Policy feedback and path dependence in energy systems

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Sonia Sebastian Pearson was born in Mumbai, India and raised in the United Arab Emirates. She received her Bachelor's degree in Business Administration from Baker College (online), Michigan, USA, and her Master's degree in Social Science (Service Management) from Copenhagen Business School. In addition to being a former TV presenter and entrepreneur, she has extensive industry experience having working in the IT and retail industries in Dubai, UAE.

Living in Azerbaijan, Ukraine, the UK and Denmark and experiencing stark differences in societal approaches towards environmental issues, led Sebastian Pearson to her research in sustainability, and in particular the interaction between culture, politics and sustainable practices.

List of published works

Pearson, S. (2021). The Effect of Renewable Energy Consumption on Economic Growth in Croatia. Zagreb International Review of Economics & Business, Vol. 24 No. 1, 2021. DOI: https://doi.org/10.2478/zireb-2021-0006

Šimurina, J., Pearson, S. (2021). Sectoral energy consumption in Croatia. Conference Proceedings of the 2nd International Conference on the Economics of Decoupling (ICED). Available at https://digitalna.nsk.hr/?pr=i&id=656762

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Abstract

This dissertation examines the role of path dependence, the idea that historical events can lead to unpredictable outcomes, in the dynamics of energy transition. Sustainable energy transitions are slow complex processes that involve institutional and socio-cultural change. Divergence in national transition outcomes can be understood by analysing the long-run consequences of policy choices as a response to exogenous shocks such as oil price increases. The policy dynamics between government, industry groups specifically sustainable energy groups, creates a policy-industry feedback effect that accounts for the rate of progress of sustainable energy transition. The key idea is that renewable energy policy has a a positive effect on the growth of green industry. By targetting externalities, both positive and negative, policies constitute rules of the game and provide a basis for understanding cross-country differences in technology diffusion rates and the resulting differences in green industry developmenthas a contagion effect.

However, this dissertation asserts that policies are selected based on its beneficiaries. Policy feedback and interest group formation form a causal loop that influences policy making with ruling political parties using policies as a strategic tool to increase political support within industries. Sequential decision making and increasing returns in collective preferences then provide conditions for path dependence with feedback processes increasing power asymmetries between industries over time.

Previous studies on the relationship between policy and industry have ignored potential causality or feedback. This dissertation tested for a Granger-causal relationship between renewable energy policy, the green industry and the brown industry in a panel dataset consisting of 36 OECD over the period 1970-2014 which covers key events such as the 1970's oil crises, the adoption of United Nations Framework on Climate Change Convention in Rio in 1992, the Kyoto Protocol in 1997 and the commencement of trading in the EU-ETS in 2005. The regression results confirm the presence of feedback effects that sustain the dominance of fossil fuels while hindering the development of clean energy technologies. The analysis also shows the highly persistent nature of path-dependent processes regardless of technology type.

Key words: Sustainable transition, path dependence, policy feedback, policy-industry feedback, renewable energy, energy systems

Prošereni sažetak

Ova disertacija ispituje ulogu iskustava prethodnih vremenskih razdoblja (engl: *path dependence*) , ideje da povijesni događaji mogu dovesti do nepredvidivih ishoda, u dinamici energetske tranzicije. Tranzicije održive energije spori su složeni procesi koji uključuju institucionalne I socio-kulturne promjene. Razlike u ishodima nacionalne tranzicije mogu se razumjeti analizom dugoročnih posljedica političkih izbora kao odgovora na egzogene šokove kao što je povećanje cijene nafte. Dinamika politike između vlade, industrijskih grupa, posebno grupa za održivu energiju, stvara povratni učinak politike I industrije koji objašnjava stopu napretka tranzicije održive energije. Ključna ideja je da politika obnovljive energije ima pozitivan učinak na rast zelene industrije. Usmjeravanjem vanjskih učinaka, pozitivnih i negativnih, politike predstavljaju pravila igre i daju osnovu za razumijevanje razlika među zemljama u stopama širenja tehnologije, a rezultirajuće razlike u razvoju zelene industrije imaju učinak zaraze.

Međutim, ova disertacija tvrdi da su politike odabrane na temelju svojih korisnika. Povratne informacije o politici (engl: *policy feedback*) i formiranje interesnih skupina čine uzročno-posljedičnu petlju koja utječe na kreiranje politike s vladajućim političkim strankama koje koriste politike kao strateški alat za povećanje političke podrške unutar industrija. Sekvencijalno donošenje odluka i sve veći prinosi u kolektivnim preferencijama tada osiguravaju uvjete za iskustva prethodnih vremenskih razdoblja s povratnim procesima koji povećavaju asimetriju snage između industrija tijekom vremena.

Prethodne studije o odnosu između politike i industrije ignorirale su potencijalnu kauzalnost ili povratne informacije. Ova je disertacija testirala Grangerov uzročni odnos između politike OIE, zelene industrije i smeđe industrije u panel skupu podataka koji se sastoji od 36 OECD-a tijekom razdoblja 1970.-2014. koji pokriva ključne događaje kao što su naftna kriza 1970-ih, usvajanje Okvirnog sporazuma Ujedinjenih naroda o klimatskim promjenamau Riju 1992., Kyotski protokol 1997. godine i početak trgovine u EU-ETS-u 2005. godine. Rezultati regresije potvrđuju prisutnost povratnih učinaka koji održavaju dominaciju fosilnih goriva dok ometaju razvoj tehnologija čiste energije. Analiza također pokazuje vrlo postojanu prirodu procesa iskustava prethodnih vremenskih razdoblja bez obzira na vrstu tehnologije.

Ključne riječi: Tranzicije održive energije, “path dependence”, “policy feedback”, “policy-industry feedback”, povratne informacije o politici, obnovljiva energija, energetski sustav

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1.0 Introduction

Mitigating climate change requires transformation of the global energy sector. Sustainable energy transition refers to the gradual replacement of climate-damaging fossil fuel by renewable energy technologies such as wind and solar power (Aklin & Urpelainen, 2013). These transitions are slow processes (Sovacool, 2016; Berkhout et al., 2012; Fouquet, 2016) and the complex nature of transition requires a multi-disciplinary approach that involves institutional and socio-cultural change (Berkhout et al., 2012). This dissertation examines transition to sustainable energy from an economic perspective. The role of path dependence is explored to understand the dynamics of transition.

1.1 Field of research and research problem

Energy transition is an emerging field of research. Path dependence is the idea that historical events can lead to unpredictable outcomes (David, 2007; Liebowitz & Margolis, 1995). It can be defined as "the set of dynamic processes where small events have long lasting consequences that economic action at each moment can modify yet only to a limited extent" (Antonelli, 1997). Irreversibility, learning processes, feedback and increasing returns play key roles in path dependence literature (Arthur, 1989; Gigante, 2016; Jakimowicz, 2015; Deeg, 2001). Path dependence processes are non-linear and "can be split in multiple steps: each of them follows feedbacks from the external environment which affect decision making processes" (Gigante, 2016; Djelic & Quack, 2007; Dobusch & Kapeller, 2011). Path dependence in energy systems (Aghion et al., 2019; Buhanist, 2015) impact economic development (Fouquet, 2016), therefore policies must be selected carefully.

Achieving energy objectives is a political process

Governmental incentives shape a country's response to international shocks. Sustainable energy transitions are largely initiated by governments who react to exogenous shocks, such as oil price increases, through policy and regulation. Despite facing similar shocks, transitions may diverge among countries because of political competition (Altman, 2000; Aklin & Urpelainen, 2013; Burke & Stephens, 2018). The 1970's oil crisis for example, had an impact on the energy policy of several industrialised countries (Ikenberry, 1986).

Countries like Denmark increased government intervention in its energy policy during this period and focussed on energy efficiency, diversifying supply and building competence (Hvelplund, 2014). The accumulated benefits of these choices led to Denmark becoming the world's leading renewable energy consumer. Thus, analysing the long-run consequences of policy choices can deepen our understanding of energy transition.

1.2 Research objective

This dissertation examines sustainable energy transition and path dependence from an economic perspective. An international comparative perspective is employed to empirically analyse how energy transition is influenced by political factors. Sustainable energy transitions are slow and difficult because of the complexity of energy systems. Understanding the dynamics of sustainable energy transition is key to climate change mitigation. The primary question explored is how states get to where they presently are in the sustainable energy transition. Starting in 1973 and facing the same exogenous oil shock, how did the countries examined get to where they are today with regards to the sustainable energy transition? The underlying hypothesis is that the respective government's choice of energy policy increases or decreases the size of the sustainable energy industry.

The literature review indicates a gap in empirical studies of path dependence in energy policy. This research proposes that a policy-industry feedback effect accounts for the shift in energy policy and sustainable energy transition. Policy choice following an energy shock such as the oil crisis or the Kyoto Protocol is dependent on the governments' reaction to the shock as well as the lobbying efforts of the sustainable energy interest group. The underlying argument of this dissertation is that transition to sustainable energy depends on how governments react to exogenous shock. The reaction is based on the strength of the sustainable energy interest group and the resulting policy further increases or decreases the strength of the interest group. To that end, this dissertation tries to answer the following question:

Does policy feedback explain path dependence?

1.3 Theory and Hypothesis Specification

Based on the literature review, we put forward three hypotheses about renewable energy development. The first hypothesis (H1) relates to the effects of renewable energy (RE) policy on renewable energy development while the second (H2) refers to interest groups politics. An increase in industry size results in increased pressure by the corresponding interest group on the government. Together, the two hypotheses lead to the third hypothesis (H3) that a feedback effect exists between policy and industry. The notion of policy feedback is used to study the evolution of the energy industry.

1.3.1 Hypothesis 1: The effect of policy

H1: RE policy has a positive effect on the green industry

Innovation, diffusion and technological change

Decarbonising the energy system can be achieved by motivating technological change and innovation. Technological change requires breaking away from the dominant design (Anderson & Tushman, 1990). Schumpeterian creative destruction refers to the mechanism by which new products replace old ones (Schumpeter, 1943) through the processes of invention, innovation and diffusion. In innovation: "path dependence shows the endogenous character of technological change" (Gigante, 2016). The diffusion of innovation has long been understood in terms of increasing returns (Antonelli, 1997). Diffusion rates depend on socio-economic, technological and institutional factors and are usually slow (Simurina & Tolic, 2008). Governments and the regulatory framework play an important role in diffusion (Chen, 2018; Rennings, 2000; Popp et al., 2009; Schaffer & Bernauer, 2014; Tirole, 2015).

One way to bring about technological change is to "change the structure of economics incentives: tax negative externalities and reward positive externalities"(Kemp et al., 1998). However taxes are not always successful in achieving environmental objectives (Šimurina & Šimurina, 2015). Instead, successful governments intervene in sustainable transition, support diversity in technology, market formation and R&D in a continuous fashion (Neij & Dannemand Andersen, 2012; Benatia & Koźluk, 2016; Hepburn, 2010; Loiter & Norberg-Bohm, 1999). As energy prices and supply security impact economic growth and prosperity, politics plays a critical role in determining how governments achieve energy objectives (Meadowcroft, 2009).

Energy Policy and renewable energy

Existing regulatory frameworks and infrastructure can form a barrier to the development of new technology (Kemp et al., 1998; Lehmann et al., 2012). Positive correlation observed between energy policy and development of sustainable energy (Gan et al., 2007) provides a basis for understanding cross-country differences in technology diffusion rates and the resulting differences in sustainable energy transition. Policies can be industrial or environmental in nature or have both attributes (Hughes & Urpelainen, 2015). Industrial policies benefit specific industries while environmental policies impose costs to reduce carbon emissions. Energy-related climate policies (Hughes & Urpelainen, 2015) aimed at reducing carbon emissions can support the sustainable energy transition. Boosting the sustainable energy industry has a contagion effect.

