CONSIDERING MATERIAL CYCLES FOR A TRANSITION TO LOW-CARBON ENERGY SYSTEMS IN AOTEAROA/NEW ZEALAND: A SYSTEMATIC REVIEW

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ABSTRACT

The decarbonisation of energy systems plays a central role in climate change mitigation strategies. Yet, the implementation of new energy infrastructure increases material demand, especially metals, and poses a challenge with managing their end-of-life. However, it is not yet clear to what extent integrated analyses of energy and material systems have been undertaken for the New Zealand context. This paper provides a systematic literature review to inform how material analyses have been incorporated in the planning of low-carbon energy systems in New Zealand. The results show that research efforts have forecasted low-carbon energy systems and modelled some of the infrastructure required, as well as the associated lifecycle emissions considering scenarios of different renewable electricity mixes and of improvements in energy efficiency. However, material systems – whether virgin material demand or implications for recycling – have not been considered in low-carbon energy pathways for New Zealand. We recommend energy and material systems analyses for New Zealand should become more integrated to inform better policy and decision-making. This could be achieved by developing a model that integrates energy system modelling with dynamic stock-flow models and prospective lifecycle analysis.

Keywords: energy system, material system, climate change mitigation, metal demand, lifecycle.

1 INTRODUCTION

Strategies to decarbonise energy systems and improve energy and material efficiencies can promote sustainable development; renewable energy systems address fossil fuel depletion while material efficiency reduces virgin material demand and emissions associated with the production value chain. The transition towards an energy system that is more reliant on renewable resources demands large quantities of resources and materials, and especially metals [1]. Material efficiency, on the other hand, can reduce resource extraction and waste generation leading to energy and emissions savings [2]. Therefore, the transition requires the careful management of the supply chains and end-of-life of alternate technologies and infrastructure that will be introduced in the energy system.

Indeed, the scientific literature points out the importance of integrating energy and material systems analyses when forecasting climate mitigation strategies. Integrated assessment pathways overlooked material cycles and misrepresented life-cycle impacts of energy technologies [3]. Energy system models should consider the whole process chain of emissions [4]. Thus, material cycles are an important aspect to be regarded in the transformation paths. Energy system models and material flow models could be coupled to assess the impacts of recycling over future energy system pathways [5].

In terms of the New Zealand context, the country ratified the Paris Agreement and, in 2019, introduced the Zero Carbon Amendment Act setting the following emissions targets for 2050: to reduce to zero all net emissions, except for biogenic methane [6]. New Zealand has the third highest share of renewable electricity generation in OECD countries; in 2019, the share was 82.4% [7]. However, the share of renewables in total primary energy was only 39.5% in 2019 [7]. New Zealand's gross domestic GHG emissions per capita was among the

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five highest in the OECD countries in 2017 [8]. The New Zealand economy is trade-dependent and relies on international markets. However, the country's policies on reducing GHG emissions overlook lifecycle emissions and the embodied emissions of imported goods and services [9].

Many countries, including New Zealand, have been modelling and forecasting energy systems to support and understand the transition to a low-carbon economy and mitigate climate change. It is, however, not clear how material cycles have been integrated – or even considered – in low-carbon pathways. The objective of the paper is to provide a critical systematic review focussed on New Zealand, in terms of how material cycles have been included in energy system analysis and provide insights on how energy and material systems could become more integrated.

2 METHOD

A systematic literature review was performed to evaluate how New Zealand has addressed material cycles in the low-carbon energy transition.

The literature was searched using the Scopus database in August 2021.The keywords used for the literature search contained the concepts of energy systems, material systems, New Zealand, and future planning. The keywords used were the following – asterisks (*) were used to replace multiple characters in a word: energy plan* (energy plan, energy plans, energy planning), energy system*, energy model*, energy framework, electricity plan*, transport energy sector, renewable*, power generation, wind energy, solar energy, geothermal energy, hydropower, biogas, biofuel, hydrogen fuel, decarbonise, decarbonize, low-carbon, energy transition, virtual energy, indirect energy, embodied energy, embedded energy, energy footprint, life-cycle, lifecycle, life cycle, LCA, material system*, material efficiency, material flow*, MFA, material demand, supply chain, product system*, commodity*, industrial symbiosis, circular economy, recycling, resource management, waste management, end-of-life, solar PV, wind turbine, hydro turbine, batter*, electric vehicle*, metal*, aluminium, aluminium, glass, plastic, paper, solid waste, New Zealand, Aotearoa, pathway*, forecast, future, scenario*, plan*, goal*, target*, simulation, and route.The selected period for the literature search was from 2011 to 2021. In addition, "grey literature" in the form of governmental and business reports was also assessed.

