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Accelerating Pathways to Net Zero: Governance Strategies from Transition Studies and the Transition Accelerator

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Abstract

Purpose After decades of delay, there are promising signs that society may finally be getting serious about climate change. But the problem is now of such urgency that accelerating transition pathways to net zero is of paramount importance. Which governance approach gives society the best chance of simultaneously realizing the multiple sectoral and industrial transformations that net zero entails? How can policymakers and broader societal actors accelerate these transformative processes, setting in motion transition pathways to desirable futures? In response to these interrelated questions, we survey the literature on sustainability transitions and present an approach that aims directly at radical system change.

Recent Findings Two decades of transition research has generated critical insights on accelerating transition pathways to net zero, highlighting key transformative strategies and pointing to the central role of the state, politics, and intermediaries.

Summary Transition research indicates that reaching net zero entails radically transforming essentially all sectors and industries as they are deeply entwined with the use of fossil fuels and the release of greenhouse gas emissions. An ambitious state in conjunction with a strong constellation of intermediary organizations can set in motion and accelerate transition pathways by actively driving niche development surrounding promising innovations, promoting the diffusion of emerging alternatives, and phasing out carbon-intensive arrangements.

Keywords Climate change · Transition pathways · Intermediaries · Mission-oriented innovation policy · Green industrial policy

Introduction

With the recent release of the Sixth Assessment Report [1], the Intergovernmental Panel on Climate Change (IPCC) has delivered a stark warning that human-induced climate change is already upon us and that many climate impacts (e.g. receding arctic sea ice and rising sea levels, ocean warming and acidification, and extreme weather events such as heatwaves and droughts) are locked in. While the science presents an increasingly bleak picture about irreversibility, it also underscores that the most serious disruptions can still be averted if society embarks on a path of rapid and ambitious climate action. There are some signs that such a path may be starting to take shape.

The proliferation of national and corporate *net zero* commitments suggests that governments, businesses, and other societal actors may finally be getting serious about tackling climate change. Although the quality of commitments varies considerably, two thirds or more of greenhouse gas (GHG) emissions are now covered by net zero pledges [2]. More importantly, framing the challenge in terms of net zero has begun to dispel the notion that some sectors or industries will be immune to the radical changes needed to reach full decarbonization. The challenge, however, remains in (i) setting all sectors and industries on pathways to net zero and (ii) accelerating these processes.

Over the past 30 years, governments have experimented with a variety of policy tools in their attempts to bring GHG emissions under control. Broadly, these include economic

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instruments, such as carbon pricing, which place economy-wide pressure on carbon-intensive arrangements to encourage individuals and business to switch to lower carbon alternatives [3]; regulatory instruments that seek to tighten emissions controls (for vehicles, gas flaring, and so on) or eliminate particularly problematic technologies, infrastructures, or processes [4]; and innovation-oriented measures, such as incentives for novel low-carbon alternatives, that help to promote rapid development and diffusion [5]. Some attention has been paid to targeting individual behaviour and lifestyles more directly [6], among other aspects of the consumption-production equation. And different assemblages of approaches have increasingly been brought together into more sophisticated policy mixes [7–9]. Taken together, traditional climate policy measures have largely concentrated on first stabilizing and then reducing emissions in an efficient and stepwise fashion.

Conventional governance approaches have, however, continued to struggle with driving the depth and scope of change needed to set existing systems on a course for full decarbonization. Research suggests that, *at base, this relates to a mismatch between the climate problem and proposed solutions – understanding the challenge as an emissions control issue or market failure rather than as a fundamental issue of how to transform the way production/consumption systems are currently configured* [10, 11]. Existing systems of social provisioning remain deeply dependent on fossil energy supplies (80% globally), and basic industrial processes (including the production of steel, cement, chemicals, and plastics) along with agricultural practices (including forest clearances, livestock operations, and chemical fertilizer use) are major GHG emission sources. Driving emissions to net zero will therefore require a fundamental transformation of core provisioning systems from energy to transport and the built environment to agri-food—a transformation involving changes to technologies and infrastructures, institutions and norms, prices and markets, as well as social practices and business models [12]. As this change transcends traditional system boundaries, it also requires new and more horizontal forms of decision-making [13].

In this article, we explore an alternative to conventional paradigms—one grounded in sustainability transition studies. This approach aims directly at envisioning, developing, and accelerating transition pathways capable of reorienting systems to net zero. Our review begins by surveying transition perspectives on the nature of system change, with an emphasis on the role of the state [14, 15], politics [14, 16, 17], and intermediaries [18–20]. Rather than seeking to comprehensively survey the full range of the rapidly expanding transition literature, we focus on prominent contributions that point to key lessons relating directly to the climate challenge. The paper then moves on to illustrate how insights from this literature can be applied in practice by presenting the activity of the Transition Accelerator [21, 22], a Canadian charity that works to create positive systems change consistent with a net zero future. Our review concludes by reflecting on the implications for accelerating the net zero transformation.

Sustainability Transition Studies

A rapidly growing body of research in the field of Sustainability Transitions [23, 24] has emerged over the past 20 years, which explores transitions in large-scale production/consumption systems, and seeks to mobilize this knowledge to accelerate movement towards more sustainable societal arrangements. A significant body of work within this field examines historical transitions processes in major 'socio-technical systems' such as the shift from surface to piped sewer systems [25], from sail to steam ships [26], and from horse drawn to internal combustion engine road transport [27]. These studies demonstrate that transition processes are marked by the coevolution of technology and society [28]. Systems that meet core societal functions (the provision of heat, power, water, food, and so on) are composed of interrelated material and social elements that seamlessly enable a dominant 'way of doing things'. The electricity system, for example, includes both technical components (power stations, transmission wires, transformers, local distribution networks) and social dimensions (contractual arrangements, regulations, pricing structures) that, together, animate the provision and consumption of electric power [29]. Transition research indicates that appreciating the interconnections among these elements is critical to understanding the function and evolution of the system as a whole [30].

Research on historical episodes of change underscores that systems typically evolve in incremental ways as established development trajectories display path dependent qualities. In this way, early choices close the envelope of available future choices and reproduce established societal arrangements [31]. Take, for example, how the internal combustion automobile has retained the same basic design since it crystallized in the Ford Model T at the turn of the twentieth century. Consider also how the built environment and consumption patterns have coevolved alongside the car, reinforcing the centrality of this form of personal transport (from the spread of suburbs to drive-through business models). That is not to say that there has not been innovation—on the contrary, automobiles have benefitted from an accumulation of advancements over more than a century improving their performance in every appreciable way (from acceleration to safety to fuel efficiency). But the mobility system as a whole and its surrounding elements have remained largely tied to internal combustion engine-based automobile transport.