Policies and the allocation of economic resources

Investment in sustainable technology is driven by policy and not market demand (Popp et al., 2011). Policies constitute important rules of the game and influence the allocation of economic resources by producing incentives. These incentives "influence the probability of particular outcomes and the payoffs attached to those outcomes" (Pierson, 1993). Although firms make choices independently, governments select policy which creates strong inducements for firms to make particular choices. Thus "public policies often create "spoils" that provide a strong motivation for beneficiaries to mobilize in favor of programmatic maintenance or expansion" (Pierson, 1993). Political conditions impact party preferences in the selection of policies (List & Sturm, 2006; J. Finnegan, 2018). When a political party increases the strength of industry support, it increases its probability of staying in power. At the same time, the future prospects of the industry also get better.

The rate and direction of technological change is influenced by market and regulatory incentives (Chen, 2018; Jaffe et al., 2005). Policies create constraints and incentives that affect the process of technological change (Jaffe et al., 2003). Continuity is an important success factor. 'Stop and go' policies create uncertainty and unfavourable market conditions for investors (Negro et al., 2012; Hepburn 2010) (Helm et al., 2003). Policies impact renewable capacity deployment (Shrimalia & Kniefel, 2011; Lacerda & van den Bergh, 2014) but there is no one-size-fits-all approach (Puig & Morgan, 2013). Renewables portfolio standards (RPS) and required green power options were found to be most effective in the US (Puig & Morgan, 2013) while feed-in tariffs were most successful in Denmark, Spain, Portugal and Germany (Shrimalia & Kniefel, 2011).

Political competition, vote maximisation and government decision making

The economic view of political processes has a long history of research. Persson uses a common agency model to study the activities of special interest groups. Becker (1983) theorises about competition between interest groups for political influence. Alesina and Tabellini (1990) study the use of public debt as a strategic tool for future policy choice.

Politicians are motivated by obtaining and maintaining public support for political survival. Political competition is guided by self-interest and vote maximisation is one of the main goals of incumbent governments. Politicians create policies that benefit their constituencies. As Industry is a source of votes and political contribution (Grossman & Helpman, 1996), energy policy can be used as a strategic choice to gather political support and create or hinder the activities of industry interest groups. When faced with an exogenous shock such an increase in oil-price, a government decides the level of support provided to clean energy. The level of spillover of public support from one government to the next creates environments that foster or hinder the growth of sustainable energy (Aklin & Urpelainen, 2013). Policies can thus be selected on the basis of the benefits and costs imposed on the different industrial sectors. Sequential decision making in conventional economics in the presence of uncertainty and imperfect information present sufficient conditions for path dependence as past decisions or beliefs influence present and future decision processes (Castaldi & Dosi, 2006).

The concept of increasing returns also applies to collective preferences making path dependence applicable to politics. Factors such as the prominence of collective activity; the role of formal, change-resistant institutions; the employment of political authority and the ambiguity of political process and outcomes make the political domain prone to increasing return processes (Pierson, 2000). Mutual interrelation between economic agents coupled with historical events lead to multiple outcomes. However, timing and sequence matter and a wide range of outcomes is possible from relatively small events. Increasing returns can change a balanced political conflict between actors into one where one set of actors imposes preferences through power relations. Further, positive feedback over time increases power asymmetries.

1.3.2 Hypothesis 2: The effect of lobbying

H2: Lobbying by the green and brown industries impacts RE policy
H2a: The green industry has a positive effect on RE policy
H2b: The brown industry has a negative effect on RE policy

The power of interest groups

Policies expand or limit market opportunities for sustainable energy by creating industry interest groups (Meckling, 2018; Svendsen, 2011; Persson, 1998). Collective action (Olson, 1965, pgs 132-135) by interest groups leads to favourable policy outcomes in democratic governments (Grossman & Helpman, 1996; Downie, 2017; Conconi, 2003). These groups influence policy outcomes through campaign contributions and lobbying (Potters & Sloof, 1996; Belloc & Guerrieri, 2008; Bennedsen & Feldmann, 2006). Policies that increase clean energy deployment thus also increase the political influence of related industries (Hughes & Urpelainen, 2015; Jacobsson & Lauber, 2006). The larger the group, the greater the influence (Potters & Sloof, 1996). However, the presence of an oppositional group decreases the influence of the interest group. Competition between the different groups for political influence determines the equilibrium structure of taxes, subsidies and other political favours.

1.3.3 Hypothesis 3: Industry and policy impact each other creating a feedback effect

H3: Bi-directional causality between industry and policy creates a feedback effect
H3a: RE policy has a significant and positive impact on the Green industry
H3b: Green industry has a significant and positive impact on RE Policy (positive feedback)
H3c: Brown industry has a significant and negative impact on RE Policy (negative feedback)

Transition is a complex dynamic phenomenon involving feedbacks between many different agents. Antonelli (1997) proposes that “the economics of path dependence suggests the analysis of the behaviour of agents at any point in time as the outcome of:

1. The structure of events as they were at time t_{-1}; and

2. The part of the structure of events that changes through time.

Understanding the process of path dependence with regards to sustainable energy transition requires studying the interaction of economics and politics.

Increasing returns, positive feedback mechanisms and path dependence

Neoclassical economics focuses on rational agents and static relationships such as supply, demand and price in equilibrium. Change is explored by comparing equilibrium conditions before and after an exogenous shock. The assumption of decreasing returns means economic actions have negative feedback leading to a predictable equilibrium (Pierson, 2000). Negative feedbacks stabilise the economy because "any major changes will be offset by the very reactions they generate (Pierson, 2000). However, the theories of neoclassical economics are insufficient for dealing with the current political, social and economic realities. The limitations of mainstream economics have led to the development of alternative theoretical frameworks such as evolutionary economics (Nelson & Winter, 1982; 2002; Metcalfe, 1994; Fagerberg, 2002) which is inspired by Darwinian theories of evolution. Evolutionary economics focusses on the dynamics of change and emergent features leading to the study of processes rather than outcomes. The path dependence framework is used to study the dynamic process of sustainable transition.

Energy systems are subject to path dependence due to technological, infrastructural, institutional and behavioural lock-ins. According to Sovacool & Sawin (2010) energy technologies gain momentum and market acceptance by coupling technology with social, political and economic factors. Technologies develop into dominant technological regimes (Kemp et al., 1998) and become locked-in (Unruh, 2000). These regimes tend to develop into systems of "related techniques; the economics of process thus depend on the cost of particular inputs and the availability of complementary technologies"(Kemp et al., 1998). The persistence of fossil fuel as the primary source of energy is attributable to the way we generate and use energy as well as the way the infrastructure has developed. This persistence also highlights the interrelationships between generation, supply, transmission and distribution of energy. Positive reinforcement processes are evident. Network industries such as electric utilties are characterised by expensive long-term invesments, network effect and a complex institutional environment which make path dependence likely (Andersson-Skog, 2009, pg 70). Path dependence is a contributing factor to carbon lock-in.

While decreasing returns are common place in industrial systems, Romer (1986) found the returns increase in the knowledge-based system where the marginal productivity of knowledge increases. Arthur (1990) adds to this view with a theory about positive feedback mechanisms that lead to dynamically increasing returns. Further dynamic increasing returns are non-linear and self-reinforcing processes that occur over time (Castaldi & Dosi, 2006). Dobusch and Schüßler (2012) propose that positive feedback mechanisms are at the core of path dependent processes. Technological standardisation such as the QWERTY keyboard have been attributed to positive feedback mechanisms.

For Arthur (1990) the assumption of diminishing returns in neoclassical economics imply a single equilibrium but positive feedback and increasing returns – make for multiple equilibrium points.” In this perspective, identical economies with significant increasing returns sectors do not necessarily converge but might instead diverge. In an increasing returns process, the probability of further steps along the same path increases with each move down that path (Pierson, 2000). Thus, Arthur’s theory portrays the economy as complex, process dependent and always evolving.

Policies create politics and policy feedback

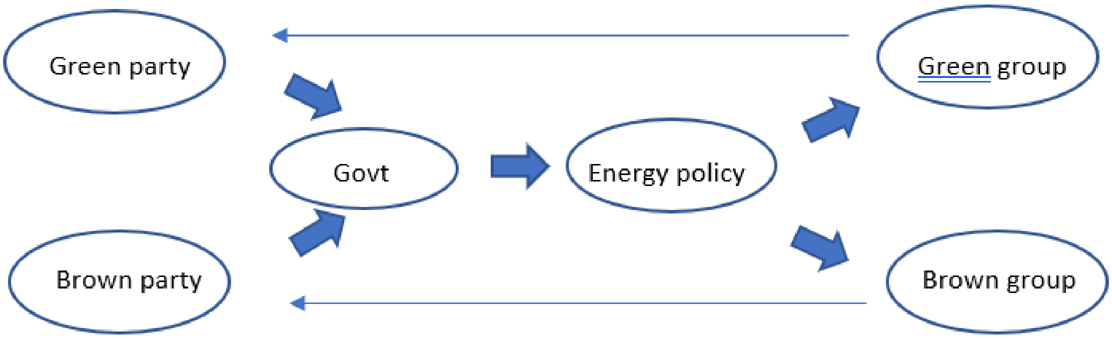
Policy is determined by political and economic self-interest (Aidt, 1998; Besley & Case, 2003; Dumas et al., 2016; Lipscy, 2013). Governments implement policies “that maximise the payoff to the constituencies supporting them” (Aklin & Urpelainen, 2013). Dumas, Rising, & Urpelainen (2014) found that differences in partisan ideology affects energy policy. Strong green constituencies can influence energy policy outcomes when the difference in strength of partisan ideology is low. Thus, policies support interest groups that support sustainable energy (Meckling et al., 2015)

Policy is generally viewed as the result of political forces (endogenous). But policy choices have political consequences. “If interest groups shape policies, policies also shape interest groups” (Pierson, 1993). Policies create politics and feedback both negative (Johnston, 2012) and positive (Mettler, 2002; Kline, 2001) by providing incentives and resources, encouraging collective action and providing access to decision makers (Moynihan & Soss, 2014; Bardach, 2011; Patashnik & Zelizer, 2009). According to Pierson (1993), “The political goals of interest groups may change in response to the nature of the programs they confront and hope to sustain or modify.” The question of who is induced to react depends on the nature of policy. For example, Weir and Skocpol (1985) found that differences between Swedish and U.S. social policies in the 1930s had an effect on farmer/worker political alliances. Further policy designs can help overcome collective action problems for example the political groups that lobby for the elderly have achieved enormous power and success in America (Day, 1990, pg 80). Thus, incentives arising from specific policies may facilitate or inhibit the formation or expansion of particular groups leading to feedback effects. Kelsey (2018) found that the type of industries present help explains initial policy preferences as well as the likelihood that policy feedback can change preferences over time.

Political parties select policies that benefit their supporters (Grossman & Helpman, 1996). These interest groups in turn influence governmental preferences on energy policy creating a feedback loop. A positive feedback loop occurs when change propagates through the system to produce more change in the same direction. The feedback loop then becomes a mechanism that increases the share of clean energy speeding up energy transition. Identifying a feedback loop can be done by examining the period preceding a critical juncture when a variety of options are available (Mahoney, 2000). Choices made during this critical juncture influence choices made after leading to path dependence (Greener, 2005).

