Influences on energy supply infrastructure: a comparison of different theoretical perspectives

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Abstract

Changes to the energy supply infrastructure are a vital component of climate change mitigation strategies. But what exactly underlies changes to energy supply infrastructure? This paper, through exploration and critical analysis of relevant literature, explores the various underpinning influences on energy infrastructure supply using a comparison of different theoretical perspectives. These influences were explored with specific emphasis on techno-economics, social psychology, socio-technical transitions, social practices and institutional dimensions to energy supply. The aim was to have a better understanding of the (direct and indirect) role of politics and the political system in influencing energy supply infrastructure decisions through the various theoretical lenses. The study revealed that techno-economics uses financial instruments and market information as intervention tools. Its effectiveness is measured by social welfare and cost effectiveness. Social psychology uses a combination of information, incentives and innovative informative instruments as its intervention tools. Its effectiveness is measured by behavioural change. Institutions use regulatory instruments as its intervention tool. Its effectiveness is measured by regulatory compliance. Social practices look at change in broader social systems. Its effectiveness is measured by social change. Socio-technical transitions focus on determining social movements and social innovations. Its effectiveness is measured by legitimacy and social learning.

Keywords:

Sustainable energy; Techno-economics; Sustainability; Energy transitions; Infrastructure; Energy conservation

1 INTRODUCTION

Over recent decades, there has been considerable effort dedicated to better evaluating the empirical and theoretical contributions of energy supply infrastructure to economic growth and development [1–3]. Connected to this, attention has also been given to the connection between infrastructure and poverty [4]. Even though current literatures on these topics appear completely distinct a consensus has been reached [5] that, under the right conditions, energy infrastructure development can play a major role in economic development through promoting growth.

A considerable part of today's prosperity rests on stable and secure access to energy [6]. For example, as experienced in most parts of the developing world - particularly in Africa - modern production grinds to a halt without the requisite energy infrastructure. Indeed Sorrell [7] argues that infrastructure has major implications for a variety of development outcomes at three different levels: (1) the household level, through social mobility, education and health; (2) the firm level, through industrial development and productivity; and (3) the global level, through climate change issues. However, what underlies changes in energy infrastructure provision, and to what extent would the research community (dis)agree over such changes/influences? It is in this way that *theory* needs discussion; “theory is a statement of concepts and their interrelationships that shows how and/or why a phenomenon occurs” (pg.12)[8].

Based on this context, the purpose of this paper is to critically review different understandings of the various factors, elements, processes and systems involved in the energy supply infrastructure provision. Specifically, this review analyses the theoretical reasoning of five perspectives, each of which puts forward its own rationale for explaining how new energy supply infrastructure has come to be:

1. Techno-economics
2. Social psychology
3. Theories of practice
4. Institutions
5. Socio-technical transitions

It is important to acknowledge that different perspectives exist beyond these five. Nevertheless these five perspectives span the range of the micro, meso and macro, in terms of conceptual and analytical foci. These perspectives also, in many ways, epitomise some of the current dominant trends in distinct social science disciplines: techno-economics reflects Neoclassical Economics and some aspects of Behavioural Economics; Social Psychology is indeed a discipline too, as well as a perspective; institutional perspective reflect traditions in Political Science that examine the organisation and dynamics within the political and policymaking institutions; theories of practice is very prevalent in current Sociology research; and the socio-technical transitions perspective reflects much of the current thinking in parts of Innovation Studies and Science and Technology Studies. Relatedly, it is important to acknowledge that other perspectives exist within these disciplines too, such as how some traditional sociological perspectives may prioritise the division and distribution of labour across society [9], or indeed other social structural issues such as the class or gender. Nevertheless, selecting these five approaches serves to give the reader a taster of the different assumptions and approaches that may be utilised when researching and conceptualising change in infrastructure – ultimately, it is for the reader to reflect on their own point of departure, as part of facilitating the adoption of a considered position.

This review explores how each theoretical perspective may broadly seek to explain changes in energy supply infrastructure, in addition to simply providing an overview of some key findings from each set of literature. Moreover, the purpose of this paper is intentionally not to advocate for one particular theoretical perspective, but instead, to make clearer the salient questions and underlying assumptions for various perspectives.

In this review, the concept of energy supply infrastructure is first introduced for background context purposes (section 2), the materials and methods utilised are presented (section 3), and subsequently the various influences are presented, as per the various theoretical perspectives (section 4). The exploration of the various perspectives starts with those that are linked more with individual cognition (techno-economics and social psychology), before moving to discuss those perspectives that are based more on social context (socio-technical transitions). It also considers two perspectives that situated in the middle ground between these individualistic and social structural perspectives. These two middle ground perspectives are focussed on social practices and institutional dimensions. The paper then finishes by identifying and discussing how these perspectives try to address the changes in energy infrastructure (section 5).

2. BACKGROUND: WHAT IS ENERGY SUPPLY INFRASTRUCTURE?

There is currently no universally accepted definition as to what energy supply infrastructure is. However, many authors have provided explanations to various subsets of energy infrastructure, with examples including electricity infrastructure [10]; petroleum infrastructure [11]; natural gas infrastructure [12]; renewable energy infrastructure [13,14]. Based upon this fragmented set of literatures, we hereby define energy infrastructure as representing the (small- and large-scale) enablers that help, directly or indirectly, with the extraction, production, transportation, and management of energy from producer to consumer. In line with this definition, also included are traditional utilities associated with energy management and transport, such as: coal fired trains [15], electricity transmission lines [16], electricity generation plants [17], and oil and gas pipelines [11]. It also includes large-scale energy management technologies such as: smart grids [18,19], smart building technologies [20], modern power plants control systems, and advanced electricity distribution and metering systems [21,22].

We argue that energy supply, in its strictest sense, is *not created* out of nothing but is inevitably *influenced* in an active and often iterative way. It is exactly this discussion that this review will contribute to. Indeed, there are many ways in which 'influences' can be said to arise and be said to shape the physical outcomes of and likely directions for energy supply infrastructure. Consequently, different perspectives will give agency to different sources, actors, evidence bases, and also inherently disagree with regard to its treatment of context (e.g. in ontological and epistemological terms) and scale.

3. MATERIAL AND METHODS

This paper critically considers existing published literatures in order to understand the various influences underpinning energy supply infrastructure decisions, within and outside of the political sphere. Some of the literatures include the International Energy Agency (IEA) world energy investment outlook report 2014, the IEA world energy outlook special report 2015, published literatures from different sources in the fields of theories of practice, socio-technical transitions, social psychology, techno-economics and institutional theory in order to understand the contribution of these fields to the understanding of energy supply infrastructure decisions and provisions. A snowballing strategy was employed as part of identifying the relevant literature for consideration and, inevitably, not all the papers that were considered are actually included within this review paper.

In investigating the (deemed) influences on energy supply infrastructure, different strands of literature have been explored. In Table 1, the various perspectives are presented, while highlighting the level with which they tend to operate in practical terms. The units of analyses for the techno-economics and social psychology perspectives exist at the *micro* (individual-scale) level, where the focus is more on the individual. Contrastingly, the units of analyses for the socio-technical transitions perspective exist at the *macro* (societal-scale) level, whereby there is a shift in focus from the 'individual' to social structures and contexts. However, theories of practices and institutional perspectives operate more at the *meso* (middle) level, which provides a middle ground between the individualistic perspectives and the structural perspectives. Table 1 briefly highlights selected papers that implicitly/explicitly represent each of the five perspectives, and as such embody much of the discussion in the following section.