Nevertheless, more dramatic changes—transitions—do occur, such as the original leap from horse drawn to automotive mobility [27], from manufacture to mass production

[32], or from gas to electric lighting [33]. The *multi-level perspective* (MLP) [26, 34, 35] has gained particular prominence in mapping the various ways such transitions unfold [36, 37]. According to this heuristic framework, transitions are driven by the interaction of multiple factors arrayed across three levels: 'regimes', 'niches', and 'the landscape'. Regimes consist of the dominant rules and institutions, technologies and infrastructures, business models and practices, and incumbent industries and interests that constitute a particular system [28]. Consider, for instance, how the established electricity regime rests on guiding principles that place particular value on dispatchable power and how this continues to privilege the build out of natural gas-fired units. Niches, in contrast, are composed of emerging innovations and approaches that have the potential to accumulate over time and may eventually displace elements of the regime [38]. Take, for example, how solar photovoltaics benefited from initial improvements in small niches in satellites and remote sites but gradually accumulated momentum in distributed power applications with policy support until diffusing widely across multiple contexts in recent years. The landscape encompasses broader developments, such as acute market shocks and changing political administrations but also more gradual shifts in culture, that may help to reinforce or exert pressure on a system. Think of how the Russia-Ukraine conflict has potentially opened opportunities for accelerated renewable energy deployment as Europe seeks to end its reliance on Russian fossil fuels.

What the MLP illustrates is that there is no single driver of transitions. Rather, it is the alignment and accumulation over time of multiple factors (e.g. the readiness of niche innovations, internal pressures within the regime, and landscape shocks) that together build towards system change [36, 39]. A considerable body of work [36, 37, 40, 41] has examined the various ways the above factors can interact to generate transition pathways that enable a system to shift from one configuration to another [42]. This literature emphasizes that timing matters, with transitions tending to unfold in multiple stages resembling an S-Curve [43–45]. At the outset, alternatives are expensive and have serious functional handicaps (think of early LEDs which produced weak light in just one colour). Experimentation with new technologies and business models can bring functional improvements and cost reductions, which open the way for more widespread adoption. At a certain point diffusion accelerates and eventually the novel arrangements can become entrenched as the new normal.

Policy-focused contributions build on these insights to show how effective interventions to accelerate change evolve as the transition progresses though different stages [21, 46, 46, 47] (see Fig. 1). Broadly, these interventions seek to build up low-carbon alternatives that form the basis for net zero systems of the future while simultaneously driving down carbon-intensive arrangements [11].

Supporting Niches At the front end of the process, the creation and development of niches is a critical means to accelerate transitions [38]. In transition studies, niches are regarded as a locus for innovation and experimentation [48, 49], sheltering novelties from harsh competitive pressures until they can crystallize around promising models [50]. But niches not only support technical improvements (in performance or efficiency), they also nurture social processes such as vision building, learning-by-doing, and networking that are necessary to attract resources (investment and human capital), secure critical early markets, and eventually scale up [51, 52]. The deliberate creation and support of niches through policy

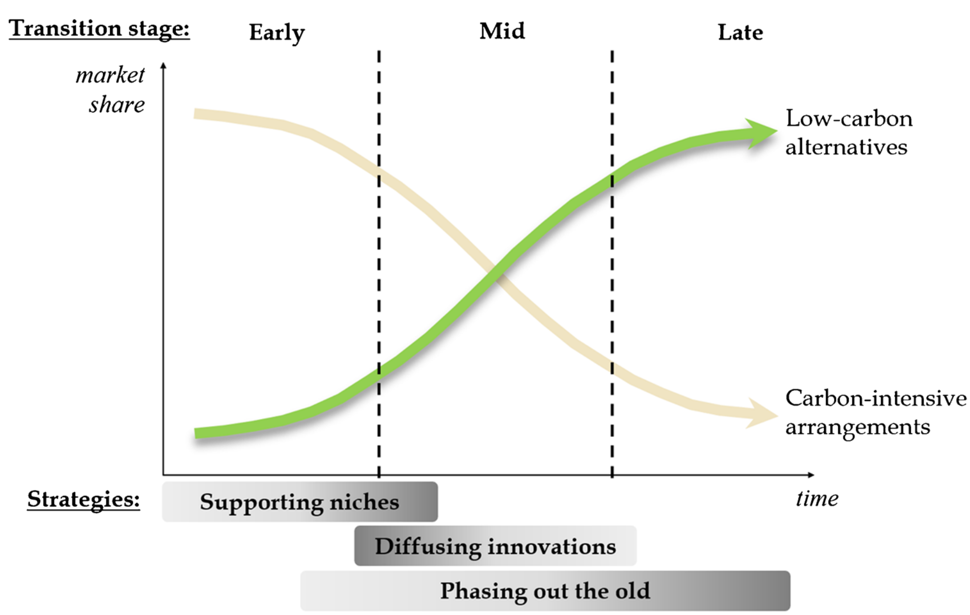

Fig. 1 Interventions to accelerate transition pathways

(e.g., investment in trials and demonstrations) is a promising avenue to stimulate learning, de-risk private investment, build coalitions and capacity, and promote public engagement [53–55]. Niche development can also be deliberately fostered by bringing together diverse innovators (entrepreneurs, academics, public officials, and others) to envision and experiment with new models and approaches [43, 56–58]. Such efforts often involve a joint process of structuring the problem and learning about the focal system, developing a vision of potential transition pathways, carrying out transition experiments, and monitoring and evaluating to derive lessons.

Diffusing Innovations At a certain point a focus on wide scale deployment and adoption is critical to accelerating change. Even as a niche innovation begins to crystalize around a promising model and accumulate momentum in early markets, harsh competitive pressures (from cost-efficiency gaps and mismatches with institutions and lifestyles) will often impede wider uptake and the eventual reconfiguration of the system. Various incentives for the adoption of novel approaches and technologies have been widely used to address these issues, encouraging them to gain market share. Consider, for instance, how feed-in-tariffs for new renewables allowed them to diffuse more widely [59] or how rebates for battery electric vehicles helped to expand initial markets [14]. Diffusion may also be incented by encouraging the building out of and/or easing access to supporting infrastructure (e.g. charging networks in the case of electric cars and grid access for distributed renewables). Political tensions can be particularly heightened during this stage as alternative approaches and innovations are no longer only 'hopeful monstrosities' with far off potential but are becoming a more immediate threat to the market share of established interests [60–62].