Abstracts were screened for relevance, and then a refined eligibility assessment was conducted based on a full-text review. Only studies available in full text and about New Zealand were selected. Other criteria used were whether the study was about any low-carbon energy system strategy, and whether it included any material or product analysis. The total number of included studies was 41.

Finally, data from the included studies were extracted and analysed, in terms of the type of material analysis performed in the context of the low-carbon energy transition for New Zealand. Previous analyses of energy and material systems in New Zealand were synthesised in material demand for low-carbon strategies, and in lifecycle impacts of low-carbon technologies.

3 RESEARCH FINDINGS

3.1 Material demand for low-carbon strategies

No estimation of New Zealand's potential share on future global demand of metals for the country's low-carbon energy transition was identified in the literature, although the Climate Change Commission [10] acknowledged that many low-carbon technologies demand metals.

Another noted weakness in the reviewed literature was an absence of studies about the end-of-life phase of low-carbon technologies in terms of the quantity of waste generated and implications for recycling. On the other hand, several reviewed studies analysed the infrastructure required for a low-carbon transition in the electricity, transport and building sectors (see Table 1).

Table 1: Reviewed literature about infrastructure required for low-carbon strategies.

Sector	Area	Specification of the study	Source
Electricity	Local	Optimised micro-grid energy systems. Optimal number of renewable generation plants; transformer; electrolyser; battery banks; capacitor bank; inverter.	[11]–[15]
	Local	Reviewed community energy initiatives and reported some of infrastructure planned.	[16]
	Local	Optimal number of tidal turbines.	[17]
	Local	Presented an historical evolution of the infrastructure of geothermal plant.	[18]
	National	Future projects to increase electricity transmission.	[19]
Transport	National	Modelled hydrogen heavy-duty vehicles uptake.	[20]
	Local	Modelled electrification of a bus route and the number of electric buses.	[21]
	Regional	Optimised freight network to improve energy efficiency. Forecasted number of railway tracks, cranes and forklifts at freight terminals.	[22]
	Local	Evaluated programme on investing in cycleways and walkways infrastructure to reduce emissions.	[23]
	Local	Evaluated perceptions for increasing cycling, they found that improving infrastructure might be a pathway.	[24]
	National	Simulated an electricity network considering EV batteries as grid storage, modelled uptake of EV.	[25]
	National	Modelled the share of EV fleet in New Zealand for light and heavy vehicles.	[10]
	National	Created scenarios of electrification of transport.	[26]
	National	Simulated uptake of low-emission vehicles (light and heavy-duty), considered consumer preferences.	[27]
	Local	Analyse the installation of solar panel in a rooftop of a bus to save energy.	[28]
Building	National	Modelled light demand and efficient lighting technology uptake. Forecasted number of different bulbs.	[29]
	National	Analysed factors that affect residential PV uptake in New Zealand.	[30]

Some of the studies assessed aspects of the infrastructure required for a low carbon transition, although a comprehensive study into all infrastructure required at a national level is lacking. A key transition pathway for the electricity sector relies on expanding renewable generation and upgrading transmission and distribution grids [10]. The reviewed studies have analysed the infrastructure required for renewable energy generation, such as the required number of turbines for a tidal energy power plant [17]. Other reviewed studies estimated the infrastructure required to transition to low-carbon micro-grid electricity systems, not considering the upgrade of the electricity transmission system [11]–[15]. On the other hand, Transpower [19], which operates the national transmission network, presented the current components of the transmission network in the country and future projections to increase electricity transfer and meet future demand.