Table 1: Theoretical perspectives, conceptual foci and selected supporting literatures

Levels	Focus	Paradigms/theory	Selected supporting literature
Micro	Individual cognition (individualistic approach)	Techno-economics	Pérez, C., 2004. Technological Revolutions, Paradigm Shifts and Socio-Institutional Change. *Globalization, económic development and inequality an alternative perspective*, pp.217–242. Freeman, C., 2002. Continental, national and sub-national innovation systems: complementarity and economic growth. *Research Policy*, 31, pp.191–211. IEA, 2014. Special Report: World Energy Investment Outlook. *International Energy Agency*. Brown, A. et al., 2016. Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results. *National Renewable Energy Laboratory Technical Report*.
		Social psychology	Stern, P.C., 1992. What psychology knows about energy conservation. *American Psychologist*, 47(10), pp.1224–1232. Weber, E., 2010. Risk attitude and preference. *Wiley Interdisciplinary Reviews: Cognitive Science*, 1(1), pp.79–88. Demski, C. et al., 2015. Public values for energy system change. *Global Environmental Change*, 34, pp.59–69. Parkhill, K. et al., 2011. Transforming the UK Energy System: Public Values, Attitudes and Acceptability. *UKERC Synthesis Report*.
Meso	Middle ground between individualistic and structural approaches	Theories of practice	Shove, E., Watson, M. & Spurling, N., 2015. Conceptualizing connections: Energy demand, infrastructures and social practices. *European Journal of Social Theory*. 18 (3). Shove, E., Pantzar, M. & Watson, M., 2012. The Dynamics of Social Practice: Everyday life and how it changes. *SAGE Publishing*. Shove, E., 2003. Comfort, Cleanliness, and Convenience. The social organization of normality. *Berg Publishers*. Strengers, Y., 2012. Peak electricity demand and social practice theories: Reframing the role of change agents in the energy sector. *Energy Policy*, 44, pp.226–234.
		Institutions	Meyer, J.W. & Rowan, B., 1977. Institutionalized Organizations: Formal Structure as Myth and Ceremony. *American Journal of Sociology*, 83(2). Gao, Y., 2016. Ideas, Institutions and Interests: The Politics of China's Energy Policy Change 1996 - 2015. *PhD Thesis*. Kaminker, C. & Stewart, F., 2012. The Role of Institutional Investors in Financing Clean Energy. *OECD Working Papers on Finance, Insurance and Private Pensions*. Michonski, K. & Levi, M. a, 2010. Harnessing International Institutions to Address Climate Change. *CFR's International Institutions and Global Governance program*.
Macro	Social (structural) contexts	Socio-technical transitions	Verbong, G.P.J. & Geels, F.W., 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. *Technological Forecasting and Social Change*, 77(8), pp.1214–1221. Hodson, M. & Marvin, S., 2010. Can cities shape socio-technical transitions and how would we know if they were? *Research Policy*, 39(4), pp.477–485. Geels, F., 2006. Transitions, transformations and reproduction: dynamics of socio-technical systems. *Flexibility and Stability in EconomicTransformation*, pp.227–256. Geels, F. et al., 2002. Sociotechnical scenarios as a tool for transition policy: An example from the traffic and transport domain. *10th International Conference of the Greening of Industry Network*,

The positioning of these different perspectives will inevitably shape the empirical contributions from each of these respective points of departure. For instance, Table 2 illustratively presents an alternative example of how mobility (transportation) links to the various perspectives and how addressing different points of foci lead to an eventual need for the supply of certain infrastructure.

Table 2: Example of how mobility influences infrastructure supply

Concerns	Points of foci	Underpinning theoretical perspective	Associated infrastructure
How much does it cost to travel from point A to B?	Cost vs benefits	Techno-economics	Payment systems, discount structure, fuel prices, etc.
What risks are there in travelling from point A to B?	Psychological benefits and risk aversion	Social psychology	Safety infrastructure to forestall travel risks and accidents.
What is the organisation of mobility practices in traveling from point A to B?	Elements of practice, inter-practice connections	Theories of practice	Infrastructure design of bus stops, train stations, etc.
What (and who) guarantees my safe travel from point A to B?	Regulatory compliance	Institutions	Traffic systems, road structure, traffic rules, law enforcement agencies, etc.
What causes changes in travel patterns from point A to B?	Systems learning, rates of diffusion	Socio-technical transitions	Maintenance schedules, infrastructure upgrades, alternative routes, etc.

Ultimately, the use of theory as a tool for research investigation helps in three major ways: first, it constitutes that which underpins a research design; secondly, it constitutes that which informs our understanding of the phenomenon under investigation; and finally, it constitutes that which emerges from our study [23].

4. COMPARING PERSPECTIVES: INFLUENCES ON ENERGY SUPPLY INFRASTRUCTURE PROVISION

In this section, the five theoretical perspectives are explored in order to understand the influences on energy supply infrastructure, particularly relating to the provision of new (and the changing of the old) infrastructure. Throughout the section, a prominent thread of the indirect role of politics in influencing increased energy supply infrastructure is also considered. By 'indirect role', we are referring to the various routes by which politics, and individuals within politics, impact energy supply infrastructure above and beyond direct legislation or public investment.

Before going in depth into current research within each perspective (sub-sections 4.1-4.5), Table 3 summarises the overarching foci of each perspective in relation to the issue of energy supply infrastructure provision. It shows the movement in focus of the various theoretical perspectives from individual cognition towards social context/structures. This Table 3 therefore provides a zoom-out contextual overview of this section as a whole.

Table 3: Overview of various theoretical perspectives and their foci

Perspective	Conceptual foci		Overview (in relation to energy supply)
Techno-economics	It focusses on Individuals, markets, prices, and investments with goal-oriented self-interest. It is all based on rational action (choice) in decision-making.	Individual cognition	It sees markets as the main technology driver. It attempts to save energy and improve efficiency by focusing on addressing market failures (such as high cost of externalities, transaction costs, and cost of information) by providing cheaper information, new institutions, and incentives. It uses financial instruments, institutions that correct market failures, and information, as intervention tools. Its effectiveness is measured by social welfare and cost effectiveness.
Social psychology	It focusses on individuals (in the context of social norms) It looks at 'what people think' – beliefs, attitudes, values, and worldviews.		It sees 'what people think' as the main technology driver. It tries to address barriers to energy (savings and efficiency) by providing feedback and information, as well as (social or economic) incentives in suitable combinations and formats. It uses a combination of information and incentives, as well as innovative informative instruments as its intervention tools. Its effectiveness is measured by behavioural change.
Institutions	Focusses on institutional rules, processes and structures. It focuses on organizational rules within institutional frameworks and structures.		It sees institutional workings, rules and organizational dynamics as the main driver of technology. It tries to address issues of energy through regulations and institutional rules (e.g. associated with politics and policy making). It uses regulatory instruments as its intervention tool. Its effectiveness is measured by regulatory compliance.
Theories of practice	It focusses on practices (doings) that are socially organized and have evolved over time. It studies the social organization and performance of activities.		It sees practices as fundamentally involving technology. One commonly used practice theory is one that is based around skills, social expectations and materials (including technologies). It tries to address issues of energy use and production through considering how practices are collectively organized. Its effectiveness is measured by change to how practices are performed.
Socio-technical transitions	It focusses on socio-technical rules, networks and systems of provisions. It studies how systems are organized that makes a technology move from niche to mainstream.	Social context / structures	It sees (changes in) social structures as the main driver of technology. It tries to address issues of energy (savings and efficiency) through reorganization of socio-technical networks, and negotiation. Its effectiveness may be measured by the large-scale (successful) diffusion of an energy infrastructure related innovation.