Phasing Out the Old Transitions involve dismantling the old system as well as building a new one [11, 45, 63–65]. Transition scholarship indicates that the emergence and diffusion of innovations alone tends to be insufficient to drive rapid system change. Rather, mounting pressure on the regime is often needed to secure objectives—without which problematic technologies, practices, or substances could persist for decades or longer [63, 65, 66]. Indeed, transition scholarship has increasingly turned its attention to the role of upsetting existing system configurations through delegitimization, divestment, phase outs, and associated measures [64]. Studies have examined the mounting number of phase-outs targeting coal [67, 68] and those announced around internal combustion engine vehicles [69]. While such interventions can help secure the decline of problematic technologies and practices, they also have the potential to exacerbate political tensions (e.g. between the urban 'elite' and rural communities) by concentrating economic and social losses in particular contexts (specific industries, communities, and so on) and moments in time (years rather than spread over a decade or longer). This introduces important equity considerations that require dedicated efforts to alleviate [70, 71]. Yet, transition research also reminds us that some losses are inevitable even as society as a whole may stand to gain from system change.

This discussion also touches on several cross-cutting features of transitions. It highlights that the *state* has a decisive role to play given its ability to wield the power, resources, and machinery needed to deliberately drive and accelerate transition pathways [14, 16, 72, 73]. Roberts et al. [16], for instance, point to the role of government in both supporting interventions that open up systems to radical change (through open-ended innovation processes) as well as close them down around particular pathways (e.g. the broad-based electrification of energy end-uses and all that goes with that). Others have similarly called attention to the role of the state in developing mission-oriented innovation and industrial policies that identify societal challenges and bottlenecks, fix objectives and timeframes, and mobilize resources to reach desirable futures [74–77]. Despite the orthodoxy that markets are the core driver of innovation trajectories, there is now substantial evidence that the mechanisms and structures of the state have always been used to select among innovations (i.e. 'pick winners'), playing critical functions in promoting market creation, scale up, and legitimacy building. This not only places the state at the centre of transition-focused strategies (e.g. as a key source of niche support), but also efforts to impede change [14, 62, 68].

As a consequence, actors continually vie for position to influence the levers of the state and shape the envelope of possibilities under consideration [14]. Given the high stakes of these struggles, *politics* can be thought of as inextricably interlinked with transition processes, alternately catalyzing or barring change depending on the outcome of individual political contests [17]. Transition research elaborates how these contests (in the form of policy debate, the political mobilization of actor coalitions, and so on) can be crucial in opening up established trajectories and pressing for change [78–80]. Similarly, this work indicates that early actions to create and resource coalitions for change may not only set in motion transition processes but also help to establish important constituencies capable of defending unfolding pathways even when resistance from incumbent actors intensifies [16, 81, 82]. Take, for example, how early policy actions to build up niches through industrial policy for renewable energy also created the constituencies needed to defend such policies later on [83]. Politics also forms the basis for strategies deployed by incumbent actors as they seek to maintain legacy entitlements, terminate niche support, or even creatively coopt or hedge against otherwise transition-focused measures [61, 62, 84]. Indeed, state actors (e.g. in finance and/or energy departments) and incumbents can sometimes be engaged in a regime-level alliance to support continued growth in incumbent (fossil fuel) industries [62].

Despite the critical role of the state, transition research also places weight on broader societal actors in accelerating pathways in line with the understanding of transitions as multi-actor processes. This has motivated a surge of interest in *intermediary organizations* as important actors for connecting networks of innovators, drawing out lessons across diverse project contexts, and aggregating efforts to build pathways for broader system change [19, 85–87]. Kivimaa et al. [88] define intermediaries as 'actors and platforms that positively influence sustainability transition processes by linking actors and activities, and their related skills and resources, or by connecting transition visions and demands of networks of actors with existing regimes in order to create momentum for socio-technical system change, to create new collaborations within and across niche technologies, ideas and markets, and to disrupt dominant unsustainable socio-technical configurations'. At base, this is about developing, interconnecting, and aggregating emerging niches while also creating openings in regimes for innovation processes to unfold [85, 89]. Such intermediary organizations can vary widely from think tanks to environmental and advocacy organizations to quasi-governmental and arm's length agencies.

While transition studies [88] differentiate among several types of intermediaries (e.g., those situated at niche or regime levels), some have suggested that it is not the specific makeup of the intermediary that is paramount but rather the functions they perform [90]. These functions include articulating visions, networking, generating and allocating resources, capacity building, and carrying out pilot projects [18]. Others have highlighted more expansive functions including bridge building between sectors, different levels of government, disciplines, and policy domains [91]. Such functions may extend across traditional jurisdictional boundaries [92]. Some note that while intermediaries may have linkages with government, a key advantage is that they can operate independently and more flexibly than government in incubating and scaling up novel approaches to accelerate transition pathways [19]. In this fashion, independence from government and the appearance of neutrality may help intermediaries build trust among diverse actors and facilitate their role as networking and vision-building organizations [86].

An Illustrative Approach: The Transition Accelerator

We now draw together many of the abovementioned insights and lessons by examining a specific intermediary organization dedicated to accelerating transitions to net zero. *The Transition Accelerator* is a national not-for-profit founded in Canada in 2019 to work with stakeholders from industry, government, and civil society to define and build out sectoral and regional transition pathways [22]. Inspired by research on sustainability transitions, this organization applies a four-stage methodology to co-develop transition pathways with innovative stakeholders. In this context, transition pathways are understood as the sequence of changes to technology, business models, social practices, policy, and public attitudes required to move a system to a more desirable, and net zero GHG emission configuration [21]. The Accelerator process starts with analysis of the target system (the specific niche, regime, and landscape contexts including actors, material and financial flows, strengths and weaknesses), then moves through vision and pathway development, modelling and stress-testing proposed pathways, and finally practical experiments, pilots, and the establishment of consortia to build out pathways in practice (see Fig. 2).