1.4 Methodology and Data

Government is a common agent for a group of special interest groups. Policy feedback and interest group formation form a causal loop that influences policy making. The formal model of policy feedback is based on Aklin & Urpelainen’s (2013) model of government choice. In the model, two governments formulate energy policy. One government is pro-sustainable energy (green) while the other is vested in the fossil fuel industry (brown). Each government strategically selects energy policy that increases the strength of the respective industry interest group (see chapter 5 for the formal analysis). This process is illustrated below:



To simplify the analysis, it is assumed that the green interest group simply votes for the green government and brown interest group votes for the brown government.

Kilinc-Ata (2016) notes, "A fixed-effect panel specification is used for testing unobserved heterogeneity." Further, these unobserved sources of renewable heterogeneity are relatively constant over time and therefore can be treated as fixed effects. Following (Kilinc-Ata, 2016) a fixed-effects panel regression will be used to estimate the following equation for **H1: *Renewable energy policy has a positive effect on the green industry***

$$Green_{i,t} = \alpha + \delta\ REpol_{it-1} + \gamma\ X_{i,t} + \upsilon_t + \varepsilon_{i,t} \quad (1)$$

where $Green_{i,t}$ measures the size of the green industry in country *i* at year *t*, $REpol_{it-1}$ measures RE policy instruments in country *i* at year *t*, $X_{i,t}$ denotes a matrix of control variables in country *i* at year *t*, υ_t captures country fixed effects at time t while $\varepsilon_{i,t}$ is the random error term that applies to country *i* at year *t*. Control variables to be included are GDP, trade, oil prices, electricity consumption and population growth. REpol is lagged one year to capture the delay of the policy effect.

A fixed-effect panel specification will also be used to estimate the impact of lobbying on RE policies, **H2a & H2b.** Specifically, the following equation will be estimated:

$$REpol_{i,t} = \alpha + \beta\ Green_{it-1} + \eta\ Brown_{i,t-1} + \gamma\ X_{i,t} + \upsilon_t + \varepsilon_{i,t} \quad (2)$$

where $REpol_{it}$ measures RE policy instruments in country *i* at year ***t*,** $Green_{it-1}$ measures the size of green industry in country *i* at year *t-1*, $Brown_{i,t-1}$ measures the size of the brown industry in country *i* at year *t-1*, $X_{i,t}$ denotes a matrix of control variables in country *i* at year *t*, υ_t captures country fixed effects at time t while $\varepsilon_{i,t}$ is the random error term that applies to country *i* at year *t.* Control variables to be included are GDP, trade, oil prices, electricity consumption and population growth. The Green and Brown variables are lagged one year to capture the delay of the lobbying effect.

Previous studies on the relationship between policy and industry have ignored potential causality or feedback. The goal of this dissertation is to test for a Granger-causal relationship between RE policy, the green industry and the brown industry. These variables will be tested using the Hurlin & Dumitrescu (HD) (2012) panel non-causality test based on the Granger (1969) test for heterogeneous panel data models. Feedback (positive) is expected RE policy and green industry while feedback (negative) is expected between the brown industry and RE policy.

Data

The panel dataset consists of 36 OECD countries which includes 23 EU countries. 5 EU countries viz. Bulgaria, Croatia, Cyprus, Malta and Romania have been excluded due to insufficient data. The time period examined is 1970-2014. The dataset covers a period of 45 years and includes 9105 observations.

To test whether the effect of RE policies varies over time, the sample will be split into 2 periods, 1970-1990 and 1991-2014. The first period represents the period before and after the 1970's oil crisis while the second period reflects trends in the global action on climate change including the adoption of United Nations Framework on Climate Change Convention in Rio in 1992, the Kyoto Protocol in 1997 and the commencement of trading in the EU-ETS in 2005.

Variables

***Green industry**:* Two proxies will be used as measures of green industry are limited:

- Share of renewable energy in electricity is used as a proxy variable.
- Share of green deputies in parliament is used as a second proxy variable as it "captures both people's preferences for environmental quality and a political voice for environmental issues i.e the green lobby" (Nicolli & Vona, 2015).

***Brown industry**:* To capture the political pressure of the brown industry, we use two alternative proxies:

- Size of energy intensive industries such as basic metal, paper and paper products (Cao, 2012).
- Share of labour force employed in the industrial sector (Fredriksson et al., 2007).

Policy measure: Following (Zhao, Tang, & Wang, 2013), we use dummy variables to record the implementation of different policy instruments as instrument type impacts RE investment (Polzin et al., 2015; Yuan et al., 2014). The dummy variable takes on a value of 0 before implementation and 1 after. These dummy variables are then used to construct 3 aggregate measures of RE policy.

- The first *REdum* is a dummy variable taking a value of 1 if the country adopts any of the policy instruments.
- The second variable *REavg* is the average of the policy dummies recorded in each year and normalised to lie within the range of 0 and 1. The last policy variable *REpca* is constructed using principle components to reduce dimensionality. Following (Zhao et al., 2013) only the first component is used as it accounts for 71 percent of the variance of its underlying variables.

***Control variables**:* The following control variables are included:

GDP: The income effect on renewables is well documented. Richer countries are more able to support the development of expensive renewable energy. This variable is measured in per capita terms in 2018 USD.

Trade: Trade openness is documented as influencing renewable energy use. This variable is measured as trade as a percentage of GDP.

Oil price: Higher oil prices have a positive effect on renewable energy growth. This variable is expressed in 2018 USD.
Electricity consumption: Higher levels of electricity consumption are associated with lower usage of more expensive renewable energy. This variable is measured in kWh per capita.
Population growth: Countries with fast growing populations generally have higher energy requirements. This variable is measured as a percentage.

Table 1 shows the definition of variables and sources.

Table 1: Variables and data sources, OECD and EU countries 1970-2014

Variable	Definition	Predicted sign	Source
1. Green	Green industry interest group proxied by: a. share of renewable energy in electricity and measured as a percentage of overall electricity	+ for H1 + for H2	OECD
	b. Share of green deputies in parliament measured as a percentage		Comparative Political Data Set (Armingeon et al., 2019)
2. Brown	Brown industry interest group proxied by: a. the contribution of energy intensive industries to GDP and measured as a percentage	- for H2	OECD STAN database
	b. Share of labour force in the industrial sector and measured as a percentage of the overall labour force		OECD
3. REpol	Energy related climate policy – composite variable ((Zhao et al., 2013)	+ for H1 + for H2	IEA Policy and Measures Database
REdum	Dummy variable taking a value of 1 if the country adopts any of the policy instruments		
REavg	Average of the policy dummies recorded in the 4 categories in each year and normalised to like within the range of 0 and 1		
REpca	Variable is constructed using principle components to reduce dimentionality. Only the first component is used.		
4. I	Country. OECD and EU countries.		
5. T	Time period. 1970-2014		
6. X	Matrix of control variables		
	-GDP measured per capita in 2018 USD		Worldbank,
	- Trade, measured as a percentage of GDP		Worldbank
	- Oil price measured as the price of crude oil per barrel in 2018 USD		BP Statistical Review of World Energy
	- Electricity consumption measured as kWh per capita		Worldbank
	- Population growth measured as an annual percentage		Worldbank
7. υ	Country fixed effects		
8. ε	Error term		

1.5 Contribution

Sustainable energy transition is an emerging area of research. Although some researchers have presented theoretical and computational models, empirical studies remain few. This dissertation examines how political decision making in energy policy increases or decreases the strength of the sustainable energy interest group which in turn affects the amount of sustainable energy produced. The cycle creates a feedback effect which increases or decreases the share of sustainable energy in electricity production. Cross-country analysis of how governmental policy yields empirical insights on the role of policy feedback in the sustainable energy transition. It provides a comparative analysis of countries that have achieved significant levels of transition as well as countries whose transition appears to have stalled. The time period examined is longer than other studies on sustainable energy.

The results of this dissertation are expected to contribute to the growing strand of literature on sustainable energy transitions. Although sustainable energy transition is a multi-disciplinary field, the economic point of view has been scarce. Promoting low-carbon energy alternatives is necessary as we enter a crucial period for reducing carbon emissions. While it is impossible to predict the success of new technology at the outset, understanding the policy feedback mechanism will further our understanding of the lobbying effect of incumbents. As far as the author can ascertain, there is novelty in assessing feedback mechanisms that contribute to technological path dependence. While research has been done on political parties and interest groups and the mechanisms of policy feedback, more research is needed. Further most research on policy feedback has been done on the United States and Europe, this dissertation examines a large pool of countries than other studies done so far.

1.6 Structure of the dissertation

This dissertation is structured as follows:
Chapter 2 provides a background on energy transition. It describes historical energy transitions and the challenges of sustainable energy transition. It also introduces policy mixes that overcome these challenges.

Chapter 3 focusses on the economics of technological change within the energy system. Theories of innovation and diffusion are discussed as well as notions of path dependence from a technological and institutional view. The political aspects of technological change are also reviewed.

Chapter 4 reviews theories of path dependence and feedback processes.

Chapter 5 provides the empirical analysis including the model specification, data sources and the econometric results.

Finally, Chapter 6 provides a summary of the main findings, limitations of the research, recommendations for further work and concludes with recommendations for policy.

2.0 Background on Sustainable Energy Transitions

Energy is a necessary component of economies and everyday life. Demand is increasing as we move to a digital way of life. Although the dangers of GHG emissions have been discussed since 1896 (Arrhenius, 1896), recent climate events worldwide, including flooding, heatwaves across Canada and Europe, and the breakaway of Arctic shelves, necessitate an urgent overhaul of the way we produce, distribute and use energy. This chapter discusses the ongoing energy transition to low-carbon fuels by providing a background on the development of energy systems and what constitutes energy transition. It explores how modern-day energy systems came to be and why transitioning to renewable energy is challenging. It looks at the drivers of renewable energy adoption with a particular focus on the impact of policy.

2.1 Historical energy transitions

Energy history and policy analyst Vaclav Smil equates human progress with our ability to master higher energy flows, specifically "the availability and quality of particular prime movers and sources of heat" and heat conversion (Smil, 2004, pp. 549-561). Human progress has depended on sourcing and using energy for survival. Energy sources and technologies shape human development, economies, and societal progress because they enable and constrain human activities. Higher and better energy use has improved quality of life astronomically since early man depended on muscle power to secure food supply. Domestication of animals and improved tools further increase food production. Water and wind energy have been used for thousands of years but were better exploited in the late Middle Ages to bring about European colonisation and the spread of technology.

The history of water wheels showcases their importance as early sources of mechanical power and their significant contributions to various industries throughout human history. The exact origin of the water wheel is uncertain, as it predates written history. However, it has been traced back to the ancient Egyptians and Mesopotamians (modern-day Iraq) around the 4th millennium BCE (Mays, 2008). These early water wheels were used for irrigation purposes and later was further developed by the Greeks, the Romans and the Persians. Water wheels were the first machines to spread in the late 11th century and gradually replaced oxen and horses for grinding wheat. The evolution of the water wheel by different civilisations and cultures saw the use of water as an energy source to power grain mills, sawmills, and other industrial processes in Medieval Europe where they evolved into horizontal water wheels and undershot wheels. The Industrial Revolution in the 18th and 19th centuries brought significant changes to water wheel technology. However, the invention of steam engines and the rapid development of hydropower dams reduced the reliance on water wheels in industrial settings.