4.1 Techno-economics of energy infrastructure provision

Techno-economics is a field that delves into the various aspects of the interaction between technology and economics. This perspective argues that most energy infrastructure investment decisions are based on economic processes. It argues that energy investment decisions are more a product of a continuous (conscious) evaluation of cost and benefits, and thereby is based on notions of objective decision-making and rational choice.

Its origins are, in part, tied to the work of Perez and Freeman [24,25], who that technology, together with its supporting institutions, constitutes a techno-economic paradigm. They identified the paradigm as an important element of *new technological styles* which drive engineering and investment decisions. It is also argued that this new technological style induces some sort of best practices/principles which serve as a sort of paradigm for designing the social tools required to grasp the new techno-economic potential, as well as steering institutional change [26].

Considering the aforementioned, it can be argued that the techno-economic paradigm constitute patterns of choices regarding research, development, establishment, and furtherance of technologies [27]. Therefore, a techno-economic paradigm which supports 'green' technologies would induce certain biases in the technological preferences of firms towards environmentally friendly choices. It also influences the choices and preferences of actors in the policy environment, as well as the role of consumers (as per 'voting via purchasing') in setting the research and development agenda of firms. For example, Freeman argues that society made choices on innovation with environmental implications between the 1970s and 1980s [28]. This resulted in the development of bias favouring environmentally friendly technologies, identified in different facets of policy choices, production, and consumption activities as experienced in the beginning of the 1990s.

4.1.1. Energy demand/supply trends: investment and cost dynamics of energy infrastructure.

Different technologies pose different advantages and constraints, particularly associated investment, maintenance, and operational cost. The potential to refine an existing technology and its consequent potential for further cost reduction is determined by the technical maturity of that particular technology. Despite very good energy yield prospects, there are also operational and technological parameters that limit the potential for cost reduction [29]. A good example would be the high associated cost for offshore installation and maintenance of wind turbines, as compared to onshore systems, due to installation conditions and transportation routes [30,31]. Indeed, inasmuch as offshore wind conditions are favourable, the huge cost associated with this technology can scarcely be optimized through technical refinement [32].

The International Energy Agency [33] – an institution which epitomizes the economics of energy infrastructure investments – in its 2014 World Energy Investment Outlook Special Report, argues along the following lines.

- Investments made today determine the future. The level of investment is what determines energy demand, supply, security, climate change, among others interconnected factors [34].
- Energy is becoming very expensive; the capital cost, between 2000 and 2012, to produce one unit of energy has doubled. The cheap energy hubs are becoming less available in the future [30]. This will require higher energy prices to incentivize those investments as capital cost has also doubled and will keep rising going into the future [35].

In the last ten years, the investment surge to meet the rising energy demand, mainly in Asia and developing countries, has led to a greater search for better exploration and production technologies [36]. The shale revolution and investment in the United States and the renewables revolution in Europe are concrete examples [37,38]. In Europe, between 2000 and 2010, half of the total investment in electricity infrastructure came from renewable energies. In the United States today, shale gas production is about 250 billion cubic meters. The IEA's techno-economic argument asserts that it is result of the right policies and investment framework, which supports economic investment in new energy infrastructure provisions, rather than pure econometric and cost-benefit calculations [39]. The IEA further argues that the investment in renewables in Europe is about three times higher than the investment in shale gas production in the Unites States, thus, implying that the increased investments in new energy infrastructure provision is a result of successes and returns on previous investments already made [33].

Investment decisions are also argued as becoming more difficult due to: the rising levels of uncertainty in forms of changing geopolitical alliances in forming energy deals; geopolitical trends that impact on energy production; fluctuations in energy prices and trade dynamics; issues of poor governance and political instability; threats to infrastructural facilities; and other environmental concerns [40]. Considering possible threats to successful investment in new energy infrastructure, the IEA argues that aside from the rising capital investment cost, other major factors include geo-political concerns which highlights the issue of energy security as the stubborn part of the decision-making process [33]. Climate change, which constitutes a change in regional and global climate patterns, is also a factor that has to be considered in the techno-economic choice of energy supply infrastructure [41].

Energy use is highly connected to climate change [42]. There seems to be a big disconnect between the climate change cause and the necessary investment decisions taken today. There are growing public pressures on energy related issues in different parts of the world – such as removal of subsidies on fossil fuel [43,44], building of carbon capture and storage facility [13], and building nuclear power plants – which affect investment decisions. Techno-economists have noticed these changes and threats, and as such, have included them within the boundaries and scope of their cost/benefit calculations and investment decision processes. The growing public pressures are now becoming part of the public and investment agenda, and as such, are being considered by policy makers and not only by investors and economists [45]. Whilst these are still only being treated as externalities that can be objectively quantified within their scenarios of technology transfer, this does suggest that something more than just the techno-economics is in play in influencing the provision of energy infrastructure.

The 2014 global energy system infrastructure investment budget, stood at $1.6 trillion [46]. This is what goes into building power plants, transmission lines, distribution lines, oil fields, gas fields, and other energy infrastructure [47]. This has more than doubled in the past 10 years. However, it has slowed down in the past three years owing partly to the reduction in investment in developing countries outside China, as well as reduced cost of renewable energy (such as solar energy) [48]. By source, about $1 trillion goes to fossil fuels (oil, gas, and coal production, as well as coal, gas, and oil fired power plants) while the rest ($0.6 trillion) goes to renewables, nuclear transmission and distribution. The IEA further argues that in the last 10 years, global renewables investment increased by five times [49]. About 60% of electricity investment came from renewables during the same period. However, in the past 3 years, we have noticed a slowdown, and even a decline in investment cost. The cost of renewables is becoming cheaper and more economical, particularly solar energy. Another contributing factor is the diversion of subsidy funds into massive investment in renewables by many countries which has led to an overall fall in required cost for renewable investment [44,50].

Typical techno-economic questions that are posed when thinking about the future include: how much money is needed to keep the lights on, to drive the kind of cars we use, among other activities, across the next 20 years? In response to such questions, the IEA argues that around $40 trillion is needed to maintain and enhance our energy supply infrastructure between now and 2035, costing around $2 trillion annually [46]. Further, around 40% of this investment will be required to meet the incremental demand growth in energy demand (oil, gas, coal, electricity), while around 60% will be required to compensate the declining oil and gas fields, as well as many power plants retiring (particularly in the western world) [19]. This means we need 60% of the investment to maintain current energy infrastructure, and 40% to add new energy infrastructure [46].

In the oil industry, around 80% of all oil investments are made to compensate for the existing declining oil fields [51]. Oil investment today has not much to do with increasing oil demand; however, it has a lot more to do with the declining oil fields. The aforementioned $40 trillion investment would be much higher if we do not invest in energy efficiency measures [52]. Energy efficiency measure helps to reduce the increasing demand for new energy infrastructure. The IEA argues that about $8 trillion will be required in the next 20 years in energy efficiency investment measures [33]. Today, about $150 billion is what is invested in energy efficiency improvement measures [46].