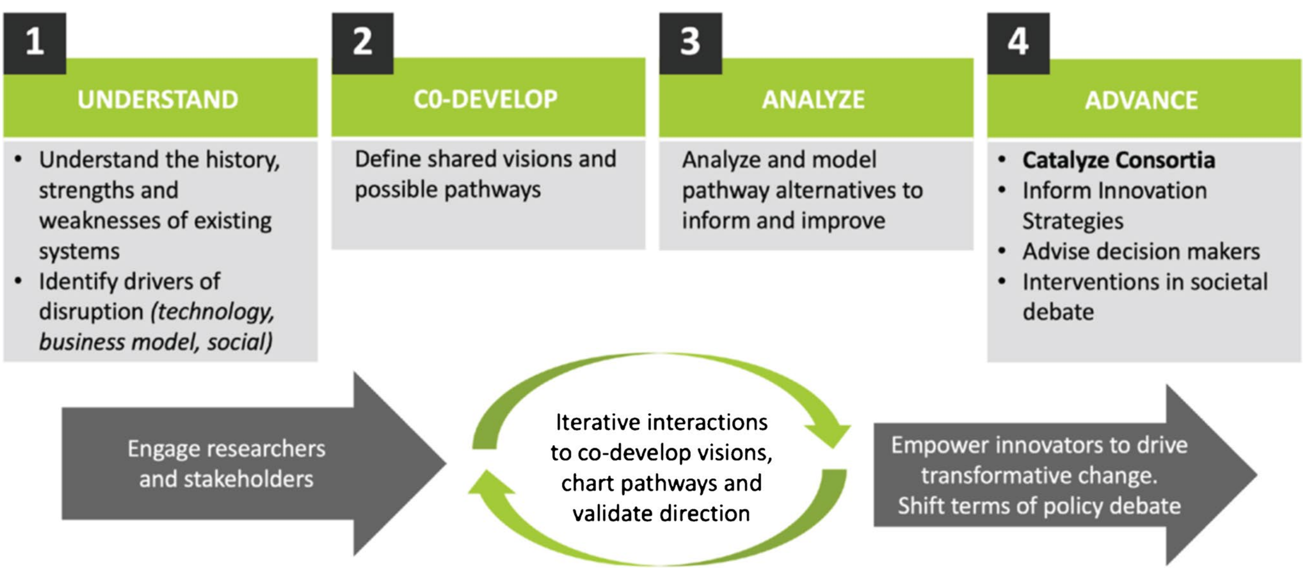

Fig. 2 Iterative process for pathway development. Source: [22]

Central to this approach is linking efforts to mitigate GHG emissions to transformative currents and emerging pressures within key systems of social provisioning and developments occurring at the landscape. The Accelerator argues that effective interventions must be tailored to the *specific* conditions in different *regions and systems*, as obstacles and drivers of change vary (agri-food is very different from transport and so on). Initial funding for the organization has been provided by charitable foundations, but pathway specific support comes from many sources including businesses and various levels of government.

The Accelerator can therefore be understood as a classic intermediary organization, which works as a facilitator to catalyze niche development, support diffusion, and encourage broader system change. It aims to accelerate movement in areas where governments have so far been unable or unwilling to act decisively. By building coalitions of innovators—those with the interest and capacity to induce change—the Accelerator helps shift relationships on the ground and achieve practical advances. It can build momentum for change that will ultimately make it easier for governments to take more ambitious action.

What this approach looks like in practice can be seen in the stepwise development of hydrogen-related pathway work in Western Canada. Launched by David Layzell's research group at the University of Calgary (Canadian Energy Systems Analysis Research, CESAR) 3 years ago, attention was initially focused on the decarbonization of heavy trucking. Detailed analysis of the road transport system turned up interesting findings including the low margins in the haulage sector, the difficulty recruiting drivers, high maintenance costs of diesel engines, and enthusiasm of some industry actors to explore cleaner alternatives. Techno-economic and lifecycle analysis and interaction with stakeholders suggested hydrogen fuel cell electric vehicles represented the most promising option for the heaviest (Class 8) trucks [93]. A collaborative exploration of transformative visions and detailed pathway analysis allowed a redefinition of the challenge from solving the GHG emission problem for heavy trucks to seeing the industry as a potential 'anchor tenant' (i.e. early volume market) for a low-carbon hydrogen economy in which Alberta, a major oil producing province, could remain a key energy provider in a rapidly decarbonizing world [94].

This vision inspired actors in the haulage industry, but appealed more broadly to stakeholders seeking a path forward in a province so dependent on fossil energy production. Alberta has significant potential as a producer of low-carbon hydrogen—both hydrogen made from fossil inputs with carbon capture and storage (CCS) and made by the electrolysis of water using renewable electricity (wind, solar, geothermal). Alberta is already one of the lowest cost hydrogen producers in the world, producing it at scale through steam methane reforming for the oil, chemical, and fertilizer industries [95]. There is also substantial experience with CCS technologies—for example, at the Quest CCS facility near Edmonton, which has been operating since 2015. Even with CCS, hydrogen can be cheaper than diesel to produce. But today there is no way to get hydrogen to potential end users, and no fleet of vehicles or other customers awaiting hydrogen fuel. The stepwise development of low-carbon hydrogen demand and supply is therefore critical to diffuse this alternative energy carrier. Technical barriers to widespread hydrogen use in heavy transport (including trucks and trains), for industrial heating (e.g. in steel or cement production), or as a storage medium for renewable electricity remain. But above all there are barriers related to investment in strategic infrastructure, market creation, standards (for safety, carbon accounting, and interoperability), the creation of new business models, and so on.

As the Accelerator's hydrogen work progressed, it has led to an expanding applied research effort and the establishment of practical pilots and consortia, each of which has helped leverage additional activity. Researchers and industry first collaborated to secure government funding for a $15-million pilot to build and test hydrogen fuel cell vehicles on the 300-km transport corridor between Edmonton and Calgary. The Alberta Zero-Emission Truck Electrification Collaboration (AZETEC) is led by the Alberta Motor Transport Association, managed by Zen Clean Energy Solutions, and financed by Emissions Reduction Alberta. Collaborators include Ballard Power (fuel cells), Air Products and Praxair (hydrogen supply), Nordressa (a Quebec-based electronic drive train manufacturer), Freightliner/Daimler (truck bodies), and HTEC (fueling equipment).