The history of wind as an energy source dates back to 5,000 BCE when it was used to power boats along the River Nile (Wind explained: History of wind power, 2023). Wind energy was effectively harnessed by sailing ships in the Late Middle Ages and marked the beginning of seafaring voyages. The Ancient Persians designed the first windmill to grind corn around 200 BCE (Elridge, 1980). These vertical-axis windmills evolved into horizontal-axis windmills in Medieval Europe. The new design allowed for better performance in varying wind conditions. The Dutch made significant advancements in windmill technology during the 16th & 17th century when windmills were used to pump water out of the lowlands and reclaim land from the sea. These improvements allowed the sails to be rotated when the wind direction changed so “that the sails were always facing the wind,” (Hoeksema, 2007). Wind power was soon adapted for a variety of industrial purposes such as pressing oil, sawing timber, crushing dyewood and beating rags for paper, turning the Netherlands into the world leader in wind technology by the middle of the 17th century (Davids, 1998). Despite new discoveries and increasing trade, draft animals, water wheels, windmills, and steam engines dominated our energy landscape and continued to be used until the late 18th century (Smil, 2004, pp. 549-561).

Historical energy transitions refer to significant shifts in the primary sources of energy used by societies over time. These transitions have occurred throughout history as societies have transitioned from one dominant energy source to another. Energy transitions generally take decades following wave-like patterns that are generalised using the life cycle concept (discussed further in section 2.3.1). They are driven by a combination of technological advancements, economic factors, environmental considerations, and societal needs. Energy transitions have had profound impacts on economic development, industrialization, transportation, and the overall quality of life. Additionally, energy transitions have often led to geopolitical shifts as countries seek to secure access to vital energy resources.

One of the most significant energy transitions in history occurred during the Industrial Revolution in the 18th and 19th centuries. Societies in many parts of the world, shifted from relying primarily on traditional biomass fuels such as wood and animal dung to the widespread use of coal. The abundant and energy-dense nature of coal fueled the rapid industrialization and urbanization of Western countries. Coal took about 500 years from the establishment of the first commercial coal mines in England to constitute 25 per cent of global energy use in 1871. Similarly, crude oil took nine decades to constitute 25 per cent of international energy use since the first commercial well in the US in 1859 (Arent, 2017, pg 18). However, countries like Denmark, Kuwait, and France have transitioned their energy systems in shorter time spans through sheer political will (Sovacool, 2016). Denmark and France's transition to sustainable energy is further discussed in section 2.4. But first, we look at the events that kicked off the global transition to fossil fuel beginning with the Industrial Revolution.

2.1.1 The Industrial Revolution and the transition to coal in England

Coal was the primary energy source behind the wave of mechanisation in Britain, known as the Industrial Revolution. Before the Industrial Revolution, economies operated under the constraints imposed by plant photosynthesis. According to Wrigley (2013), "Plant photosynthesis, by capturing a small fraction of the energy reaching the surface of the Earth in the form of insolation, provided the basis for all animate life, both for herbivores and, higher up the food chain, for carnivores. The annual amount of energy captured by plant photosynthesis, therefore, represented an upper limit to the energy available for any productive activity by human groups" (Wrigley, 2013). Growth was limited because the energy supply was constrained by the amount of energy plants could capture annually. This changed with the rise of coal as an energy source. England had abundant coal reserves, particularly in regions such as Yorkshire, Lancashire, and the Midlands. The availability of large coal deposits provided a reliable and accessible source of energy for industrial activities. Coal played a crucial role as a source of heat and energy to power steam engines in factories, textile mills, and ironworks.

England's transition from wood to coal began in the 16^{th} and 17^{th} centuries following a crisis of deforestation (Nef, 1977). Voyages of discovery before 1550 carried explorers to different parts of the world and established empires that fuelled commerce. The expansion of printing and production of books and rising population growth in England further increased the demand for wood. High wages in England in the 17th and 18th centuries led to high levels of consumption and education. The Scientific Revolution that preceded the invention of the steam engine and other new technologies also changed thinking. Work started to be viewed as a production process that could be mechanised by applying scientific and experimental methods (Allen, 2009).

Although coal had been used before, mining for resources was considered unethical. The foul smell produced during burning, coupled with impurities introduced into manufactured goods, meant that demand for coal was low. However, as wood prices increased because of population growth and attitudes towards mining changed, coal became the preferred fuel source (Nef, 1977). Learning how to use coal spurred technological development in firing methods to prevent materials from coming into contact with the burning coals and gases. Technological innovations in mining, transportation, and machinery during the 18th century improved the efficiency and productivity of coal extraction. The development of transportation infrastructure, particularly canals and later railways, facilitated the movement of coal from mining regions to industrial centers and ports. Canals such as the Bridgewater Canal and the Trent and Mersey Canal provided a cost-effective means to transport coal over longer distances, while the growth of railways in the 19th century further improved coal distribution.

Coal-powered industries created job opportunities and contributed to rising living standards. High wages and cheap energy in Britain spurred the invention of the steam engine, the water frame, the spinning jenny, and the manufacture of iron with coal and coke. These technologies “saved inputs that were scarce in Britain and increased the use of inputs that were abundant and cheap” (Allen, 2009, p. 2). The scientific discoveries that were necessary for these technologies were made in other countries as well as England; however, “turning the scientific knowledge into working technology was expensive” ” (Allen, 2009, p. 7) and was only made worthwhile in Britain, where vast coal fields provided cheap energy. Cheap energy allowed businesses to pay high wages and remain profitable. This unique wage and price structure made it “profitable to invent technologies that substituted capital and energy for labour” (Allen, 2009, p. 15). Coal and its technological spin-offs, the steam engine, the railway, and new metallurgical processes formed the basis of mechanisation and new industries. The industrial revolution resulted from these new processes and technologies, such as Newcomen’s steam engine and James Watt’s separate condenser, which were developed during the transition to coal (Smil, 2004, pp. 549-561).

The coal industry’s growth fuelled Britain’s success and the development of London. As London expanded and demand for residential housing grew, design innovations such as the coal-burning house were invented. According to Allen (2009, p. 90), “Converting from wood to coal was not, however, simply a question of chucking one fuel rather than another onto the fire. Switching fuels presented complex design problems, “beginning with the layout of the house. The traditional medieval large hall that housed the hearth was replaced with chimneys, hoods, and smaller rooms for efficient combustion and to prevent the spread of smoke. These innovations diffused to other parts of Britain, further fueling the demand for coal. The relationship between cheap coal, which provided an incentive to replace wood-burning houses, and the building of new dwellings fuelled further demand for coal (Allen, 2009, p. 96), creating a **feedback effect**.

The distinction between macro-inventions, such as the steam engine and the spinning jenny, and micro-inventions, such as technological improvements (Allen, 2009, p. 136) is crucial in understanding the diffusion of technology. Newcomen’s steam engine, for example, was a new technology that was highly inefficient. However, decades of engineering improvements resulted in a highly fuel-efficient engine that could power locomotives, ships, and machines. Thus, macro-inventions induce “long trajectories” (Allen, 2009, p. 136) of advancement, while micro-inventions make these technologies more cost-effective, thereby increasing demand for these technologies. Both were necessary for the transition to new manufacturing and energy-use methods. The pre-industrial prime movers, the windmill and the water wheel, began to decline as prime movers based on thermal energy such as steam engines and turbines spread. These powerful new machines could be adapted to a variety of uses and were not dependent on the vagaries of nature. The global diffusion of the cotton mill, the steam engine, and the coke blast furnace marked the end of the Industrial Revolution between the1830 and 1850. However, the emergence of new industries, such as the railroad and steamship, continued the demand for coal.

2.1.2 The second industrial revolution and energy transition in America

The second industrial revolution or the American industrial revolution, dated between 1860 to 1900 (Gordon, 2000), refers to the rapid pace of technological developments in energy, material, chemicals and medicine towards the end of the 19th century. Building upon the foundation laid during the First Industrial Revolution, this period saw the proliferation of inventions and innovations, and transformative changes in society and the economy. These developments led to the growth of new industries with vast economies of scale, such as railroads and shipping, all powered by a new energy source, fossil fuels. The advent of railroads, factories, automobiles and mechanised agriculture transformed America from an "overwhelmingly rural character and a subsistence-oriented economy" to an economic powerhouse (Hillstrom & Hillstrom, 2005, p. vii).

America's navigable rivers, vast coastline, and abundant wood and water power provided wind, steam and hydroelectric power resources. Windmills, introduced to America by Dutch immigrants in 1624, enjoyed widespread use for pumping water, agriculture and the steam locomotive until the 1930s. The steam engine allowed thermal fuel to be converted to mechanical work and thus replaced draft animals and human labour. By the late1880s, coal comprised 50 per cent of energy use (O'Connor & Cleveland, 2014). Machines were connected to centrally located prime movers such as a water wheel or steam engine that turned iron or steel line shafts connected to pulleys and leather belts. Steam engines dominated the American economy at the turn of the century, providing 80 per cent of the mechanical drive capacity (Devine, 1983). However, introducing electric power as a commodity in 1882 revolutionised the American economy (Devine, 1983).

One of the defining features of the Second Industrial Revolution was the widespread adoption of electricity. Inventors like Thomas Edison and Nikola Tesla made significant contributions to the development of electrical power generation, distribution, and lighting systems. The availability of electric power revolutionized industries, transformed urban landscapes with street lighting, and brought electricity into homes and businesses.

The start of the American industrial revolution is credited to English-American industrialist Samuel Slater who was the first to introduce the factory system of manufacturing with its use of power, machinery and division of labour to produce textiles in Rhode Island (Tucker, 1981). The first electric motors, developed by a former employee of Edison, were promoted by Edison Electric Light Company so daytime power usage "would complement nighttime illumination loads" (Devine, 1983). The diffusion of electric motors first occurred in industries that valued clean and speedy manufacturing methods, such as textiles and printing. However, large-scale diffusion of the electric motor occurred when it became apparent that electricity could be transmitted, allowing factories to be located where it was convenient. The transition from steam power to electric power was accompanied by new methods of power transmission and distribution along with changes in factory design to benefit from the advantages of using electricity, making the electric motor the principal provider of power for manufacturing after the First World War.

The transition from water and steam to processed energy forms such as electricity and fuel reduced energy use and increased productivity by enabling industry to obtain a greater output per unit of capital and labour input. By 1920, electricity had replaced steam as the primary motive power source, representing 78 per cent of the mechanical drive capacity (Devine, 1983). The introduction of railways changed freight services, particularly for heavy goods such as coal, iron and steel. As canal and river transportation was geographically constrained, the proliferation of railways brought down freight charges and delivered goods to previously unserved areas (Fouquet, 2010). The introduction of steamships triggered improvements in the speed and performance of sailships in the late 1800s. However, the transition from sailships to steamships occurred because steamships proved to be more reliable (O'Connor & Cleveland, 2014).

Electricity facilitated the transition to a new economy where the lowered costs of manufactured products found demand in urban and rural households. The Bessemer steel making process fueled the production of steel and the growth of heavy industry (Lord, 1945). Steel became a vital material for construction, infrastructure development, and the manufacturing of machinery and transportation equipment. Industries such as railroads, shipbuilding, and construction experienced significant growth during this period. Goods were manufactured using electricity and transported in trains and vehicles by rail and road across the US. Between 1885 and 1900, U.S. pig-iron, steel and coal production overtook British production (Hughes, 1990).

The expansion of the industrial sector was fueled by fossil fuels which were previously underutilised. The adoption of steam (technology) required iron and an infrastructure of water and energy systems. The industrial processes that emerged during this period required increasing amounts of energy. The onset and duration of the transition to fossil fuels was highly country-specific (Smil, 2004, pp. 549-561). Different parts of Europe relied on draft animals, water wheels or turbines, windmills and steam engines between the late 18th and mid-20th centuries. In Czech, for example, Nielsen (2017) posits that the transition from an agricultural to an industrial economy was fueled by coal resources and the development of energy-intensive industries, which shaped the country's economic structures. Czech's transition to coal (35 years) was faster than countries like Germany (50 years).