In terms of ownership, which gives an idea in terms of financing, the IEA report shows that around half of the power plants in the world belong to state owned companies [46]; more than three-quarters of the global oil and gas reserves are owned by state or state owned corporations. This has a lot of implications as the investment decisions would not be based only on the commercial considerations of such investment, but may also be based on implementation of the national energy priorities and strategies of the concerned states [53]. The role of states will be much more pronounced in global energy decisions in the years to come. This indicates that energy infrastructure investment decisions may not be based on economic processes and indices alone. Policy makers and governments are, and will continue to be, very important players in the decision-making process.

In the beginning of the 2000s, around one-third of the global electrical power markets were ruled by the market principles. Today, it has reduced to around 10%. Most of the markets today are regulated and, in the future, less decision will be made under the market rules as it will be even more regulated. Electricity transmission and distribution, renewables and nuclear power, as well as fossil fuels in the emerging economies are highly regulated. Only a small part of the fossil fuel market, in the Organization for Economic Cooperation and Development (OECD) countries, has a look of a competitive market, (i.e., not regulated). However, the market in the real sense, are regulated through institutional dynamics and mechanisms and not through market forces of demand and supply [54].

We argue that these aforementioned considerations of investment, budget, ownership, risks, prices, and markets are clear indicators that decisions on new energy supply infrastructure cannot be based only on pure econometric calculations and considerations. Inasmuch as economic evidence is important, many would argue that policy makers directly influence energy infrastructure decisions, as well as the economic landscape itself. Moreover, these policy makers are also influenced by the opinions of the people they represent, and that of other interest groups – and this is still largely assuming that what is important is the conscious ways that individuals make decisions.

4.1.2. Implications of the techno-economic paradigm.

In this perspective, it is all about the rational choices that are said to underpin economic processes, and there have been many critiques associated with this [55] . The implication of this is that if there is a fall in supply of certain resources, and/or rise in demand of certain resources, certain types of energy infrastructure becomes more expensive. It is the resulting energy infrastructure costs that dictate investment, and thus the energy infrastructure that we end up with. Economic analyses are based on a vast array of assumptions, which often creates a fictive vision of the world that does not reflect reality. For instance, some would argue that the role of politics and the political decision-making process is increasingly influencing how these 'objective' economic decisions are made, in addition to the fact that the strategic priorities of governments can contradict the 'optimal' techno-economic decision (as per, for instance, the IEA reports).

4.2 Social psychology of energy infrastructure provision

In addressing this perspective, a demand-side approach to energy infrastructure supply provision is intentionally adopted. The primary reason for approaching the social psychology of energy infrastructure from a demand-side is because social psychology literature is dominated by studies on energy demand, as opposed to energy supply. Thus, this perspective looks at how social psychology affects demand for energy, and its corresponding impact on energy supply provision. However, we will draw lessons from the demand-side approach to explore energy supply issues later.

Lowering energy consumption can be achieved through energy conservation or energy efficiency [56]. Energy conservation entails modifying a task to achieve it with less energy [57]. Energy conservation, which can take the form of walking or cycling to a destination rather than drive there, or not using air conditioner in one's residence, helps in reducing the need for new energy supply infrastructure. Energy efficiency entails accomplishing the same task with less energy in a much more innovative way, which could take the form of use of different lighting technologies (such as Light Emitting Diodes – LED technology), or driving a simple car that consumes less energy. Energy efficiency [58] has financial gains for the consumers, societal gains for the environment, and reduced needs for building new power plants for utilities. This is important as energy efficiency and energy conservation impact will therefore *reduce* the need for energy supply infrastructure capacity. The following sub-section delves into the interaction between social psychology, energy behaviour, and energy infrastructure provision.

4.2.1. Social psychology, energy behaviour, and energy infrastructure provision.

Much of this literature would say that: for most consumers, energy is invisible and intangible, just like air. It is not used directly and it permeates every aspect of our lives. Its use is habitual and unconscious [59]. It is rarely thought about, but mostly considered when energy bills arrive [35]. Unlike other bills, it seems to most consumers that there is no direct link between energy use and cost [60]. It is unintelligible and complex. The meters and metrics for measurement are unfamiliar to energy consumers. A myriad of devices use energy, such as: mobile phones, home heaters, etc. It is a relatively insignificant subject for most consumers, and they view the monetary value (in relation to the incentives derived) as too small when compared with other bills. It is on the basis of such assumptions and challenges, that many social psychologists may argue for a greater focus on other (psychological) and perhaps less obvious benefits, in driving energy consumption reductions. Relatedly, it is argued that an increased demand for energy, which has led to an increased need for energy supply provision, is embedded in the fact that individual energy consumers are not ready to change their consumption patterns and behaviour [61].

The traditional approach towards achieving energy conservation has been through technological innovations [29,31]. Relating back to the previous section (4.1), another approach is through standard economic theory, which assumes that all people are rational; that they make decisions by weighing the cost and benefits of options; that they act in their self-interest, which underpins the techno-economic paradigm [62]. In order to achieve energy efficiency, it is argued that all that needs to be done is to give information (such as 'saving energy saves money'), or create motivation (mainly through financial incentives), or improve technology designed by engineers. This underpins the techno-economic paradigm; however, the social psychology perspective aims to do more through its conceptualization of the influences that surround the individual. Thus, it is argued that the psychological influences behind human behaviour (e.g. beliefs, attitudes, values) impact the degree to which energy efficiency is embraced, which poses certain barriers to its adoption, and as such, impact more on increased need for energy supply infrastructure. Four major psychological diagnoses that affect energy efficiency technologies, which in turn impact on increased need for energy supply infrastructure, are hereby considered [63]:

- *Many energy choices are automatic and habitual – more like a result of inertia* [64,65]. Many choices have become almost automatic, which are done without thinking, perhaps because we have seen other individuals do them in the same way. Cost-benefit analysis cannot change an automatic behaviour because one will not always stop to do the conscious 'calculations' [66].
- *Fear of problems with new technology – more like uncertainty avoidance* [67]. Some individuals are afraid of change particularly when asked to do something new. The fear that new technologies can come with new forms of hidden hazards or drawbacks that will only be known over time, leads to a situation where individuals may try to avoid actions with high (or indeed any sort of) uncertainties. As such, individuals may tend to be cautious when dealing with new technologies [68,69].
- *Upfront higher costs loom large, and future savings are discounted – more like prospects theory* [70]. The prospects theory describes how individuals respond to potential gains and to potential losses. It touches more on individual's emotional response to losses and gains. Losses loom larger because any kind of product that seem to have a high upfront cost, such as energy efficient products that pays back over time does cost more initially. This discourages people because they are not quite sure if they will still be alive to reap the benefits of the high initial investment cost of energy efficiency measures. Looking at things from a psychological currency perspective, using prospect theory, one could say that the initial investment cost is huge, and the gains come in small increment over time. Additionally, (in the future) the gains will not have the same impact as the initial losses of funds, they get discounted very heavily. It is not seen – psychologically – as a net positive transaction, which is why people don't do it.
- *Savings too small to be worth the attention – more like diminishing returns* [71]. An individual's attention, or interest, is limited regarding energy efficiency measures because of the savings being too small. When they try to add up their monthly savings and discover how little it is in comparison with what their perceived savings ought to be, it discourages them and generally leads to a *business as usual* situation.

