wellbeing benefits of having a warm and energy efficient home are backed by epidemiological evidence. Adverse effects were rare and usually avoidable with improved communication with resident/s and were outweighed by health benefits.	Housing energy efficiency intervention should be assessed over short- and longer-terms to identify health and wellbeing effects. Studies need to maximise the likelihood of detecting health changes using objective medical testing and multiple stages of follow-up. Need to determine circumstances, characteristics and behaviours that influence health outcomes.
Epidemiological studies					
Breyse <i>et al</i> 2011. Minnesota, USA. 3 building, 60 unit apartment complex, Minnesota 2006–2007 Baseline = 1-4 months after moving in Follow-up = 12-18 months later.	Renovating low-income housing using green principles One adult interviewed per dwelling. Indoor CO ₂ Indoor radon	Interview questionnaire. Self-report: general health status, respiratory symptoms, injury. Energy (electricity and gas) usage.	Study participants were largely immigrants of minority race/ethnicity and all low-income. Adult health status was better at follow-up than at baseline ($p < 0.05$).	Results suggest that the benefits of improved housing for low-income households include reduced morbidity and significant health All green housing standards should include health-related requirements.	Details of health-related questions were not reported. Objective measure of health status not obtained. Response bias.

Table 6. (Continued.)

Area, Author, Year, Title	Exposure/Intervention	Outcomes	Results	Discussion/Conclusion	Comments
Garland <i>et al</i> 2013 South Bronx, USA Affordable (low-income) green residential housing that meets LEED Platinum standards. Sept 2009– Oct 2011. Pre-test—Post-test N = 14 (out of 43 possible participants)	Education and environ- mental interventions. Home visits—interview questionnaires— prior to moving in, within 4 weeks of moving in, at 6 months, 12 months and 18 months.	Frequency of respiratory/asthma symptoms, exacerbations, impact of asthma on quality of life, limits to daily activities and sleep, and medical care utilisation.	Significant results from baseline to 18 months: decrease in respiratory symptoms that con- tinued throughout the day; decrease in mean number of nights with asthma symptoms; reduction in mean number of doctor visits for asthma treatment; decrease in number of days missed from work, school or day- care; decrease in number of asthma epi- sodes in previous 3 months.	Housing impacts both the environment and health; Interdisciplinary approach to hous- ing is needed to ensure that the current needs of improving health care costs, health of individuals and reducing health care and energy costs can be achieved.	People with chronic, serious co-morbid condition with pulmonary symptoms were excluded. Small sample.
Grey <i>et al</i> 2017. Wales Quasi-exper- imental field study Pre-test—post-test Control = 418 2013–2015 Intervention = 364 Questionnaire	Domestic energy effi- ciency program.	Self-reported physical and mental health outcomes using the SF-12v2 composite scales and subjective well-being. Self-reported respiratory and asthma symptoms.	The energy efficiency programme was not associated with improvements in physical and mental health or reductions in self- reported respiratory and asthma symp- toms. However, the programme was asso- ciated with improved subjective wellbeing ($\beta = 0.38$, 95% CI 0.12 to 0.65), as well as improvements in a number of psychosocial outcomes, including increased thermal satisfaction (OR = 3.83, 95% CI 2.40 to 5.90), reduced reports of putting up with feeling cold to save heating costs (OR = 0.49, CI = 0.25 to 0.94), fewer financial difficulties ($\beta = -0.15$, 95% CI -0.25 to -0.05), and reduced social isola- tion (OR = 0.32, 95% CI 0.13 to 0.77).	Investing in energy efficiency in low- income communities does not lead to self- reported health improvements in the short term. However, investments increased sub- jective wellbeing and were linked to a num- ber of psychosocial intermediaries that are conducive to better health. It is likely that better living conditions contribute to improvements in health outcomes in the longer term.	Relatively large sample. Short term impacts Potential contamination of control group.

Table 6. (Continued.)