Transition is rarely uniform, as tension exists between early and late adopters. The steam engine, electricity production, growth in transportation and iron production brought about the US transition from wood to coal. In 1850, American fuel comprised 90 per cent of wood and 9 per cent of coal, but by 1895, coal's share had grown to 65 per cent. Between 1910 and 1955, coal gave way to oil and gas, which comprised 65 per cent of the fuel base (Nef, 1977). Oil became more dominant with the growth of transportation.

Although oil was introduced in 1859, the transition from coal to oil was slow because of coal's dominant economic position. Oil got a boost from the development of gasoline and diesel engines which gradually replaced steam engines. However, it wasn't until motor vehicles were widely adopted after the Second World War that oil use peaked at 50 per cent in the late 1970s (O'Connor & Cleveland, 2014). The explosion of the internal combustion engine (ICE) which defeated steam and electric powered vehicles as subsitutes for the horse and carriage in the early 20th century, came about as a result of cheap petrol. At the same time, a series of 'shocks' to the existing horse and carriage transportation sytem, in the form of the closure of "horse troughs used to supply steam vehicles and a 1895 victory in a horse-less carriage race" boosted the diffusion of the ICE. The Fordist system of mass production led to increasing returns to scale that drove down the price and boosted the diffusion of the ICE (Unruh, 2000). The discovery and development of oil fields, along with advancements in drilling and refining technologies, made oil an increasingly important energy source. It quickly replaced coal in many applications, such as transportation and electricity generation.

The American Industrial Revolution resulted in the increasing urbanisation of society and associated energy demand. The rise of mass production and the assembly line revolutionised manufacturing processes and increased productivity. Innovations such as interchangeable parts, division of labor, and mechanization enabled the efficient and cost-effective production of goods. New chemical processes and discoveries led to the production of synthetic dyes, fertilizers, plastics, and other chemical products which further increased demand for fossil fuel. The availability of new manufactured goods led to the beginning of mass retailing and the rise of the consumer society. Innovations in communication such as telegraph and telephone along with the expansion of transportation played a vital role in facilitating trade and commerce. The Second Industrial Revolution saw the emergence of powerful industrial conglomerates and companies such as General Electric, U.S. Steel, Standard Oil, and Ford Motor Company that dominated their respective industries, amassing significant wealth and influence while shaping the economic landscape. It brought about profound changes in society, economy, and technology fuelling economic growth, urbanization, and increased living standards. However, it also brought challenges such as labor exploitation, environmental degradation, and social inequalities. The advancements and transformations during this period laid the foundation for the modern industrialized world and set the stage for further technological and societal developments in the 20th century.

2.1.3 The Electricity System

The transition to electricity has been underway since 1882, when the world's first electricity companies were commissioned in London and New York (Smil, 2004, pp. 549-561). The first electricity systems were decentralised as "power losses of direct-current transmission necessitated small, locally situated power stations" (Mez, Midttun, & Thomas, 1997, p. 3). These facilities generated electricity using steam engines or water turbines connected to electrical generators. The electricity produced was primarily used for lighting and industrial applications.Edison realised the need for a commercial system of electric light that would include electricity generation, transmission and metering (Smil, 2017). Commercial electricity generation, transmission and use came about following the work of Thomas Edison and George Westinghouse on electric current, Charles Parson's steam turbine and William Stanley's transformer and Nikola Tesla's electric motor in the 1880s. The invention of the transformer allowed the move away from local generation centres and connected thermal and hydropower stations. It also stimulated further technological developments, such as the diffusion of alternating current, which allowed electricity to be transmitted over long distances cheaply and safely. The electric system was perfected in the following decade, and the size of generators and overall efficiency grew with every passing decade (Mez, Midttun, & Thomas, 1997).

Electrification transformed industrial production by introducing inexpensive electric motors of all sizes that could be used in various ways. Workers were no longer dependent on the "rhythm of the steam engine or the mill" (Fouquet, 2010), increasing flexibility. Workers could start and stop equipment independently. Economies of scale and efficiency increased as the source of power production no longer had to be situated close to the user. As demand for electricity grew, efforts were made to expand the electrical grid. This involved building transmission and distribution networks to transport electricity from power stations to consumers. Infrastructure development, such as power lines and substations, became necessary to extend the reach of electricity. Networks of interconnected power stations brought down the price of electricity, making it competitive with the steam engine (Fouquet, 2010). The mechanisation of manufacturing pioneered by Henry Ford brought about new specialised industries. The period after the Second World War ushered in the new computer and information age, transforming Western countries into high-energy societies. The expansion of utilities from regional to national systems accelerated after World War II (Smil, 2017), turning electricity into a "general-purpose technology" (GPT). This type of technology affects the whole economy and requires uninterrupted service. Steam and information technology (IT) are two other GPTs.

Governments and regulatory bodies played a role in shaping the electricity system. They established rules, regulations, and safety standards to ensure the reliable and safe delivery of electricity. Standardization efforts helped achieve compatibility among different electrical systems and equipment. Over time, advancements in electrical engineering and technology improved the efficiency, reliability, and safety of the electricity system. These innovations included the development of more efficient generators, improved transmission and distribution methods, and the introduction of protective devices and meters. The process of establishing the electricity system was not a linear progression but rather involved continuous innovation, competition between different technologies and systems, and the adaptation of infrastructure to changing needs and advancements. The establishment of the electricity system required significant investments in infrastructure, equipment, and research and development. According to Mez, Midttun, & Thomas (1997), "the perception of electricity as a public infrastructure with natural monopoly characteristics, and the organisation of the sector into publicly owned or franchised institutional monopolies' led to a build-up of powerful sectoral configurations, dominantly operating as closed national systems." The development of the electric utility industry was shaped on the basis of the following four assumptions:

1. All costs would be borne by consumers or tax-payers
2. Utility policy was considered mainly synonymous with national government policy regardless of the ownership of the utility
3. Electricity should be available to all and affordable
4. Electricity supply companies were primarily national and self-contained (Mez, Midttun, & Thomas, 1997)

These assumptions meant that investment decisions were underwritten by taxpayers but were considered aligned with the long-term interests of the consumer, authorised by the government and concentrated power in the hands of the utility industry. However, as the electricity system can be broken down into activities where only transportation and distribution have natural monopoly elements, the pressure for competitiveness pulled apart previously bundled power generation services to regular market competition.

Cheap reliable electricity supply underpins modern economies. However, modern electrical utilities face several challenges. Utilities such as gas, electricity, telephones, and water were largely vertically integrated state-owned natural monopolies regulated to safeguard the public interest. The utility model of electricity favours sources of electricity supply that can be matched to any load. Low price volatility and security of supply are some of the guiding principles behind this model. The model is at odds with the characteristics of renewable energy, which requires a different paradigm. Electricity utilities face the peak-load problem for a commodity that cannot be stored cost-effectively and for which demand fluctuates depending on the time of day and year. Peak-load pricing discourages consumption during peak periods and encourages consumption during off-peak hours. Electricity utilities must therefore make trade-offs between social welfare, pricing and investment decisions. Regulatory commissions, which are supposed to be independent and control the undesirable features of monopoly power, face similar issues. In terms of operation, the primary aim of the commission is to prevent monopoly price along with excessive price discrimination while maintaining high levels of public safety are considered mainly incompatible (Crew & Kleindorfer, 1979).

Liberalisation

Electricity demand varies depending on the time of day and year. While peak demand only reaches its highest levels for a few hours every year, the electric utility must be able to provide for this demand. The energy market differs from other markets because of the characteristics of electricity:

- It is homogenous
- It cannot be stored
- It must be consumed where it is produced
- Electricity demand is highly inelastic and has no substitutes

For these reasons, the energy sector was organised as a state-owned monopoly. However, the idea that introducing competitive wholesale power markets by unbundling generation, transmission, distribution, and retail supply would incentivise controlling costs and providing better services while stimulating innovation and investment (Joskow, 2008) saw the liberalisation of the energy market.

Chile was the first country in the world to reform its electricity sector in 1981, leading to the vertical and horizontal breakup of the state-owned electricity system (Pollitt, 2004). The success of reforms provided lessons for the generation, transmission and distribution sectors as well as regulation leading to similar reforms in other parts of the world. The liberalisation of energy markets started in the 1980s in the US and the UK and moved ownership away from bureaucratic state control to markets to deliver efficient outcomes. The 1989 Electricity Act began the liberalisation of the energy market in the UK.

Deregulation of the electricity industry in the US began by opening up generation (wholesale competition) and retail supply (retail competition) to competition. This was supported by several regulatory changes to support the new power market. However, the California Electricity Crisis of 2000–2001 severely impacted the progress of reform (Joskow, 2012). Although problems related to restructuring and regulatory reform are better understood now, the main challenge is “whether governments properly can choose between competing solutions and have the political will to resist interest group pressures" to pursue reforms that ensure better-functioning markets (Joskow, 2008).

Retailers purchase electricity at different prices throughout the day. The continuous balancing of supply and demand has implications for the spot price of electricity in an unregulated market and the shadow price of electricity in a regulated environment. As most residential consumers are charged a retail price per kilowatt hour, the standard residential utility bill must reflect the significant variation in wholesale price and the marginal cost of generating electricity (Joskow, 2012). A consumer's electricity bill consists of consumption charges, network charges representing the liberalised portion of prices, and taxes that individual governments set. Electricity being a homogenous commodity, renewable energy impacts electricity prices through the merit-order effect and the marginal-cost effect. The merit order effect hypothesises that increasing electricity production with low marginal costs lowers the overall price of electricity. It appears when network operators prefer generators with lower marginal costs, such as renewable energy providers.

Liberalisation allows the entry of new market players, which positively affects renewable energy policy as free access to the energy grid favours decentralised energy production compatible with RE generation (Nicolli & Vona, 2019). Lowering entry barriers eases the entry of new energy players who are more likely to invest in small-scale production. Small firms are essential as they contest the position of incumbents. Incumbents are generally not motivated to innovate or pursue research as expensive overheads and ageing equipment keep costs high and returns low. Further, as they are locked into a centralised mode of producing and delivering electricity, if they look for low-carbon alternatives, they are likely to innovate around other options that work with the current infrastructure, i.e., maintain the existing paradigm of large-scale electricity production.

Structural, regulatory and market reforms were introduced in many countries, resulting in performance improvements and investments in new generating capacities in several countries. However, these reforms have also resulted in electricity crises in Brazil, Chile and California and scandals involving energy trading companies like Enron, which have slowed down or halted the liberalisation process. Instead, public policy has focused on modernising and expanding transmission and distribution networks in the transition to a 'smart grid' that improves monitoring and control to manage consumer demand while providing real-time price information so consumers can make informed energy-related decisions. This restructuring of the electricity grid is necessary for adding intermittent renewable energy and ‘prosumers’, who supply excess self-generated electricity back to the grid. The future of electrical utilities may lie in flexible, decentralised power systems where smart grids, microgrids, and demand response technologies work alongside energy storage. Energy efficiency would be a vital feature of this paradigm.