Appreciation of potential economic opportunities in an emergent hydrogen economy allowed creation of 'Alberta's Industrial Heartland Hydrogen Taskforce' in May of 2021—a coalition led by the mayors of five municipalities (including Edmonton), with participants from industry, the federal and provincial governments, and academia [96]. The group's extensive consultation, networking, and analysis paved the way for the subsequent establishment of the Edmonton Hydrogen Hub. Funded by all three levels of government, this is the first regional hydrogen hub in Canada. The Hub has already produced a foundational analysis that anticipates the sequencing of hydrogen roll out over the coming decade. The work is detailed and concrete, involving a geo-spatial mapping of hydrogen sources and end users, identification of pipelines and delivery routes, and the build out of alliances to support pilots with multiple technologies and business models. The Accelerator is currently working with a variety of groups to establish other regional hydrogen hubs and corridors in Alberta and other Canadian provinces.

In developing these hydrogen hubs, the Accelerator has emphasized strategic visioning, rigorous analytics, and collaborative engagement. As part of this, the Accelerator has maintained that Hub activity, infrastructure investment, and regulatory and policy initiatives should be guided by the public interest in deployment of a dynamic low-carbon hydrogen system rather than by the narrow concerns of an individual company, which might, for example, seek to maximize revenue by slowing uptake or controlling supply. Of course, hydrogen will be just one part of a net zero energy system, and care must be taken to ensure hydrogen solutions ultimately result in full decarbonization. Thus, while hydrogen made from fossil inputs with CCS can play a role in scaling hydrogen infrastructure today, residual carbon emissions associated with its continued deployment would need to be fully neutralized by negative emissions in a net zero world.

Many actors played a role in the relatively rapid uptick of interest in low-carbon hydrogen in Canada. Internationally, hydrogen has been recovering from the disappointment of the hype-cycle in the 1990s as the technology has matured and the scale of the challenge of reaching net zero has become clear [97]. The long downturn in the oil and gas sector in Alberta in the 2010s encouraged some exploration of alternative development trajectories. And the relative absence of attention paid to hydrogen as a net zero energy carrier over the previous decade created an opening where the Transition Accelerator—with its data and analysis driven approach, and emphasis on activating innovators through a pathway design methodology—could have influence out of proportion to its modest organizational means.

Nevertheless, the example shows the potential for intermediary organizations to catalyze progress, especially at the niche development/early diffusion stage of transition processes. To date, the Accelerator has been active across a number of sectors and regions—work which has, for example, created new coalitions to promote integration and modernization of electricity grids (Canada Grid) [98] and the manufacture of zero emission vehicles in Canada (Accelerate: Canada's Net Zero Supply Chain Alliance) [99]. In addition, the organization conducts broader educational work to popularize its pathway development methodology and analytical approach for assessing net zero priorities [21]. A critical point in relation to public authorities is the argument that carbon pricing and tax credits for green investment are not enough to induce system change at the required scale. Thus the Accelerator advocates government application of a full range of policy instruments to drive niche development, diffusion, and phase out, including public investment, regulatory measures, and mission-driven innovation and industrial policy. It emphasizes the need for governments to adopt a strategic approach to net zero, concentrating resources where they can make the most difference. This means applying policy mixes suited to the particular phase of transition in each sector, focusing on mass roll out where solutions are now clear (e.g. electrifying light duty vehicles) and on niche development and experimentation where solutions are still under development (e.g. in agri-food).

Conclusions

This review has drawn several lessons for governing accelerated change towards net zero that emerge from the sustainability transition literature, and are being applied (in a modest way) in the activity of the Transition Accelerator. Above all, it underscores the significance of moving towards a governance approach that rests on developing and realizing pathways to net zero, charting a course for the transformation of key systems of social provisioning to achieve full decarbonization (the key features of such an approach are summarized in Table 1). Indeed, there are many ways to reduce GHG emissions that are not steps on a pathway to net zero (e.g. the shift from coal to natural gas in the electric power sector or from gasoline to corn-based ethanol for light duty vehicles can yield emissions reductions but do not represent progress towards net zero). By focusing on regional and sectoral provisioning systems, and identifying the sequences of reforms (to technologies, business practices, regulation, public attitudes, and so on) required to flip these systems into alternative net zero configurations, a governance approach based

Table 1 What a transition pathways approach brings to climate action

	Transition pathways approach
Goal	System change to deliver multiple benefits and net zero GHG emissions
Theory of change	Co-developing visions and building out pathways can empower innovators, alter facts on the ground, and open the way to more ambitious action
Scope	Sector and regional transitions
Policy instruments	A complex policy mix that is sensitive to sector and regional context and the phase of transition and includes 'mission-driven' innovation and net-zero industrial policy
Obstacles identified	Path dependence of dominant system (technology, infrastructure, regulations, consumer expectations, and so on) and power of incumbent interests
Outcomes	Build out of coalitions, practical change, opening space for system transformation

Caption: Adapted from [21]

in sustainability transitions can avoid the waste of time and money associated with 'dead end' pathways which cannot deliver on long-term decarbonization.

A governance approach embedded in transition thinking foregrounds the application of multiple policy tools to advance system change in different sectors at different stages of the transition process. It underscores the centrality of coupling policy measures to work towards building up alternative innovations with the potential to reconfigure incumbent arrangements while at the same time winding down problematic technologies, practices, substances, and so on. Simply put, such an approach involves simultaneously accelerating the emergence of 'the new' and the decline of 'the old'. It also highlights the importance of accounting for non-climate related problems in specific sectors and regions and integrating climate goals with other societal objectives. And it illustrates why equity and distributive issues cannot be avoided in plans to accelerate system transformation.

Beyond this, our review has highlighted the decisive role of the state and politics in transition processes. Only the state can ultimately marshal the resources necessary to accelerate, and carry forward to conclusion, change on the scale envisaged here. And because politics determines governmental action, measures which can strengthen the political coalitions that stand behind climate policy are of particular importance. The deliberate effort to build economic constituencies which support a deepening of decarbonization is crucial, hence the Transition Accelerator's emphasis on building the net zero emission vehicle supply chain in Canada and promoting the potential of a hydrogen economy.