Regarding the transport sector, there is no specific analysis of material demand for the future transport electrification in New Zealand. Although the sizes of New Zealand's electric vehicles fleets have been forecasted for electric heavy-duty vehicles [20], [26], and for passenger vehicles [10], [25], [26]. These studies used different assumptions for calculating electric vehicle uptake in the country.

Global materials demand for low-carbon energy transitions has recently been modelled. Low-carbon energy transition scenarios from integrated assessment models or from energy system models were used to translate future material demand by combining the scenarios with Input–Output analysis [31], lifecycle inventories (LCIs) [32], dynamic material flow analysis, or dynamic stock-flow modelling [1], [33], [34]. Input–Output models aggregate information in economic flows, so information were disaggregated to model physical flows of commodities, which, however, can lead to model biases and discrepant results [31]. In lifecycle assessment models, it is difficult to discern what part of material demand stems from the electricity generation capacity and what stems from upstream production [1]. Indeed, a strategy to disaggregate LCI information of material intensity from electricity production into construction, decommission and operation was developed to calculate future material demand [32]. However, LCIs might consider different system boundaries, and disaggregating information can generate discrepancies in material demand [32]. On the other hand, dynamic material flow analysis or dynamic stock-flow models model the actual physical flows and stocks of materials and can produce more accurate estimations of the future material demand of low-carbon technologies.

Regarding the end-of-life management of low-carbon technologies for New Zealand, no study was identified that specifically analysed this aspect. However, the Climate Change Commission [10] acknowledged that managing the end-of-life of low-carbon technologies can be challenging, as they are not (yet) easily recycled and it is difficult to dispose of them. Since low-carbon technologies will demand large quantities of metals, recovering metals will become even more relevant in the future. Recycling will be crucial for future resource availability, as it is a long-term option to mitigate resource scarcity. Nevertheless, it is insufficient for short-term demand [35]. Moreover, recycling can save energy and emissions, although there are constraints for recycling. Indeed, there are worldwide examples of models that considered circular economy strategies when modelling the material demand for low-carbon energy system, such as substitution [33], lifetime extension, reuse, and recycling [35].

The transition to low-carbon technologies will increase demand of metals, minerals, and rare earth materials. Thus, it is very important to forecast material demand when planning a low-carbon transition, as well as analyse material supply together with circular economy strategies. The decarbonisation of energy system is essential for a sustainable future, and it should be planned alongside efficient material resources systems.

3.2 Lifecycle impacts of low-carbon strategies

Low-carbon energy technologies have energy and emissions embodied in their materials and manufacturing processes. The indirect emissions are generally considered to be modest compared with the impact of avoiding fossil fuel combustion during the use phase [36]. However, it might become relevant in a low-carbon economy [36]. The study of lifecycle impacts of low-carbon technologies for New Zealand is a strength in the body of knowledge (see Table 2). Some of the reviewed studies performed life cycle assessments (LCAs) of products and processes involving low-carbon strategies, while others were more focused on embodied energy and emissions. The reviewed studies analysed lifecycle impacts for the electricity and transport sectors at a national level, whereas lifecycle impacts for the building, industry, and other sectors were more specific to an establishment.

The reviewed studies evaluated lifecycle emissions of renewable electricity generation using different approaches and assuming different renewables uptake scenarios for New Zealand. In Crossland et al. [37], scenarios of renewable electricity generation to meet electricity demand were created and lifecycle emissions of electricity systems were estimated using lifecycle carbon intensity factors for renewable plants as provided by the Intergovernmental Panel on Climate Change [38]. Energy Return on Investment (EROI) was combined with Carbon Emission Pinch Analysis (CEPA) to account for direct and embodied emissions of renewable generation plants, considering future scenarios of electricity demand and supply [39], [41]. EROI was linked to Energy Return on Carbon calculations in order to estimate emissions of current and consented wind energy farms in New Zealand [40]. The approaches used to calculate emissions of the transition to renewable electricity considered a stationary behaviour of emissions. No dynamic lifecycle emission model considering changes during low-carbon energy transitions was identified for New Zealand.