Unintended consequences

Deregulation has profound implications for GHG emissions. By exposing utilities to market forces, deregulation was intended to decrease electricity prices and improve service. However, it also increased air pollution as private utilities maximised profit by generating electricity using inexpensive coal. As large energy companies divest thermal power plants for greener and more sustainable power, these assets are typically bought by smaller, private utilities who are unencumbered by investors with strict climate goals. These companies intend to keep the plants running for the next 10-30 years and is one of the reasons why GHG emissions usually rise when publicly-traded fossil fuel companies divest. For example the Czech power company EPH, has been buying gas and coal-fired power plants from larger power companies in Europe, the UK and US (Thomas, 2017) and has become one of the largest polluters in Europe (Naik & Sorge, 2023).

A reduction in R&D spending is another consequence of deregulation. R&D aimed at developing future energy supply options is a public good subject to the problems associated with common goods and the tragedy of the commons. During deregulation, Dooley (1998) found that funding for alternative energy options decreased substantially in the public and private sectors. R&D support for energy programs declined from 1985-1995 in the critical countries known to perform such research: Canada, France, Germany, Italy, Japan, the Netherlands, Switzerland, the UK and the US (Dooley, 1998). This reduction in R&D spending has a detrimental effect on the transition to renewable energy.

For example, R&D into unpopular low-carbon energy sources nuclear could propel the transition to low carbon energy. Despite other fissile atoms such as Thorium, the nuclear energy industry has developed around uranium fission due to its widespread availability. However, uranium needs to be enriched before it can be used. Controlling the nuclear reaction within the reactor is the primary issue in atomic fission. Since the first generation of reactors was built in 1970, the evolution of reactors has been slow partly because of opposition to nuclear energy. However, despite the accident at Fukushima in Japan, there has been increased interest in nuclear power to generate relatively clean energy. Nuclear waste disposal, however, needs to be improved. Newer nuclear reactor designs such as small modular reactors hold the promise of cleaner energy generation and reduced problems associated with nuclear waste but are unlikely to reach mass deployment without investment in R&D.

2.2 Understanding transition pathways

2.2.1 Transition theory

Originating in innovation studies, transition studies examine technological regime shifts and aim to explain and guide processes of societal and systemic change towards more sustainable and desirable futures. The literature is rooted in institutional theory, evolutionary economics and the sociology of technology providing insights into how societies can navigate complex and interconnected challenges and transform their social, economic, and environmental systems. It recognizes that societal change occurs at multiple levels, including the niche level (where innovations and new practices emerge), the regime level (where dominant systems, rules, and structures are entrenched), and the landscape level (where external factors and trends influence transitions). A technology regime is defined as a technology path based on technicians' beliefs about technological feasibility (Nelson & Winter, 1977). Technological transition refers to substituting large complex technology systems with a new system. This involves a technological paradigm shift and systemic changes. The key idea is that patterns in technological change follow a specific path which can be studied to induce technological change (Kemp, 1994).

As transitions by themselves do not imply sustainability, these changes may be directed towards sustainable technologies and practices to make it a sustainable transition. Thus, sustainability transitions can be defined as "long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption" (Markard, Raven, & Truffer, 2012). However, existing systems and regimes may exhibit resistance to change due to vested interests, established power structures, and dominant paradigms. Transition theory offers insights into the challenges and barriers inherent in transitioning away from entrenched systems and is often applied in the context of sustainability transitions. The sustainability transitions literature is broader and includes industrial ecology and environmental economics. This perspective is interested in the ‘bigger picture’ and non-linear phenomena that occur over long timeframes. Explaining the varied progress of transition and different sectors and countries is an area for research within the sustainability transition literature (Kohler, et al., 2019).

Energy transition vs sustainable energy transition

Energy transition is a complex field encompassing diverse disciplines such as environmental science, policy studies, political geography and many more because it requires restructuring the existing energy industry and building greener industry and infrastructure while ensuring the participation of the affected parts of society. Several definitions of “energy transition” exist without a universally accepted definition. Energy historian Smil (2010) believes energy transition “encompasses the time that elapses between the introduction of a new primary energy source (coal, oil, nuclear electricity, wind captured by large turbines) and its rise to claiming a substantial share of the overall market.” O’Connor (2010) on the other hand defines energy transition as “a particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services.” Similarly, Hirsch and Jones (2014) view energy transition as “a change in fuels (e.g. from wood to coal or coal to oil) and their associated technologies (e.g., from steam engines to internal combustion engines.

Fouquet & Pearson (2012) take a broader view of energy transition, which they define as “the switch from an economic system dependent on one or a series of energy sources and technologies to another.” Araujo (2014) refers to the systemic nature of energy transition, defined as “a shift in the nature or pattern of how energy is utilised within a system”. This change is associated with changes in “fuel type, access, sourcing, delivery, reliability, or end use as well as with the overall orientation of the system. Change can occur at any level – from local systems to the global one – and is relevant for societal practices and preferences, infrastructure, as well as oversight”(Araujo, 2014). Miller et al. (2015) refer to transition as “significant transformations” in the way energy is produced, distributed and consumed between people and the machines they use. These definitions share a systemic view of the changes in fuels, technology, and energy usage. The complex nature of energy transitions can therefore be understood as combinations of changes in individual energy technology use that must occur for energy transition to take place. Thus energy transition consists of a bundle of smaller conversions instead of one significant change. At the same time, the definitions point to supporting changes in economic development, technological innovation, and policy change.

Sustainable energy transition

A sustainable energy transition (SET) differs from past energy transitions as it implies the replacement of fossil fuel in the energy system with sustainable energy sources and reducing energy demand. This demands system-wide transformations in the sociotechnical energy provision system as it requires changes in technology and behaviour alongside adopting sustainable energy behaviour such as using sustainable technologies such as electric vehicles, insulation and energy-efficient devices. Further energy-conserving measures include walking, cycling, using public transportation instead of driving and reducing dryers and other energy-consuming appliances.

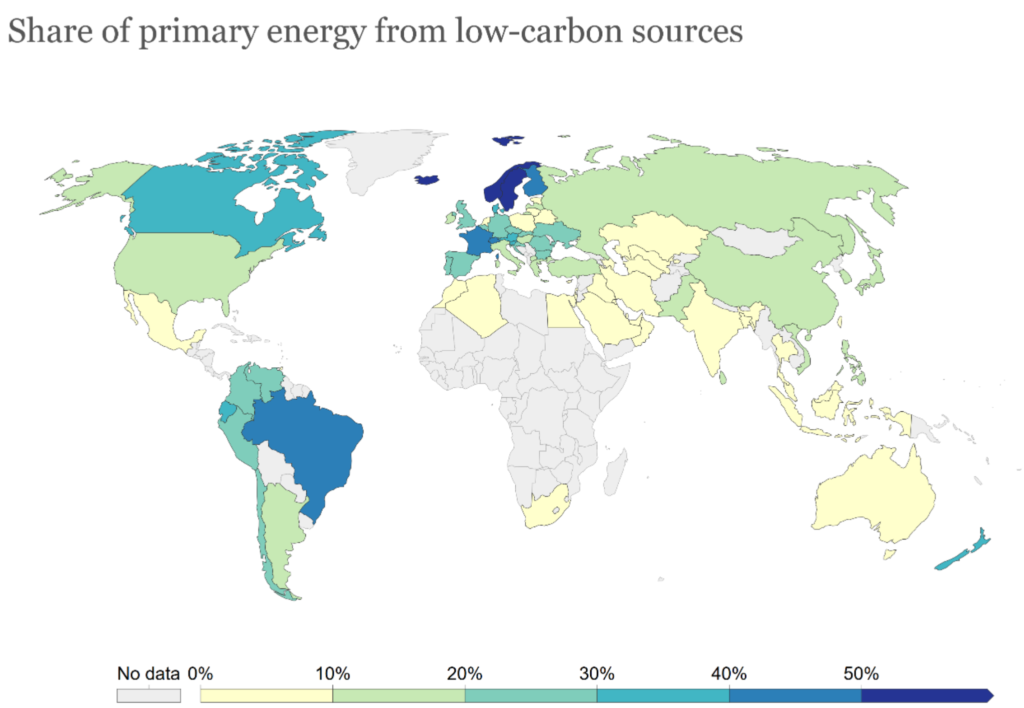
A literature review shows that while “energy transition” implies a transition to renewable energy, the term “sustainable energy transition” has not been used extensively. Akin and Urpalainen (2013) believe SET “consist of the extensive deployment of clean energy, such as wind and solar power, to reduce the environmental burden of the national economy. ” Kuzemko et al. (2020) describe a sustainable energy transition as “complex sociotechnical processes of decarbonisation within energy systems and involve both bringing in low, or zero, carbon energy and phasing out old, high carbon energy. ”

Researchers such as Solomon and Krishna (2011) discuss the transition of sustainable energy systems and the characteristics of such a system. The International Energy Agency believes “a sustainable energy transition needs to address the interlinked challenges of climate change, air pollution, economic competitiveness and energy security, as well as overcoming the current widespread lack of energy access in large parts of the world” (IEA, 2017, p. 10). Neofytou, Nikas & Dougas (2020) assess the sustainable energy transition readiness of 14 countries and propose an index to determine the capacity of the countries to achieve sustainable energy transitions without defining the term “sustainable energy transition”.

Sgouridis and Csala (2014) define a sustainable energy transition as “a controlled process that leads an advanced, technical society to replace all major fossil fuel primary energy inputs with sustainably renewable resources while maintaining a sufficient final energy service level per capita.” Fossil fuels are limited by extraction capacity in the short term but “exhibit ample margins to increase power availability before the peaking of the resource”. On the other renewable energy has a complex power limit based on “the yield of the extant renewable energy generation capacity at given environmental conditions plus any storage capacity” (Sgouridis & Csala, 2014, p. 2602).

As the sustainable energy transition aims to mitigate climate change, this dissertation defines sustainable energy as all low-carbon forms of energy, including traditional renewables such as wind, solar, geothermal, wave and tidal and bio-energy, as well as hydroelectricity and nuclear power. Figure 1 below shows the share of primary energy from low-carbon sources in 2019.

Figure 1: Share of primary energy from low carbon sources in 2019



Source: Ourworldindata.org, BP Statistical Review of World Energy (2020)

The Nordic countries, France and Brazil, have the highest share, with more than 40% of primary energy coming from low-carbon sources. Primary energy is the raw form of energy before its conversion to other forms such as electricity, heat or transport.

It is clear that the transition must be based on social, political-regulatory, economic and technological aspects. This implies:

- Energy system change
- Changes in finance and investment
- Changes in societal behaviour

2.2.2 The energy system

Fouquet (2016) describes an energy system as the production, distribution and consumption of energy in an economy. It can also be defined as a system of "energy inputs and outputs, involving suppliers, distributors, and end users along with institutions of regulation, conversion and trade" (Araujo, 2014) Taking the social dimension of energy into account, Miller et al. (2015) define an energy system as "sets of interlinked arrangements and assemblages of people and machines involved in the production, distribution, and consumption of energy, in their supply chains and in the lifecycles of their technologies and organisations." This dissertation defines an energy system as the production, distribution and use of energy with the associated institutions, technology and users.