Energy efficiency on the demand-side provides less of a need for new energy supply infrastructure. However, the aforementioned social psychological drivers are said to be key contributors to, for instance, an increased demand for new energy supply infrastructure as many individuals are not yet open to changing their energy consumption patterns and behaviour [72]. However, how would individuals respond to changes in energy systems, and what kind of scenarios will people find more acceptable? The next sub-section delves into some of these issues.

4.2.2. Social psychology, policy decisions, and energy systems change.

The social psychological perspective asserts that energy systems transformation is highly influenced by public values, attitudes, and social acceptability. A background consideration is that we will need to change our global energy system over the coming decades, not just because the current energy systems will be reaching their retirement and needs to be replaced, but because we need to do things in a different way [73]. There are three policy reasons why current energy systems will be replaced in the near future:

1. Climate change, and the various commitments by different countries to reduce the effects of climate change [74].

2. Energy security, which is driven by the need to develop energy systems that guarantees continuity of energy services [75].
3. Affordability, which is driven by the need to make energy cheaper for the end user [76].

The three aforementioned policy reasons are often collectively referred to as the 'policy trilemma' around energy systems change, because addressing one may lead to difficulty in addressing another [77]. There is also a fourth driver of energy systems change, which comprises the non-climate change externalities, which deals with environmental issues and an individual's perception of the environmental impacts of energy systems change [78–80]. For example, covering an area with a number of wind turbines will have some implications for the local environment, the people's perception of the landscape, as well as potential aspects of the landscape. These are environmental issues to be taken into account, which evolves from people's values of the land and resources around them [81].

Current thinking on energy systems change tolls the line of *whole systems transformation,* which means thinking about how the whole energy systems might change, and the type of energy systems change that are likely to occur in the future [82]. To meet our policy goals of energy systems change, there will be a need to change things on the supply-side, i.e., production of more renewable energy and new technologies to achieve that, as well as demand-side changes, such as, the way we travel, the manner we provide energy in our homes, etc.

In studying different scenarios of change with respect to energy systems, lots of people are implicated at various points, either as energy producers or consumers, as proponents and protesters (as is the case with some countries where nuclear power is highly objected, particularly since after the major accident in Japan), or votes by citizens for a certain political party that promises particular policies around energy. On the demand-side, individuals also respond differently to particular changes in energy systems, such as in the use of smart metering in the home, electrification of transport, and other technical changes, all of which would require consumers buying into the idea in some way [82].

The next sub-section, delves into the relationship between social psychology (specifically attitudes) and political cultures, which we given attention to because as part of creating the link between those who are making energy policies and the tangible (infrastructural) outcomes of those said policies.

4.2.3. Implications of social psychology - attitudes, political culture, and energy decisions.

Attitudes generally vary across populations. However, behaviours and attitudes may not necessarily correlate well. For instance, social psychological research has shown that generally, in terms of demography, older people tend to be more conservative about change than younger people, and that women tend to be more risk-averse than men [68]. Further, it is precisely the impact of attitudes on energy use that has led to increased demand (and then supply) of energy infrastructure [83]. The increased consumerist tendency of individuals - which is a result of habits, beliefs, and values - is a contributing factor to increased energy use which imparts the increased supply of energy infrastructure.

Essentially, this perspective asserts that just as attitudes influence culture, individual attitudes of policy makers also influences culture in the political sphere. By 'culture', we mean "*those shared beliefs that people learn from society*" [84] (Pg. 3), and there is much evidence that argues that decision-making in politics is influenced by the political culture [85]. And by 'political culture', we mean "*the distinguishing habits, attitudes, and behavioural patterns which characterize a political community*" [84] (Pg. 5). Whilst the political culture in the United States focuses more on individual freedom, some other cultures may be more concerned with other issues such as collective equality [86] - these settings matter for policy decisions that are taken.

Riemer argues that different political systems tend to support different political cultures [87]. They argue along the lines on how different political systems deal with the constant power tussle within a nation and how politics (which is seen more as a struggle for power) and political patterns advance accommodation, promote cooperation, and resolve conflicts in domestic politics [84]. These tensions, necessitated by the political culture, also affects energy infrastructure decisions, which can either favour new energy infrastructure provision, or otherwise.

Energy infrastructure provision are connected with other factors, which directly influence the political culture, such as: climate, kinds of natural resources (as is common in many countries with fossil fuel reserves), population, and the larger environment [88]. Other factors include a nation’s historical experiences, language, art, literature, memories, economics, geography and social norms, which also shape the political culture as well as the cultural ethos. The fundamental agreements and trust - without which politics cannot advance as a civilizing process - is provided by the cultural framework that offers sound rules for the political game [89].

This perspective focuses more on the role of the individual, their habits, and the impact they have on energy infrastructure decisions. Attitudes are influenced by context and are contingent, meaning that attitudes to the same subject can vary under different circumstances. These attitudes are then said to influence and drive behaviour. In the political sphere, it is the attitudes and values of individual actors that are argued as shaping decisions within institutional contexts. Moreover, making decisions strictly on the grounds of social psychology can lead to increased disproportionate supply of an inefficient energy infrastructure mix that may not truly cater for the energy needs of the people since human habits and beliefs keeps changing. As such, the social psychological perspective continues to give agency to the individual (in comparison to the techno-economic perspective), but with more a focus on socially influenced cognition.

4.3 Practices of energy infrastructure provision

This perspective argues that changes in energy infrastructure come about through changes in social practices. It is important to note that there are many theories of practice out there, but, nevertheless, there is a consensus across them that practices (socially organised doings) are what are constitute social order [90]. Across these many theories, one common approach is to construct ‘elements’ as part of artificially conceptualising what exactly makes up a practice [91–93]. This perspective is often presented as being directly at odds with the more individualistic notions seen in techno-economics and social psychological perspectives.

In considering theories of practice with respect to energy infrastructure provision, a consumption/demand side approach can be considered. The demand-side approach is adopted here because the existing literature has predominantly only considered the linkages between social practices and energy infrastructure provision from the demand-side perspective, albeit often only implicitly. However, the review of this section focuses on people’s doings and practices, how it affects demand and consumption of energy and what lessons from this can be drawn to apply to the social practices involved in energy supply infrastructure provision.

4.3.1. Background and origins

There has been an increasing use of the conceptual frameworks, based on ideas from theories of practice, in the study of energy consumption [94]. Shove [95] argues that energy is not used for its own sake. Rather, energy is used to achieve the services that are provided by very particular context-dependent social practices, which are organised across time and space, in addition to having their own specific histories. Relatedly, Warde shows the link between the study of consumption and theories of practice by arguing that social practices inherently involve consumption of resources, such as energy [96].

The works of Bourdieu, Giddens, Shove, and Warde [91,95–102], forms part of the foundation for the theories of practice. Through Giddens' Theory of Structuration, he argues that practices represent that means by which both individuals and social structures are jointly governed. As such, Giddens argues that *'systems'* and *'institutions'* do not exist independently of individual activity, rather they only exist insofar as they are continually produced and reproduced via the duality of structure [99]. He further argues that structures both *enable* and *constrain* action. Structure exists only at the instance where rules and resources are employed in social activity.