Finally, the analysis points to the potential functions performed by intermediary organizations—linking innovators in business, government, and civil society—in transition processes. Expanding the number and diversity (both geographic and system/industrial focus) of these types of solution-oriented actors can help promote the multiple transitions that reaching net zero entails. Such groups can be funded privately or publicly, but in either case they can play leading roles in exploiting opportunities and breaking path dependent processes to drive system change. Together with civil society movements that intensify pressure on political and business leaders as well as efforts at building coalitions to give weight and stability to climate policy, mutually reinforcing state and intermediary actors can serve as decisive enablers of the transition to net zero.

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Declarations

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References

1. IPCC. Summary for policymakers. In: Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L., Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield,, O. Yelekçi, R. Yu and B. Zhou, editors. Clim Change 2021 Phys Sci Basis Contrib Work Group Sixth Assess Rep Intergov Panel Clim Change. Cambridge University Press; 2021.
2. Black R, Cullen K, Fay B, Hale T, Lang J, Mahmood S, Smith SM. Taking stock: a global assessment of net zero targets [Internet]. Oxford: Energy & Climate Intelligence Unit and Oxford Net Zero; 2021. Available from: https://ca1-eci.edcdn.com/reports/ECIU-Oxford_Taking_Stock.pdf?mtime=20210323005817&focal=none. Accessed 20 Aug 2021.
3. Baranzini A, van den Bergh JCJM, Carattini S, Howarth RB, Padilla E, Roca J. Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations: Carbon pricing in climate policy. Wiley Interdiscip Rev Clim Change. 2017;8:e462.
4. Rosenbloom D, Rinscheid A. Deliberate decline: an emerging frontier for the study and practice of decarbonization. WIREs Clim Change [Internet]. 2020 [cited 2020 Jul 27]; Available from: https://onlinelibrary.wiley.com/doi/abs/,https://doi.org/10.1002/wcc.669
5. Anadon LD, Chan G, Harley AG, Matus K, Moon S, Murthy SL, et al. Making technological innovation work for sustainable development. Proc Natl Acad Sci. 2016;113:9682–90.
6. Stern PC. A reexamination on how behavioral interventions can promote household action to limit climate change. Nat Commun. 2020;11:918.
7. Axsen J, Plötz P, Wolinetz M. Crafting strong, integrated policy mixes for deep CO 2 mitigation in road transport. Nat Clim Change Nature Publishing Group. 2020;10:809–18.
8. Rogge KS, Reichardt K. Policy mixes for sustainability transitions: an extended concept and framework for analysis. Res Policy. 2016;45:1620–35.
9. Kern F, Rogge KS, Howlett M. Policy mixes for sustainability transitions: new approaches and insights through bridging innovation and policy studies. Res Policy. 2019;103832.
10. Levin K, Cashore B, Bernstein S, Auld G. Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. Policy Sci. 2012;45:123–52.
11. Rosenbloom D, Markard J, Geels FW, Fuenfschilling L. Why carbon pricing is not sufficient to mitigate climate change—and how

"sustainability transition policy" can help. Proc Natl Acad Sci. 2020;5.
12. Geels FW, Sovacool BK, Schwanen T, Sorrell S. Sociotechnical transitions for deep decarbonization. Science. 2017;357:1242–4.
13. Rosenbloom D. Engaging with multi-system interactions in sustainability transitions: a comment on the transitions research agenda. Environ Innov Soc Transit. 2020;34:336–40.
14. Langhelle O, Meadowcroft J, Rosenbloom D. Politics and technology: deploying the state to accelerate socio-technical transitions for sustainability. In: Meadowcroft J, Banister D, Holden E, Langhelle O, Linnerud K, editors. What Sustain Dev Our Common Future Thirty [Internet]. S.l.: Edward Elgar Pub; 2019. p. 239–59. Available from: https://doi.org/10.4337/9781788975209.00024
15. Meadowcroft J. Let's get this transition moving! Can Public Policy. 2016;42:S10–7.
16. Roberts C, Geels FW, Lockwood M, Newell P, Schmitz H, Turnheim B, et al. The politics of accelerating low-carbon transitions: towards a new research agenda. Energy Res Soc Sci. 2018;44:304–11.
17. Meadowcroft J. Engaging with the politics of sustainability transitions. Environ Innov Soc Transit. 2011;1:70–5.
18. Kivimaa P, Hyysalo S, Boon W, Klerkx L, Martiskainen M, Schot J. Passing the baton: How intermediaries advance sustainability transitions in different phases. Environ Innov Soc Transit. 2019;31:110–25.
19. Gliedt T, Hoicka CE, Jackson N. Innovation intermediaries accelerating environmental sustainability transitions. J Clean Prod. 2018;174:1247–61.
20. Matschoss K, Heiskanen E. Making it experimental in several ways: the work of intermediaries in raising the ambition level in local climate initiatives. J Clean Prod [Internet]. 2017 [cited 2017 Sep 16]; Available from: http://www.sciencedirect.com/science/article/pii/S0959652617304729
21. Meadowcroft J, and contributors. Pathways to net zero: a decision support tool. Ottawa: The Transition Accelerator; 2021 p. 120. Report No.: Volume 3 Issue 1.
22. Meadowcroft J, Layzell D, Mousseau N. The Transition Accelerator: building pathways to a sustainable future. Ottawa: The Transition Accelerator; 2019. p. 65.
23. Markard J, Raven R, Truffer B. Sustainability transitions: an emerging field of research and its prospects. Res Policy. 2012;41:955–67.
24. Köhler J, Geels FW, Kern F, Markard J, Onsongo E, Wieczorek A, et al. An agenda for sustainability transitions research: state of the art and future directions. Environ Innov Soc Transit. 2019;31:1–32.
25. Geels FW. Co-evolution of technology and society: the transition in water supply and personal hygiene in the Netherlands (1850–1930)—a case study in multi-level perspective. Technol Soc. 2005;27:363–97.
26. Geels FW. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy. 2002;31:1257–74.
27. Geels FW. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). Technol Anal Strateg Manag. 2005;17:445–76.
28. Geels FW. From sectoral systems of innovation to socio-technical systems. Res Policy. 2004;33:897–920.
29. Foxon TJ, Hammond GP, Pearson PJG. Developing transition pathways for a low carbon electricity system in the UK. Technol Forecast Soc Change. 2010;77:1203–13.
30. Hofman PS, Elzen B, Geels FW. Sociotechnical scenarios as a new policy tool to explore system innovations: Co-evolution of technology and society in the Netherlands electricity domain. Innov Manag Policy Pract. 2004;6:344–60.
31. Berkhout F. Technological regimes, path dependency and the environment. Glob Environ Change. 2002;12:1–4.
32. Geels FW. Major system change through stepwise reconfiguration: a multi-level analysis of the transformation of American factory production (1850–1930). Technol Soc. 2006;28:445–76.
33. Rosenbloom D, Meadowcroft J. The journey towards decarbonization: exploring socio-technical transitions in the electricity sector in the province of Ontario (1885–2013) and potential low-carbon pathways. Energy Policy. 2014;65:670–9.
34. Rip A, Kemp R. Technological change. In: Rayner S, Malone EL, editors. Hum Choice Clim Change Vol II Resour Technol [Internet]. Columbus, OH: Battelle Press; 1998 [cited 2015 Nov 14]. p. 327–99. Available from: http://doc.utwente.nl/34706/
35. Rip A. Introduction of new technology: making use of recent insights from sociolcmgy and economics of technology. Technol Anal Strateg Manag. 1995;7:417–32.
36. Geels FW, Schot J. Typology of sociotechnical transition pathways. Res Policy. 2007;36:399–417.
37. Geels FW, Kern F, Fuchs G, Hinderer N, Kungl G, Mylan J, et al. The enactment of socio-technical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014). Res Policy. 2016;45:896–913.
38. Kemp R, Schot J, Hoogma R. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol Anal Strateg Manag. 1998;10:175–98.
39. Fuenfschilling L, Truffer B. The interplay of institutions, actors and technologies in socio-technical systems — an analysis of transformations in the Australian urban water sector. Technol Forecast Soc Change. 2016;103:298–312.
40. Smith A, Stirling A, Berkhout F. The governance of sustainable socio-technical transitions. Res Policy. 2005;34:1491–510.
41. Papachristos G, Sofianos A, Adamides E. System interactions in socio-technical transitions: extending the multi-level perspective. Environ Innov Soc Transit. 2013;7:53–69.
42. Rosenbloom D. Pathways: an emerging concept for the theory and governance of low-carbon transitions. Glob Environ Change. 2017;43:37–50.
43. Rotmans J, Kemp R, Van Asselt M. More evolution than revolution: transition management in public policy. foresight. 2001;3:15–31.
44. Markard J, Geels FW, Raven R. Challenges in the acceleration of sustainability transitions. Environ Res Lett. 2020;15:081001.
45. Loorbach D, Frantzeskaki N, Avelino F. Sustainability transitions research: transforming science and practice for societal change. Annu Rev Environ Resour. 2017;42:599–626.
46. Asquith M, Backhaus J, Geels FW, Golland A, Kemp R, Lung T, et al. Perspectives on transitions to sustainability. Copenhagen: European Environment Agency; 2017.
47. Victor DG, Geels FW, Sharpe S. Accelerating the low carbon transition: the case for stronger, more targeted and coordinated international action. London: UK Department for Business, Energy and Industrial Strategy; 2019.
48. Raven R, Ghosh B, Wieczorek A, Stirling A, Ghosh D, Jolly S, et al. Unpacking sustainabilities in diverse transition contexts: solar photovoltaic and urban mobility experiments in India and Thailand. Sustain Sci. 2017;12:579–96.
49. Raven RPJM. Strategic niche management for biomass: a comparative study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark. Eindhoven: Technische Universiteit Eindhoven; 2005.