The main characteristic of the energy system is the quantity of energy required and the power it produces. These systems require infrastructure such as transmission lines, pipelines, and organisational resources and consume considerable energy. The most straightforward systems use a small number of energy sources for basic needs such as subsistence. In contrast, modern systems have evolved to produce energy from various sources and use them in complex ways. This evolution has come about because of changes in the shares of individual fuels, the origins of electricity generation, the adoption of new prime movers and new patterns of final energy uses (Smil, 2010). As they have evolved, energy systems have become more interdependent, integrated and global. However, all energy systems share the following basic properties:

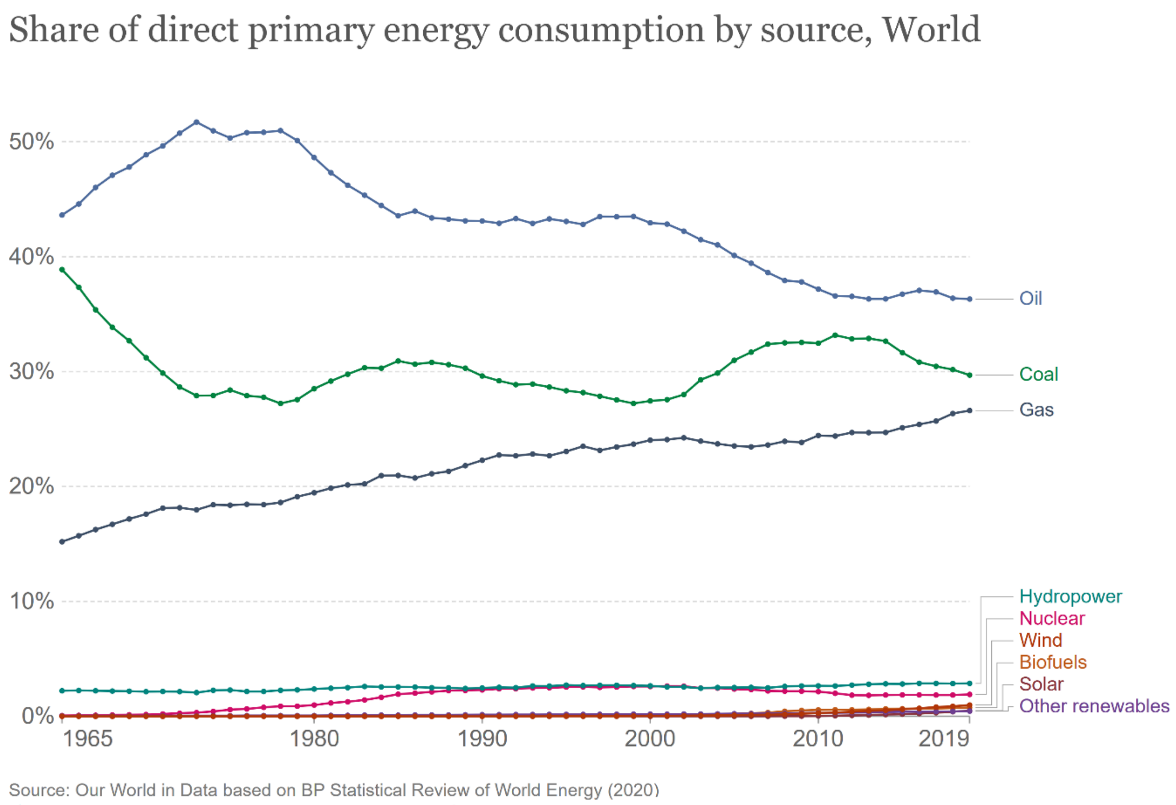
- Resources such as renewable/non-renewable or primary/secondary energies and prime movers that convert energy into useful forms are used. Different energy sources have specific uses and are categorised into primary energy and final energy. Primary energy refers to natural sources such as coal, gas, oil, wind, sun, uranium, etc. Energy from renewable sources can be replenished and is therefore regarded as flows. On the other hand, fossil fuels and nuclear fuel can be exhausted and are consequently considered stocks. Final energy refers to transport fuels, electricity and heating and cooling. Early prime movers used to be humans who converted energy from food to carry out tasks. Gradually draft animals became prime movers, and these prime movers are generally mechanical.
- Modern societies use different forms of energy to provide heat, light, and power for residential, commercial and industrial consumption, freight and passenger transportation. All energy conversions involve some loss.
- All but the simplest forms of energy conversion require particular infrastructure. These could be simple but are generally complex to suit modern societies' needs. The extraction of hydrocarbons has created several supporting industries. Similarly, electricity generation also requires demanding infrastructure such as transmission and distribution lines and converters.

Transformation of the energy system requires changes to how energy is produced, distributed and used. The following sections briefly describe the development of major fossil fuel sources of energy.

Energy sources

As oil was the first primary energy source traded worldwide, all other energy sources are analysed in terms of oil. Primary energy sources are transformed to produce final energy, which domestic or industrial consumers use for electricity, transportation and heating. Some energy content is lost during the transformation to electricity (Furfari, 2021, p. 11). Figure 2 below shows the world's share of direct primary energy consumption by source in 2019. The direct method of primary energy calculation does not account for inefficiencies in energy conversion like the substitution method, which corrects this loss.

Figure 2: Global share of direct primary energy consumption by source up to 2019



Source: Ourworldindata.org, BP Statistical Review of World Energy (2020)

Although technology and policies impact primary and final energy, primary energy is more closely affected by international relations and geopolitics. In contrast, final energy is impacted by the targets or mandates of energy policy. Apart from the oil shocks of 1974-75 and 1980-83 and the financial crisis of 2008, global primary energy demand has been growing steadily. While demand in OECD countries has been relatively steady, countries such as China and India have rapidly increased energy demand. Oil, coal and natural gas comprise 81 per cent of global energy demand (Furfari, 2021, p. 11). Although renewable energy use has been increasing, unless energy demand is managed effectively, the absolute values of fossil fuels will continue to grow, exacerbating climate change.

Coal: Coal's abundance worldwide makes it a priority fuel for countries focused on the development and the second primary fuel used to generate electricity. Although the Han Dynasty used coal in China to produce iron, England was the first country to transition from plant fuels to coal during the 16^{th} and 17th centuries. Coal was gradually replaced by coke as a higher-density and cleaner fuel that could be used for more advanced products such as iron. As furnaces no longer had to be located close to forested regions, they could also increase capacity and production. The introduction of the steam engine powered by fossil fuel brought about improvements in manufacturing and construction, bringing about the industrial revolution. At the same time, the introduction of railroads and steamships revolutionised transportation.

Oil: The oil industry began in modern-day Azerbaijan in 1837 when the Russians built the first commercial oil-drilling factory (Smil, 2017). The early oil industry was dominated by the US, Canada and Russia. Post-World War II industrialisation led to increasing demand for fossil fuels. Fears of oil scarcity have existed since 1924 when US President Calvin created the Federal Oil Conservation Board to save oil. Oil's strategic value in transportation led to the creation of an oil cartel of the major oil companies called the Five Sisters to control oil prices. The fear of oil scarcity gained a stronghold during the oil crises of the 1970s and the publications of the Club of Rome. It led to the creation of the Organisation of Petroleum Exporting Countries (OPEC) and the International Energy Agency (IEA) for providing energy policy advice. Since then, drilling and information technology advances have considerably reduced drilling costs and made previously uneconomical petroleum reserves profitable. (Furfari, 2021, p. 14).

The high energy density of liquid fuels and easy portability coupled with the internal combustion engine paved the way for new markets such as cars and aviation. Demand for crude oil led to the development of oil tankers and transportation pipelines that span the world and turned oil into an affordable global commodity. Oil is converted to oil products such as gasoline, diesel, etc. which are used for specific purposes. Chemicals derived from oil are the products of the petrochemical industry and play a significant role in the products used in modern living. According to Smil (2017), the energy transition to fossil fuel has been marked by three trends:

- Global expansion of coal mining and fossil fuel production; and trade
- Technical advances in production, transportation and processing methods have also brought down costs.
- A shift to higher-quality fuels

Gas: The gas market is a considerably newer energy market that has gained prominence since innovations in transportation, the move to cleaner fossil fuels and the introduction of the UN Convention of the Law of the Sea (UNCLOS). UNCLOS extended the territory of coastal countries up to a distance of 360km and more into the sea, bringing about new areas of gas reserves under sovereign control. Business model innovations in LNG export, such as removing oil-linked prices and minimum orders, have also increased demand (Furfari, 2021, pp. 20-25). The development of gas pipeline links creates the obligation to buy from a particular country and creates path dependence and lock-in.

If the goal of the energy transition is to reduce fossil fuel use and, thereby, carbon emissions, the simple addition of renewable energy is unlikely to accomplish that goal (York & Bell, 2019). They view the development of infrastructure and production facilities for renewable energy as adding new energy sources to the energy system. They point out that introducing new energy sources has historically increased the overall energy demand but has yet to cause the decline of established energy sources. A genuine transition would mean a reduction in the use of fossil fuels. This can only be achieved through regulation, as supply will continue as there is demand for fossil fuels.

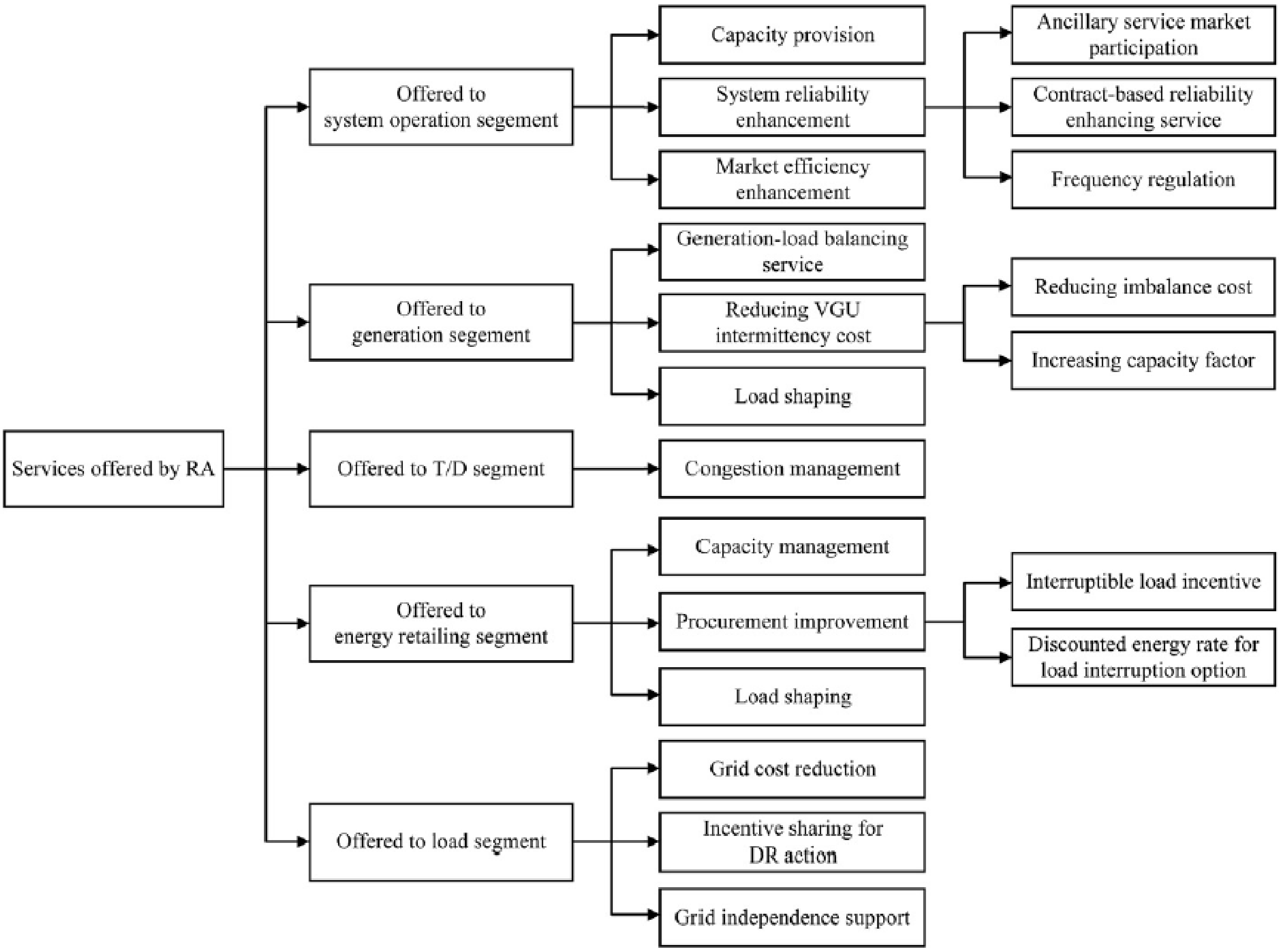
Virtual power plants and electricity markets