Practices are blocks of activities that people share. Many practices require the co-participation of other practices to be performed in a satisfactory way (Røpke 2009). Everyday examples of practices include cooking, cleaning, showering and hosting guests, but practices all exist in less 'everyday' domains. These everyday practices may well be a focus for the demand-side considerations of energy supply infrastructure [105]. However, it is these more 'professional' practices – such as policy making – which would be interesting to explore further in the explicit context of supply-side governance of energy supply infrastructure.

4.3.2. Elements of practices and energy infrastructure provision

Shove and Pantzar, as well as Warde, all agree that there are no generally dominant or accepted lists of elements that constitutes a practice [96,106]. But in this section, we illustrate the theories of practice perspective by intentionally drawing on one specific (and increasingly used) practice theory, which was developed by Shove et al. [93].

Building on the ideas of Reckwitz [93], Shove et al. [91] argue that earlier theories of practice have insufficiently accounted materiality. Consequently, this is incorporated into their (intentionally artificial and streamlined) proposition of three elements, which in turn builds on previous work done by Shove and Pantzar [106]. They argue that these elements come together as socially formed, and infrastructurally mediated, groups of elements: practices. The three elements are as follows:

- *Materials* – this covers all the physical aspects of the performance of a practice, which involves interaction with the human body. Examples therefore include small devices, technologies and large-scale infrastructure, all of which represent something tangible in the world. Therefore, whilst energy supply infrastructure would indeed represent a material, so too would the desks, computers and buildings that the energy policy makers use.
- *Meanings* – this involves the social expectations of a practice. For instance, what does one think of ('image') when they think of a person ('practitioner') performing a particular practice? In many ways, this elements represents the unconscious pull as to why then someone would want to perform the practice in the first place.

- *Competences* – this refers to the practical knowledge and skills that are required to perform the practice. These may be tacitly learnt over time and may even be sensory, or they could be formally learnt through various institutionalised means.

To study energy infrastructure, using theories of practice, is actually to study how practices have changed over time with respect to energy systems, and these elements would be a way in which this perspective would conceptualise the change – i.e. a change to the infrastructure is manifested through a change to the above elements of practice. Ultimately, then, infrastructure and practice cannot be separated.

4.3.3. Implications of social practices: how do energy demand, energy supply infrastructure, and social practices interact?

Shove et al. [106], reiterates that theories of practice is a response to the ever pressing need to comprehend the nature of social change [126]. Through that work, they discussed the emergent dynamics, transformational potential, and reproduction of social practices, as well as the constituting elements and links that are bound with social practices. Some of the key arguments which are relevant to the understanding of human consumption include:

- Practices are composed of materials, meanings, and competences [106]
- Consumption is just a moment in a social practice centred on achieving other targets [96] – which they described as a result of the pursuit of three key targets of convenience, comfort, and cleanliness [109].
- Individuals are not independent agents of rationalized choices but rather merely carriers of various social practices.

The aforementioned postulations have far-reaching implications on how we conceptualize consumption. Holtz argues that within the context of logic, consumption as an end goal does not make sense because it does not have value in and of itself, but rather occurs within and for the sake of other practices [110].

In developing theories of practice further in recent years, there has been a move to better conceptualise large-scale infrastructure. One such example would be how Shove and her colleagues explored the interconnections between energy demand, infrastructure, and social practices [111]. They noted that "*it is true that many infrastructure are massive and easy to spot, but whether above ground or below, and whether large or small, in normal use, infrastructure remain relatively invisible"*. They also specifically identified four shared characteristics of infrastructure and social practices [111]:

- Infrastructure is often (but not always) *connective* - linking different places and having both entry and exit points and usually more than one of these.
- Unlike many appliances and devices, infrastructure typically sustains a range of different practices at once.
- Infrastructure is generally *collective* - the services they provide are usually for more than one user.
- Infrastructure, are often relatively obdurate.

Again, this perspective emphasises the socio-technical nature of the problem, and thus how infrastructures and practices are not only connected, but are responsible for additional connections to other infrastructures and practices. This directly links to Schatzki's notions of a flat ontology [112]. Furthermore, and as already highlighted, extending this framework further could allow for more research on the social practice of policy making itself. For example, the materials, meanings, and competences [106] of policy making, in terms of energy infrastructure provision, could provide a novel alternative framing. But more simply, and in relation to the other perspectives, theories of practice stress that social structures and individual agents are intertwined through practices.

4.4 Institutional dimensions of energy infrastructure provision

In this section, we present the perspective that argues for institutions playing a vital role in the governance of energy infrastructure provision. It argues that the individual actors, irrespective of their orientation, exercise their influence in areas of financing, investment, governance, and decisions making, but – crucially – within institutional frameworks.

In considering the techno-economics of energy infrastructure provision (sub-section 4.1), the argument of Perez was presented that technology, together with its supporting institutions, constitutes a techno-economic paradigm [24]. Perez argues that the changes in technology lead to best practice in the designing of social tools for steering institutional change [24,25]. Institutional change, as well as the introduction of a new pervasive technology marks the beginning of a new techno-economic paradigm [113]. It introduces a strong bias in both organizational and technical innovation, which are increasingly embodied in both software and capital equipment. Perez argues that this cumulative bias tends to lock out alternative technological innovations and trajectories, disguised under prevailing political agendas [24,26]. Energy issues form part of the political agenda within many institutions since the governance of energy affects all in varying degrees.

The Multi-Level Perspective (MLP) – which is a key focus of the following sub-section (4.5) – argues that changes in institutional actors and structures do indeed affect and influence transitions, particularly through decision-making processes that lead to a policy formulation or public decision [114]. However, how have institutions emerged? Within what contexts do institutional actors influence decisions that lead to, and supports, changes and transition in energy use and the kind of energy infrastructure we end up with?

4.4.1. Institutional theory and the rise of institutions.

Institutional theory is a theory that studies how organizations can increase their ability and capacity for a given service, such as the provision of energy supply infrastructure, as well as survive in a competitive environment by satisfying their stakeholders [115]. Institutional influences are primarily situated at the meso-scale, sitting between (and thereby actively connecting) individuals and social structures.

Meyer and Rowan argue that social processes, obligations, or actualities that come to take on a rule-like status in social thought or actions give rise to institutions [116]. Herein, institutions constitute the basic building blocks of social, political, and organizational life. They are said to shape choices, behaviour, and perceptions, through their inclusion of social arrangements, government/governance structures, rules or norms, and ways of thinking in an organization [117].

It is argued that institutions reduce transaction costs to meet social needs, including energy, and that they continue to persist due to costs associated with institutional change, as well as the interests of those embedded within those institutions [118]. Satisfying the interests of actors within institutions also implies that institutions are not always operating in the most optimal and efficient ways. Relatedly, the backbone of institutional theory is survival and social legitimacy [119]. There are organizational and environmental structures that work together to achieve some of the ambitious goals set by institutions. However, since structures originate within institutionalized contexts, activities that are commonplace may be taken for granted, which leads to the ceremonial adoption of some policies, rules, products, and services. The existence of external norms, or rationalized myths [120], helps organizations in shaping their thoughts into actions within their structure, with the aim of protecting the technical form of the institution [121]. When institutions go through this process, organizational isomorphism is created, which ensures its survival [122].

Isomorphism is simply the similarity of shape, form, structure, or identity [123]. With respect to institutions, it is about similarity in structure of institutions [116]. There are three major pillars that help institutions to arise, change, and exist. These are:

1. *Regulative* – This operates by coercive isomorphism, using force or threats to ensure compliance to rules and sanctions.
2. *Normative* – This operates by normative isomorphism, which ensures compliance to social obligations, accreditations, and certifications.
3. *Cognitive* – This operates by mimetic isomorphism, which ensures compliance to things that are generally taken for granted, with prevalence as its major indicator.