50. Smith A, Raven R. What is protective space? Reconsidering niches in transitions to sustainability. Res Policy. 2012;41:1025–36.
51. Schot J, Geels FW. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Technol Anal Strateg Manag. 2008;20:537–54.
52. Naber R, Raven R, Kouw M, Dassen T. Scaling up sustainable energy innovations. Energy Policy. 2017;110:342–54.
53. Rosenbloom D, Meadowcroft J, Sheppard S, Burch S, Williams S. Transition experiments: Opening up low-carbon transition pathways for Canada through innovation and learning. Can Public Policy. 2018;44:368–83.
54. Kivimaa P, Hildén M, Huitema D, Jordan A, Newig J. Experiments in climate governance – a systematic review of research on energy and built environment transitions. J Clean Prod. 2017;169:17–29.
55. Bai X, Roberts B, Chen J. Urban sustainability experiments in Asia: patterns and pathways. Environ Sci Policy. 2010;13:312–25.
56. Loorbach D. Transition management: new mode of governance for sustainable development. Utrecht: International Books; 2007.
57. Kemp R, Loorbach D, Rotmans J. Transition management as a model for managing processes of co-evolution towards sustainable development. Int J Sustain Dev World Ecol. 2007;14:78–91.
58. Loorbach D, Rotmans J. The practice of transition management: examples and lessons from four distinct cases. Futures. 2010;42:237–46.
59. Smith A, Kern F, Raven R, Verhees B. Spaces for sustainable innovation: solar photovoltaic electricity in the UK. Technol Forecast Soc Change. 2014;81:115–30.
60. Rosenbloom D, Berton H, Meadowcroft J. Framing the sun: a discursive approach to understanding multi-dimensional interactions within socio-technical transitions through the case of solar electricity in Ontario. Canada Res Policy. 2016;45:1275–90.
61. Hess DJ. The politics of niche-regime conflicts: Distributed solar energy in the United States. Environ Innov Soc Transit. 2016;19:42–50.
62. Geels FW. Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. Tyfield D, Urry J, editors. Theory Cult Soc. 2014;31:21–40.
63. Turnheim B, Geels FW. Regime destabilisation as the flipside of energy transitions: lessons from the history of the British coal industry (1913–1997). Energy Policy. 2012;50:35–49.
64. Kivimaa P, Kern F. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res Policy. 2016;45:205–17.
65. Kivimaa P, Laakso S, Lonkila A, Kaljonen M. Moving beyond disruptive innovation: a review of disruption in sustainability transitions. Environ Innov Soc Transit. 2021;38:110–26.
66. Turnheim B, Geels FW. The destabilisation of existing regimes: confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). Res Policy. 2013;42:1749–67.
67. Isoaho K, Markard J. The politics of technology decline: discursive struggles over coal phase-out in the UK. Rev Policy Res [Internet]. 2020 [cited 2020 May 13];n/a. Available from: http://onlinelibrary.wiley.com/doi/abs/https://doi.org/10.1111/ropr.12370
68. Rosenbloom D. Framing low-carbon pathways: a discursive analysis of contending storylines surrounding the phase-out of coal-fired power in Ontario. Environ Innov Soc Transit. 2018;27:129–45.
69. Meckling J, Nahm J. The politics of technology bans: industrial policy competition and green goals for the auto industry. Energy Policy. 2019;126:470–9.
70. van Oers L, Feola G, Moors E, Runhaar H. The politics of deliberate destabilisation for sustainability transitions. Environ Innov Soc Transit. 2021;40:159–71.
71. Kuzemko C, Lockwood M, Mitchell C, Hoggett R. Governing for sustainable energy system change: politics, contexts and contingency. Energy Res Soc Sci. 2016;12:96–105.
72. Cherp A, Vinichenko V, Jewell J, Brutschin E, Sovacool BK. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. Energy Res Soc Sci. 2018;37:175–90.
73. Johnstone P, Newell P. Sustainability transitions and the state. Environ Innov Soc Transit. 2018;27:72–82.
74. Hekkert MP, Janssen MJ, Wesseling JH, Negro SO. Mission-oriented innovation systems. Environ Innov Soc Transit. 2020;34:76–9.
75. Schot J, Steinmueller WE. Three frames for innovation policy: R&D, systems of innovation and transformative change. Res Policy. 2018;47:1554–67.
76. Busch J, Foxon TJ, Taylor PG. Designing industrial strategy for a low carbon transformation. Environ Innov Soc Transit. 2018;29:114–25.
77. Johnstone P, Rogge KS, Kivimaa P, Farné Fratini C, Primmer E. Exploring the re-emergence of industrial policy: perceptions regarding low-carbon energy transitions in Germany, the United Kingdom and Denmark. Energy Res Soc Sci. 2021;74:101889.
78. Foxon TJ, Pearson PJG, Arapostathis S, Carlsson-Hyslop A, Thornton J. Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future. Energy Policy. 2013;52:146–58.
79. Rosenbloom D, Haley B, Meadowcroft J. Critical choices and the politics of decarbonization pathways: exploring branching points surrounding low-carbon transitions in Canadian electricity systems. Energy Res Soc Sci. 2018;37:22–36.
80. Hess DJ. Sustainability transitions: a political coalition perspective. Res Policy. 2014;43:278–83.
81. Rosenbloom D, Meadowcroft J, Cashore B. Stability and climate policy? Harnessing insights on path dependence, policy feedback, and transition pathways. Energy Res Soc Sci. 2019;50:168–78.
82. Schmidt TS, Sewerin S. Technology as a driver of climate and energy politics. Nat Energy [Internet]. 2017 [cited 2017 Dec 11];2. Available from: https://www.nature.com/articles/nenergy201784.epdf?author_access_token=PLwaUzRzuLuaeAZwcFfufdRgN0jAjWel9jnR3ZoTv0OGh7T-xtHMOF-GsmUWY57YIOdmXLovj_KGA5qzOSaiAqIUqalqtjnfBRpQRkmA-6keUF6Lvjtt7oCRxtWDOhAQQvY0tIoY_P-XBJQCcx_0VQ==
83. Jacobsson S, Lauber V. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. Energy Policy. 2006;34:256–76.
84. Markard J, Rosenbloom D. Political conflict and climate policy: the European emissions trading system as a Trojan Horse for the low-carbon transition? Clim Policy Taylor & Francis. 2020;20:1092–111.
85. Hargreaves T, Hielscher S, Seyfang G, Smith A. Grassroots innovations in community energy: the role of intermediaries in niche development. Glob Environ Change. 2013;23:868–80.
86. Kivimaa P. Government-affiliated intermediary organisations as actors in system-level transitions. Res Policy. 2014;43:1370–80.
87. Kivimaa P, Bergek A, Matschoss K, van Lente H. Intermediaries in accelerating transitions: introduction to the special issue. Environ Innov Soc Transit. 2020;36:372–7.
88. Kivimaa P, Boon W, Hyysalo S, Klerkx L. Towards a typology of intermediaries in sustainability transitions: a systematic review and a research agenda. Res Policy. 2019;48:1062–75.
89. Seyfang G, Hielscher S, Hargreaves T, Martiskainen M, Smith A. A grassroots sustainable energy niche? Reflections on community energy in the UK. Environ Innov Soc Transit. 2014;13:21–44.