Because of the high share of renewable electricity in New Zealand, the impacts of electric appliances during usage were usually small compared with the impacts at their production and disposal, such as the impacts of electric bikes in [47]. An EV in New Zealand reduces about 60% of emissions across its full lifecycle when compared to an equivalent internal combustion engine vehicle (ICEV) and reduces 80% of emissions during the use phase [44]. Considering the uptake of renewable electricity generation, the emissions during the use phase could change and get even lower. Likewise, in the building sector, environmental impacts of low-carbon strategies are mainly due to producing materials and most of the impacts reduce in the operational phase [50]. Considering the high embodied energy of materials used in the building sector, studies have analysed the benefits of reuse, recovery or recycling those materials [49], [52]. The building sector is in the early stage of a low-carbon transition [48], and the Ministry of Business Innovation and Employment [60] is in the process of developing the Building for Climate Change programme, which will consider the whole-of-life embodied emissions.

In addition to changes in the use phase, the lifecycle emissions in the production and end-of-life stages might also change over time. In the mining process, easily mined ore deposits have declined [61] and ore grades from existing mined deposits have decreased [62]. Although new mining deposits could be discovered, it is expected that the energy needed for mining and processing virgin metals will increase [61]. Until a transition to a low-carbon energy system is not reached, the energy used for metal extraction will come from fossil fuels [61], which have high levels of associated emissions. Moreover, the end-of-life management of low-carbon energy technologies might change, and recycling of metals might increase and alleviate long-term resource extractions and associated emissions.

Table 2: Reviewed literature about lifecycle impacts of low-carbon strategies.

Sector	Area	Specification of the study	Source
Electricity	National	Assessed electricity decarbonization scenarios and used lifecycle carbon intensity factors from [38].	[37]
	National	Calculated carbon footprint of renewable generation plants considering different generation scenarios.	[39]
	National	Estimated the embedded energy and carbon emissions of current and consented wind farms.	[40]
	National	Calculated emissions of electricity system, analysing scenarios of renewables uptake.	[41]
	National	Measured energy of emergy generation. Emergy is all the energy used to produce a product or service, usually, it is expressed in solar equivalents.	[42]
Transport	National	Analysed acceptability of transport emissions reduction policies.	[43]
	National	Life cycle assessment of electric vehicles.	[44]
	National	Analysed emissions reductions in the transport sector.	[45]
	National	Analysed pathways for sustainability of road transport. Considered lifecycle impacts of transport.	[46]
	Local	Life cycle assessment, cradle-to-grave scope, of a greater uptake of E-bikes displacing ICE cars.	[47]
Building	National	Reviewed approaches used in New Zealand to assess embodied emissions at building sector.	[48]
	Local	Calculated embodied emissions of materials; analysed emissions benefits of reuse, recovery or recycling.	[49]
	Local	Calculated environmental impacts of refurbishment, considering improvement of construction practice, PV usage, and increase of renewables share on electricity.	[50]
	Local	Calculated environmental impacts of a deep energy efficiency refurbishment.	[51]
	Local	Estimated embodied energy/emissions saved by recycling materials from a deconstruction site.	[52]
	Local	Optimised photovoltaic-plus-battery for residences, considered embodied energy of PV and battery.	[53]
	Local	Calculated embodied energy of a house.	[54]
Industry	Local	LCA of a cheese factory, considered scenarios of introducing geothermal and biomass energy.	[55]
	Local	LCA of dairy sector, considered scenarios of moving from coal, natural gas towards biomass energy.	[56]
	Local	Energy efficiency of using bark (by-product from wood-processing) to produce briquettes and tannin.	[57]
Other	Local	Analysed indirect and direct energy to produce organic fruits at an orchard.	[58]
	National	Reviewed energy efficiency strategies in NZ.	[59]