Within the 'energy institutions', an example of the *regulative* pillar could be that players within the energy sector involved in resource extraction and production must ensure a safe environment. An example within the *normative* pillar could be the accreditation and certifications by authorized bodies and institutions, guaranteeing that the technical, environmental, operations and technological practices meet the minimum regulatory requirements. The *cognitive* pillar could be that there are qualified professionals involved in the workings of the energy industry [124].

4.4.2. Institutions, policy decision-making, and energy infrastructure supply.

Thinking of how governments go about making decisions naturally raises some questions, such as: does a policy capture the public imagination? Does it tend to benefit the interest of a particular firm or industry over and above another? Does a policy try to shift competitive advantage in ways that benefit domestic firms and harm the profitability of their international competition? In the energy sector, is that the case in terms of energy security, development of resources and infrastructure, or mitigation and adaptation of climate change? [54].

Energy policy issues have a fundamental characteristic which refers to its boundary spanning nature [125]. Energy policy is not just about energy issues. It is affected by decisions taken in the domains of economic policy, environmental policy, security policy, international relations (more generally), and social policy, to name only a few. Thus, the energy policy field provides much more insights than other policy areas for which there are policy activities. The fact that energy policy is a boundary spanning policy field also means that a large number of actors are involved in energy policy with backgrounds from different sectors, such as economic, security, or environmental backgrounds. This indicates that the wide range of strategies used by these actors should be observed in order to understand their workings [126].

With respect to energy supply infrastructure, there are several factors, which pose themselves as challenges that institutional policies will have to directly account for and that will play a vital role in ensuring (or not) a stable future energy supply [83]. These challenges include the following:

1. Hydrocarbon resources will become more difficult to access, and increasingly challenging to produce.

2. Technological requirements will be an increasingly complex and demanding issue, particularly technologies required for greater energy efficiency and energy conservation.
3. Cost of producing and delivering energy will escalate.
4. Demand on current and future infrastructure are growing
5. Human resources may be inadequate to meet projected growth requirements.
6. There are greater and indeterminate environmental constraints

4.4.3. Institutional investors and energy infrastructure supply.

It is generally argued by this perspective that institutional investors are those who will rebuild the energy network. Every technological device that makes up large-scale infrastructure is different, and different technologies have their own stage in the maturity process. However, the sole interest of most investors (with respect to technology) is reliability, simplicity, and consistency of policy. Consistency of policy with respect to energy and energy technologies is what is required to unlock most investment capital through policies that support upfront capital expenditure and lower operating cost [127].

Institutional and private investment in a clean energy economy is crucial. As such, the financing of energy infrastructure to achieve a clean energy economy can be viewed from three main perspectives of institutional, private (individual) investment, and program related investment, such as projects championed by some foundations [128].

With heavy national budget constraints in many countries, policy makers look towards private investments and funding for energy infrastructure provision. Nelson [128], in a recent publication argued that institutional investors in energy participate in one of the following ways:

1. *Investment in corporations* - this is through corporate bonds or equity shares. Nelson argues that institutional investment in corporations has very little impact on energy financing dynamics since most corporations make investment decisions based on their own financial consideration and strategy [128].
2. *Direct investment* – this poses the most difficulty to institutional investors. Direct investment is limited by the skills, expertise, and expense required for such investments.
3. *Pooled investment or investment funds* – investment funds, such as pension funds or insurance, which are funds aggregated from different individual investors for the purpose of investment, are examples. The mechanisms of accessing these funds vary for different institutional investors.

It is then unsurprising that based on all of these arguments that addressing climate change issues and clean energy requires, is said to require significant institutional support and investment – especially because, in past years, government projects have been decreasing year-on-year [129]. Reduced investments by governments are influenced by the rising cost of infrastructure provision [33]. Over time, most governments have been compelled to change their economic and investment models towards energy infrastructure investments and energy infrastructure provision so as to reduce the investment burden off governments, while creating opportunities for private sector participation in energy investment and energy infrastructure provision. This is what has led to a lot of public private partnerships in (energy) infrastructure supply [130]. However, challenges remain in providing stable long term policy frameworks required by the private sector [131]. This is also the reason why development finance institutions are not able to release their capital as much as they want, because, among other reasons, they are funded by governments, and their available funds are limited [132].

4.4.4. *Implications of policy decision-making using the institutional paradigm.*

The core assumption within this perspective is that institutions constitute the framework for all the activities of governance, and thus change to infrastructure comes about through changes to the dynamics within the institutional setup (which, for example, has direct implications for commitment in investment). Indeed institutions have distinct regulatory boundaries defining the scope of their power. Within those boundaries, there are rules that define the nature of those powers, how they ought to be wielded, and to what effect. This implies that during periods of great change or crises, it is often required to reform or renew institutions

An institution can be any particularly large or important association, an organized or established procedure, or a significant relationship or organization in a society or culture. This perspective stresses the need for governance of energy market and energy systems through changes to how key institutions are managed (which will span a mix of public and private actors). Essentially, this perspective stresses the need for a better understanding of the institutional frameworks within which decisions, and therefore energy supply infrastructure decisions, are taken.

4.5 Socio-technical transitions of energy infrastructure provision

This perspective argues that changes to energy supply infrastructure are underpinned by structural changes to the socio-technical systems that they form a part of. It is argued that it is the organization of these systems that need to be investigated to understand how infrastructure transitions, as part of servicing the need of society. This perspective focuses on socio-technical rules and stresses that it is how a system is organized that determines the kind of energy infrastructure we end up with.

4.5.1. *Socio-technical transitions, technological change, and energy infrastructure provision*

Socio-technical transitions represent a joint transformation of coupled technological and social systems, which enables society to realize benefits from technological innovation" [133]. These transitions can occur via various pathways, but often require widespread learning and behavioural change [47,134].

Geels [135] – as a prominent figure in this research area – argues that there are three sectors that are responsible for high energy consumption, thereby driving the need for increased energy supply infrastructure, which are critical in the consideration of socio-technical transitions: (1) housing and energy, (2) food and drink, and (3) mobility – the latter of which we now reflect on further as an illustration. Geels highlighted that when one considers mobility, one notices that there are several infrastructures that are interconnected in order to ensure smooth and easy mobility [136,137]. For example, the use of cars will require more elements to get the car to function (e.g., fuel infrastructure, lifestyles and markets). This reiterates how cars have become embedded in our lifestyles; organized our cities; relied upon for taking our children to school; essential to how we do our shopping; and vital for commuting [138]. Geels further argues that industry structure - and therefore massive economic interests - also plays a role in the car industry (especially as the car industry is still one of the biggest industries). Other interconnected systemic influences would include the maintenance networks (when ones car breaks down), regulations, road infrastructure, and cultural dimensions. Essentially, there are a wide range of elements that need consideration if we are to understand the structuring of socio-technical systems [139].