90. Sovacool BK, Turnheim B, Martiskainen M, Brown D, Kivimaa P. Guides or gatekeepers? Incumbent-oriented transition intermediaries in a low-carbon era. Energy Res Soc Sci. 2020;66:101490.
91. Frantzeskaki N, Bush J. Governance of nature-based solutions through intermediaries for urban transitions – a case study from Melbourne. Australia Urban For Urban Green. 2021;64:127262.
92. Van Boxstael A, Meijer LLJ, Huijben JCCM, Romme AGL. Intermediating the energy transition across spatial boundaries: cases of Sweden and Spain. Environ Innov Soc Transit. 2020;36:466–84.
93. Lof J, MacKinnon C, Martin G, Layzell DB. Survey of heavy-duty hydrogen fuel cell electric vehicles and their fit for service in Canada. Calgary: The Transition Accelerator; 2020 p. 87.
94. Layzell DB, Lof J, Young C, Leary J. Building a transition pathway to a vibrant hydrogen economy in the Alberta Industrial Heartland. Transition Accelerator; 2020 p. 71.
95. Layzell DB, Young C, Lof J, Leary J. Towards net-zero energy systems in Canada: a key role for hydrogen. Calgary: The Transition Accelerator; 2020 p. 53.
96. The Transition Accelerator. Alberta Industrial Heartland Hydrogen Task Force [Internet]. Transit. Accel. 2020 [cited 2021 Oct 7]. Available from: https://transitionaccelerator.ca/our-work/hydrogen/alberta-industrial-heartland-hydrogen-task-force/
97. UK Committee on Climate Change. Hydrogen in a low-carbon economy [Internet]. London: Committee on Climate Change; 2018. Available from: https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/. Accessed 20 Aug 2021.
98. Canada Grid. About [Internet]. Réseau Can. Grid. 2021 [cited 2021 Oct 7]. Available from: https://www.canadagrid.org/about
99. Accelerate. About Accelerate [Internet]. Can. ZEV Supply Chain Alliance. 2021 [cited 2021 Oct 7]. Available from: https://acceleratezev.ca/about-accelerate/