Prospective LCAs have been developed worldwide to account for future lifecycle impacts of emerging technologies. The future is inherently uncertain, and a common approach at LCA studies is to create future scenarios based on specific assumptions about the future [63]. At the scenario generation, studies usually use multiple databases for the assumption of future technological changes, which make it difficult to trace all the assumptions made [63]. In addition, when comparing different technologies, disparate databases could lead in an inconsistent LCA comparison, because of the different assumptions and system boundaries [64]. It is preferable to use a single analytical structure, in which the same background data for common processes among technologies are used [64]. Existing models project future technological, economic, social, and environmental changes, they are based in approaches such as optimisation, simulation, or general equilibrium, and could be used to complement prospective LCAs. However, those models might not consider all possible dynamic changes from all sectors. Recent studies integrated information from future energy scenarios from Integrated assessment models and energy systems models with prospective LCAs [63], [64], and that is a possible solution for LCAs to consider dynamic changes and overcome subjective assumptions at scenario generation. Other studies first performed prospective LCAs and integrated the results generated at prospective LCAs into integrated assessment models [65] and energy system models [66] aiming to assess long-term environmental impacts of energy pathways.

The reviewed literature about lifecycle impacts of low-carbon strategies for New Zealand present snapshots in time, and this limitation is related to the approaches that were used. The transition towards more renewable energy with sustainable supply chains might be a complex situation, with dynamic changes over time, multiple players, and interdependencies among different systems [67]. However, no dynamic studies assessing lifecycle emission of new energy systems were identified. In addition, LCA approaches are not able to assess actual material demand, and energy system or economy-wide emissions [36]. Therefore, a model to investigate the total material demand and emissions of a low-carbon energy transition, considering all lifecycle stages and dynamic changes, is lacking in the body of knowledge.

3.3 Recommendations for New Zealand’s low-carbon transition models

Our review showed a lack of analysis about material demand for a low-carbon transition in New Zealand, and that lifecycle emissions analysis could be developed to consider dynamic changes in the system. In addition, New Zealand pursue recent energy system models, such as the Climate Change Commission model [10] and the TIMES-NZ model [68]. Energy system models consider changes throughout the economy but overlook material cycles and indirect emissions. Thus, there is an opportunity to develop a model to include material demand and lifecycle emissions for the low-carbon transition, considering the characteristics of the country.

There are recent worldwide efforts to analyse the implications of low-carbon transition on material systems. As previously discussed, integrated assessment models or energy systems models have been combined with dynamic stock models to analyse future material demand, and with prospective LCAs to analyse future environmental impacts. However, usually, they are global models and either focus on material demand or lifecycle emissions. Thus, developing a model that encompasses material demand and the implications of the circular economy in the supply chain together with environmental impacts could expand the understanding of low-carbon transitions [69].

Therefore, we suggest the development of a national model for New Zealand to integrate in one framework dynamic material supply–demand and prospective lifecycle emissions of low-carbon strategies. New Zealand has energy models that could be augmented to integrate energy planning with material cycles and lifecycle emissions. A possible solution for including material cycles in low-carbon pathways is to integrate them with dynamic stock-flow models and consider the implication of different circular strategies in the material supply. In order to account for future changes in lifecycle emissions of low-carbon technologies, prospective LCAs can be integrated with low-carbon pathways. In addition, to evaluate emissions flows, lifecycle emissions can be linked to material flows.

4 CONCLUSION

The decarbonisation of energy systems plays a central role in climate change actions and material analyses are very pertinent in this context. Although low-carbon technologies contribute significantly to reducing emissions in their usage phase, they require an increase in resource consumption during build out and have associated environmental impacts during their production and end-of-use phases. Recycling could relieve constraints around the supply of materials in the long-term. Therefore, the efficient use of the most sustainable and least polluting technologies available is required for a well-managed low-carbon transition. This systematic literature review was unable to identify a single study of material demand for future low-carbon technologies to be implemented in New Zealand, nor any about end-of-life management of low-carbon technologies, in terms of quantity of waste generated and recycling. On the other hand, many studies have analysed lifecycle impacts of low-carbon energy systems in New Zealand. However, lifecycle emissions have been calculated using static approaches, and the assumption of future scenarios represent only snapshots of lifecycle emissions using historical data, and no dynamic changes have been modelled. Developing a modelling framework that incorporates energy systems with material cycles is critically important in order to have a comprehensive understanding of low-carbon transitions. A possible solution is to develop dynamic stock-flows and prospective lifecycle emissions models integrated with energy system models.

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