Geels and colleagues further solidify their arguments by highlighting some of the kinds of systems that should be thought about when considering long-term energy transitions [135,140]:

- *Decentralize micro-generation + smart grids* – Geels argues that this is not just limited to micro-technologies such as solar photovoltaic (PV) cells, micro-wind, heat pumps, etc., but that this shift is also about consumer routines and lifestyles. Once people start generating their own power, they may become more energy aware for instance, and consequently they may start thinking about energy (saving/generation) in different ways [105].
- *District heating + Combined Heat and Power (CHP) + biomass* - This will lead to a shift from our individual heating systems, which are not very efficient, to district heating, where a lot of efficiency can be gained. There will be new infrastructure built in this system, such as piping infrastructure, as well as a new change in billing system. However, Geels argues that this will not lead to a change or a shift in lifestyles but a shift in technology used to achieve the same purpose [141].
- *Battery-electric vehicles + smart grid + vehicle-to-grid* – Geels argues that the millions of batteries that are used in cars can be used for electricity if the wind doesn't blow. He further stresses that this would be seen as part of a wider way in which electricity and transport systems are being interlinked. This, he argues, will be part of a wider system change.
- *Inter-modal transport systems or new transport modes* – Geels argues that this will mean going away from the normal modes of transport – which are having bicycles, cars for individual use, trains, trams, or metro for public use – to the use of different ways of sharing, such as bicycle sharing, car sharing, car-pooling, chartered services, and other intelligent ways of generating more transport modes [142]. This will also translate to shift in ownership, advance bookings, etc.

Technological change tends to involve the improvement of a product or process, which is then used to get a bigger reward for the same amount of work [143]. In this respect, it is then clear that energy systems for electricity generation have undergone technological changes over time. It started (for fossil fuel based systems) with the use of steam engines, then dynamos, internal combustion engines, and later large coal fired power stations and thermal power plants. In the case of renewables, it started with small hydropower plants, later much larger capacity hydro plants, wind turbines, nuclear power, and solar photo-voltaic power systems. Processes or products, such as energy systems, move through technological change in three stages [144]:

1. *Invention* – the creation of a new product or process.
2. *Innovation* – the (early) application of the invention.
3. *Diffusion* - how fast others adopt the innovation.

Following the aforementioned arguments, this perspective acknowledges that changes in social structures are highly influenced by the technology-in-use [145,146], and indeed this is exactly why social and technological systems are conceptually joined together. Indeed, the provision of certain energy supply infrastructure (say electricity or natural gas) is intimately connected to how that infrastructure will be practically used/adopted across society. Thus, energy supply infrastructure provision leads to a situation where there is a shift in the technology used to achieve particular energy services; from *niche* to *mainstream* within the fabrics of the existing regime of social structures.

4.5.2. How do transitions happen? The Multi-Level Perspective (MLP)

Whilst not the only transition theory, we focus here on one commonly used conceptual framework, as part of further illustrating the questions posed by this broader perspective: the multi-level perspective (MLP). The MLP has emerged as a result of increased research in transition management [140,147]. It focuses on changes in institutional actors and structures over time, with three hierarchical levels explicitly considered:

- *Niches* – niches provide a platform for the development of radical innovation, free from excessive external pressures. This is because niche technologies operate at a micro-level with minimal regulatory pressures, which aids the development of new technologies and innovation.
- *Regimes* – this operates at the meso-level. It includes a host of varying number of inter-linked actors from different social groups with varying interests, whose activities are guided by socio-technical rules [141]. It represents the complex array of interconnected technologies, procedures, infrastructure, practices, and institutions, which governs and constitutes technological change.
- *Landscape* – this operates at the macro-level. It is heavily influenced by a broad range of economic, social, cultural, environmental, geographic, and class pressures. At this level, it is argued that changes occur quite slowly due to the presence of multiple external pressures [141].

Geels argues that there are no guarantees that a new novel technology or piece of infrastructure will be used in the mainstream, mainly because of issues to do with experimentation, start-ups and exits, trial and error, loaning, visions and multiple visions, uncertainty about where to go, and the opposition from competing technologies already operating in the mainstream (regime) [142]. Thus, the point of a transition is that point when the internal momentum is maintained, which is represented by a convergence of social, political, and cognitive interests which leads to an agreement on where to go, which makes investors agree to put in their money in it and hence, make things work.

Momentum arises through: learning by doing, course performance improvement, as well as powerful and influential actors putting their support behind the innovation. This acknowledges the role of powerful individuals - who could be political actors - in decision-making. However, Geels argues that this does not happen unless the existing regime starts to fall apart as a result of tensions and cracks, which come through external pressures from a landscape that could include war, oil shocks, crisis, climate change, etc. Geels argues that the whole point of a transition is that you need multiple developments at the same time [140]. It is not enough to have new innovations and clamouring for change, but one needs to also consider the other external contexts.

4.5.3. Implications of decision-making using the socio-technical transitions perspective

In sum, the socio-technical transitions perspective acknowledges the active and iterative relationship between the social and technical worlds, which inevitably has parallels to how the theories of practice define the problem at hand too. A key point here though is that the transitions perspective focuses on how exactly innovations (in this case, technological/infrastructural) emerge, diffuse and subsequently become embedded across society. In considering it in this way, the perspective positions the problem at a macro level in a way that the other perspectives do not.

5 CONCLUDING DISCUSSION

This review explores how each theoretical perspective may broadly seek to explain changes in energy supply infrastructure, in addition to simply providing an overview of some key findings from each set of literature.
Techno-economic perspective would argue that the evidence presented by financial instruments and cost-benefit analyses are directly driving the choices made by key decision-makers in changing energy supply infrastructure. In contrast, the social psychological perspective focuses goes beyond this more rational conceptualisation (as per techno-economics), and thereby considers the attitudes, beliefs and values of those key individual decision-makers. In addition though, there are also insights available through this perspective as to how consumers are operating on the demand-side of things, which of course indirectly shapes the infrastructure required at the other (supply-side) end. Its effectiveness is typically measured by behavioural change. The institutional theoretical perspective focuses on regulatory instruments as drivers of energy supply infrastructure change. Theories of practice consider how change in social practices – which in turn inherently constitute and transcend materials – would dictate changes to energy supply infrastructure. Finally, the socio-technical transitions theoretical perspective focusses on the emergence and diffusion of new technological innovations in the mainstream.

In summary, the key outcomes and conclusions of this study stress the fact that techno-economic theory uses financial instruments, institutions that correct market failures and market information as intervention tools. Its effectiveness is measured by social welfare and cost effectiveness. Social psychology uses a combination of information, incentives and innovative informative instruments as its intervention tools. Its effectiveness is measured by behavioural change. Institutions (and institutional theory) use regulatory instruments as its intervention tool. Its effectiveness is measured by regulatory compliance. Social practices theory looks at change in broader social systems. Its effectiveness is measured by social change. Socio-technical transitions theory focusses on determining social movements and social innovations. Its effectiveness is measured by legitimacy and social learning.

Each of these perspectives offers a useful insight and approach into exploring the various influences on the provision of energy supply infrastructure. A number of these perspectives are more often applied to energy consumption however this paper has attempted to lay out in detail the limitations, characteristics and advantages of each lens as applied to energy production. It does not advocate the use of one perspective over another.

Over the next few decades the energy systems of most countries will require radical change and significant investment. Using a myriad of theoretical perspectives to develop different solutions to achieving this energy transition is important. Understanding when and how to use these perspectives and whether the recommended solutions may be influenced by their use is vital. There is a need for further research on how to combine these perspectives to achieve the best outcome, and how to define the best outcome, in a future energy system that works for all.

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