Area, Author, Year, Title	Exposure/Intervention	Outcomes	Results	Discussion/Conclusion	Comments
Howden-Chapman <i>et al</i> 2011 New Zealand Community-based randomised controlled trial N = 409 household with a child with doctor diagnosed asthma.	Retrofitting insulation and improved heating in older homes. Indoor temperature. Levels of NO ₂ .	Self-report: Respiratory symptoms and medication usage. Self-administered lung function tests: peak expiratory flow rate (PEFR) and forced expiratory volume in 1 s (FEV ₁). Data linkage: general practitioner visits and hospitalisations.	Indoor temperatures increased by 1.1 degree Celsius in living room and 0.53 degree in child's bedroom. Levels of NO ₂ halved. Parents in the intervention group reported less poor health (OR = 0.44, 0.28-0.7). Sleep disturbance due to asthma symptoms reduced significantly. No difference in lung function between intervention and control group.	Multidisciplinary housing studies show that working in partnership with communities and government agencies to retrofit insulation and install more effective heating has led to significant improvements in health and wellbeing.	Response bias may impact results. Did not report on potential contamination of the intervention/control sites. Limited discussion of the impact of moderating or interacting characteristics.
Modelling					
Gens <i>et al</i> 2014 Switzerland (CH), Czech Republic (CZ) and Greece (GR). Exposure Simulation Modelling and Assessment Tool (ESMAT) using Monte Carlo analysis	Impact of improved insulation on indoor particulate matter. PM ₁₀ and PM _{2.5} Three scenarios of well-insulated buildings (old, new, renovated): 0%, 50% and 100%.	Health effect: DALY (effect, severity, duration, damage costs, monetary value). Bronchodilator usage. Cardiac hospital admissions. New cases chronic bronchitis. Infant mortality. Lower respiratory symptoms. Respiratory hospital admissions. Minor restricted activity days. Restricted activity days. Work loss days. Years of life lost.	Compared to 0% insulated, modelled scenarios of 50% and 100% led to increased DALYs. Opposite contributions identified: (1) The reduction in outdoor PM emissions due to reduced energy demand results in decrease in DALYs: CH & GR = 2500; CZ = 5000. (2) air tighter buildings led to accumulation of indoor PM resulting in increased DALYs: CH = 3300; CZ = 4100; GR = 7600.	Both effects together indicate that accumulation of PM indoors if high indoor PM sources are present. The effect of these PM accumulations may outweigh the benefits of reduction in outdoor PM on the population average. Need to consider ventilation when increasing energy efficiency of buildings.	Only PM considered, not impacts on levels of fungal spores, radon or relative humidity and associated health effects. Changes in assumptions will influence the results. Considerable uncertainties.
Shrubsole <i>et al</i> 2015 London and Milton Keynes, United Kingdom. Modelling: SCRIBE, a building physics-based health impact model of the UK	Combined home energy efficiency and electricity grid decarbonisation scenarios from 2020-2050. Energy Efficient (EE): Business as Usual (BAU) with range of housing energy efficiency and purpose	To examine changes, 2010-2050, in end-use energy demand, CO ₂ emissions, winter indoor temperatures, airborne pollutant concentrations and associated health impacts: all cause and cardiovascular, cerebrovascular, myocardial infarction, cardiopulmonary, lung cancer mortality data.	The average net impact on health (change to life-expectancy at birth) per 1000 population was greater in magnitude under all scenarios in London compared to Milton Keynes and more beneficial when it was assumed PPV would be part of energy efficiency interventions (London ~+4 months; MK ~+3 months), but more detrimental when interventions were assumed not to include PPV (London ~-5 months; MK ~-2 months).	Important to consider ventilation measures for health protection (not adversely affecting indoor air quality) and the potential variation in the impact of home energy efficiency strategies, suggesting the need for tailored policy approaches in different locations, rather than adopting a universally rolled out strategy.	Modelling relies on assumptions and hold many uncertainties. Results are indicative and relative, rather than evidence of direct impact.

Table 6. (Continued.)

Area, Author, Year, Title	Exposure/Intervention	Outcomes	Results	Discussion/Conclusion	Comments
housing stock linked to the Eng- lish Housing Survey.	provided ventilation (PPV) interventions; Energy Efficient Plus (EE+): BAU plus sub- stantial efficiency and ventilation interven- tions focussed on heating; Low Carbon Supply (LCS): major decarbonisation scenario with housing interventions (EE) and electrified heating.				

energy sources, for example, waste to energy technologies or electrification of vehicles. We recommend that the consistent gap in knowledge that has emerged from this review could be addressed by conducting life-cycle HIA or modelling studies of current and developing energy transitions technologies, interventions, and policy decisions on health. There is a need to conduct individual systematic or in-depth reviews for each of the energy transitions themes to identify the key stages that would inform the development and implementation of life-cycle HIAs or modelling. Toxicological research could also inform the development of life-cycle HIAs for this purpose. An example of an energy transition field that would benefit from toxicological data is that related to biofuel production and use. Given the rapid speed with which some of these energy transitions are occurring it is imperative that such assessments and studies be conducted as soon as possible so that policy decisions and investment priorities are supported by a solid evidence base that protects not only the environment but also public health.

Funding

This review was funded through a seed grant from the National Health and Medical Research Council funded Centre of Research Excellence, Centre for Air pollution, energy and health Research (CAR)(NHMRC APP1030259; [SEED05.2017]).

Author contributions

All authors contributed to the conception of this review and methodology. RT and CC undertook the search and synthesis of the research papers. RT drafted the first version of the manuscript and all authors contributed to the manuscript.

Description of article

The aim of this work was to conduct a scoping review of evidence from peer-reviewed literature of the health impacts and co-benefits of transitioning from fossil-based fuels to other forms of low/no carbon energy. Overall, our review found that most research involves modelling health co-benefits from climate change strategies but there are substantial gaps in understanding potential health impacts associated with the transition to individual renewable energy technologies.

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