Distributed generation has several advantages, including reduced carbon emissions and the avoidance of constructing new transmission lines and large power plants. However, the “fit and forget” approach of connecting DG to electric power systems creates complex balancing problems for transmission operators (Pecas Lopes, Hatziargyriou, Mutale, Djapic, & Jenkins, 2006). As distributed energy resources proliferate, Virtual Power Plants (VPPs) are considered the best way of managing them. In 1997, Shimon Awerbuch defined the Virtual Power Plant (VPP) as “a flexible collaboration of independent, market-driven entities that provide efficient energy service demanded by consumers without necessarily owning the corresponding assets” (Awerbuch, 1997). For Awerbuch (1997), the virtual power plant “seeks to shape an electric generation and delivery process that fully avails itself of the special attributes and complementarities of modular generating technologies” instead of simply merging them into existing processes. The modern VPP is a network of distributed electricity-generating units operating as one and supplying the electricity grid as a single entity. The VPP manages the electricity supply within the cluster of units and in exchange with the grid.

VPPs maximise profit by participating in multiple electricity markets. Geographic flexibility is one of the critical advantages of a VPP, as there are no constraints to integrating components. Smart grids are crucial to developing VPPs as VPPs gather information from the components connected to the network to control, model and optimise energy resources. VPPs represent intelligent energy consumption through optimal demand management and power generation. Therefore, communication bandwidth and efficient algorithms play crucial roles in a VPP.

A related concept used in the literature is the aggregator. Aggregators are emerging electricity market participants who pool electricity supply or demand (Kerscher & Arboleya, 2022). They track electricity consumption and transmission system operators' requirements in real-time and sell the timing of demand in electricity markets. Aggregators may aggregate load, demand or production and sell flexibility, capacity and balancing services as other ancillary services described in Figure 3 below, enhancing overall system flexibility.

Figure 3: Services provided by aggregators



Source: (Lu et al., 2020)

Energy systems face inertia because of the vast sums of money sunk into transmission and distribution grids and investments in power plants. Although oil and gas consumption has decreased since 1965, as fossil fuels continue to dominate our economies, Berkhout (2002) envisions transition as a series of multiple, cumulative changes where inferior technological systems are replaced with the help of institutions. Transition pathways to reduce carbon emissions in the energy sector may be designed from the bottom up or top down but share the following key points:

- Technological innovation in a new or existing market, such as pathways for large-scale incumbent systems or renewable electricity systems
- Policy mix to support these innovations, such as pathways towards energy efficiency

- Societal response such as pathways towards changing household behaviour

2.2.3 Electrification and transition pathways

The electrification of the energy system and society is viewed as a transition pathway to a low-carbon energy system. For Verbong and Geels (2010), electricity transitions would require changes at the meso-level of the socio-technical regime. These include resources, grid infrastructure, generation plants, and actors such as utilities, industrial and private users and institutions. They identify four transition pathways: transformation, reconfiguration, technology substitution, dealignment, and re-alignment.

Transformation is characterised by hybridization of the infrastructure. Pressure from the landscape level or interest groups create 'windows of opportunity' and force existing regimes to modify the direction of development. Here, change is enacted by regime actors who change their guiding principles and R&D investments, but these changes are modest leading to a gradual change in the regime trajectory (Verbong & Geels, 2010). "The utilities focus on constructing large-scale offshore wind farms and large-scale biomass gasification and combustion plants, but coal or multi-fuel fired plants (co-combustion of biomass) in combination with Carbon Capture and Storage (CCS) and nuclear power plants remain important" according to Verbong & Geels (2010). As the market mechanism focusses on cost-effectiveness as the most important criterion in the scenario, small-scale renewable energy production does not disrupt the basic architecture of the regime.

In the Reconfiguration pathway, development in renewable generation leads to the emergence of a 'Supergrid'. Transition is driven by existing regime actors who adopt new technology into the existing system as add-ons due to major external landscape pressures such as security of supply issues. Integration and policies become more dominant and network management and control takes place at the international level. This in turn leads to gradual reconfiguration of the system and changes in some guiding principles, beliefs and practices. Here, the new regime also grows out of the old regime because of adoption. Regime and niche actors interact to develop and supply new technologies. (Verbong & Geels, 2010). Political dynamics are the important criterion and the shift to the international level requires institutional change.

In technological substitution, pressure creates ‘windows of opportunity’ for new technology and diffusion allows new technology to enter bigger markets, eventually replacing the existing regime. In this pathway, new technology competes with incumbent actors (Verbong & Geels, 2010).

The ‘de-alignment and re-alignment pathway’ is dominated by distributed generation and a focus on more local infrastructures. The existing regime collapses as a result of major changes in the landscape such as high oil prices. This collapse creates uncertainty when a number of new technologies co-exist. Experimentation with different technologides at the local or regional level grows until they gradually replace incumbents and restructure the system. (Verbong & Geels, 2010). The guiding principle is a strong preference for local or regional generation and balancing with cultural change emphasing regionalism and self-reliance. Such an electrical system would comprise of micro-grids connected to other systems to increase reliability. Large-scale generation units will be required to provide backup capacity resulting in redundant capacity in the system. Balancing demand and supply will be the main issue but the development of storage facilies and ‘smart grid’ is expected to ease these problems (Verbong & Geels, 2010).

As the resistance and resilience of incumbent producers such as coal and gas negates the benefits of increasing renewable energy production (Geels, 2014), policy-makers should focus on destabilizing the existing fossil fuel regimes. However, the energy policy literature stresses the necessity of coordinated sets of policies for driving sustainable innovation and transitions. Policymakers should implement a range of policies such as financial instruments (taxes, subsidies, grants, loans), regulatory instruments (standards, laws, performance targets), and processual instruments (demonstration projects, network management, public debates, consultations, foresight exercises, roadmaps) to combat the multi-dimensionality of sustainable transition. Further the policy mix must be dynamic and the appropriate mix will vary depending on each country’s situation. (Geels et al., 2017).

California for example, complemented “its mandatory renewable portfolio standard with the removal of excessive utility tariffs, the introduction of tax credits for renewable energy systems, and the use of large consumer awareness programs. In addition, regulators offered streamlined permission for small-scale solar projects, required net metering, and created a rigorous rebate program.” Denmark achieved “decarbonization of electricity and heat through a mix of carbon pricing, FiTs, government procurement programs, demand-side management, and R&D subsidies." While 'demand-pull' instruments such as the FiT and 'supply-push' mechanisms such as R&D subsidies was coupled with collaborative research projects and systems of knowledge exchange in Germany (Geels et al., 2017).

2.3 The challenge of sustainable energy transition

In 1896, Swedish scientist, Svante Arrhenius (1896), predicted that burning fossil fuels such as coal would increase CO2 levels in the Earth's atmosphere leading to what would later be termed "the greenhouse effect". His idea that human activity would lead to damaging effects on the environment was largely ignored until the advent of environmentalism in the 1970s.

In 1938, British engineer Guy Stewart Callendar identified the link between the artificial production of carbon dioxide and global warming. The "Callendar Effect" as it came to be known, stated that atmospheric concentration of carbon dioxide was "rising due to human activities, which was causing the climate to warm" (Fleming, 2007, p. xiii). In the 1950s, American scientist, Charles David Keeling developed a new method to accurately measure CO2 and found that CO2 concentrations were far steadier than previously believed leading to predictions that global warming would become apparent around the year 2000 (Weart, 2008). The Mauna Loa Observatory was set up in 1958 to monitor CO2 levels and the Keeling Curve showed that the level of carbon dioxide concentration from 1958 has been rising year by year. But it was not until the rise of environmentalism in the 1970s that concerns about climate change reached the public domain and led to the creation of the United Nations Environment Program (UNEP). However, as the climate system was poorly understood, the US National Academy of Sciences convened a panel of experts in 1979 who found that "when CO2 reached double the pre-industrial level, sometime in the following century, the planet would probably warm up by about 3°C (5.4°F), plus or minus a degree or two" (Weart, 2008). Further they found that the climate is an intricate system sensitive to many influences such as deforestation and that rising levels of other greenhouse gases such as methane and chlorofluorocarbons would raise temperatures far sooner than previously predicted.

The first World Climate Conference was organised by the World Meteorological Organization (WMO) and the UNEP in 1979 to discuss the climate change problem. This was followed by a conference in Villach in 1985 which led to the creation of the Advisory Group on Greenhouse Gases (AGGG), a predecessor of the IPCC, to review the impact of rising GHG levels (Kreienkamp, 2019). The 1980s would see a series of conferences and institutions that would continue the discussion on how climate change should be addressed. These included :

- The Adoption of the Montreal Protocol in 1987 to address the thinning of the ozone layer which would later serve as the model for the 1997 Kyoto Protocol to address climate change
- The publication of the Brundland Report (1987) which linked global environmental and development problems and;
- the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 by the UNEP and the WMO.

The 1990s saw governmental involvement in the global climate change agenda. The IPCC's First Assessment Report laid the groundwork for the Second World Climate Conference and United Nations Framework Convention on Climate Change (UNFCCC). The report suggested policy options for the energy, industry, agriculture, and forestry sectors as well as public education and technology development alongside economic, financial, legal and institutional mechanisms (Kreienkamp, 2019). The UNFCC was signed in 1992 at the Earth Summit in Rio de Janeiro with the aim of "preventing dangerous human interference with the climate system" (United Nations Climate Change, 2022). It entered into force in 1994 and has been ratified by 198 countries which are called Parties to the Convention and who meet on a regular basis. The Kyoto Protocol with 192 signatories, committed industrialised economies to limit and reduce GHG emissions in accordance with individual targets. It was adopted in 1997 and entered into force in 2005. However, several environmental problems including melting of the icecaps, heatwaves, acidification of the oceans, floods and droughts had started to occur by 2010 leading the Kyoto Protocol to be deemed a failure (Weart, 2008). The Paris Agreement of 2015 was signed by 194 parties deals with the challenges of post-2020 climate policy which include climate mitigation as well as adaption as well as the establishment of climate finance to compensate for climate induced loss and damage. The Conference of Parties in 2021 in Glasgow saw further pledges to reduce emissions. However, it was unable to rule out coal power and fossil fuel subsidies and is also considered unsuccessful.

The primary challenge to achieving consensus is the constraints posed by the large scale reduction of carbon emissions required to avoid further anthropogenic climate change. Irreversible damage to the environment and climate change precipitate a need to move away from a highly developed and convenient energy system and entails leaving economically viable fossil fuel reserves in the ground and abandoning certain types of energy sub-systems. Countries heavily dependent on fossil fuel exports may face economic challenges and need to diversify their economies. Additionally, geopolitical factors can influence the availability and access to critical minerals and resources required for renewable energy technologies, such as lithium and rare earth elements. All these factors have implications for national economies as the energy transition will be driven by:

- Changes on the supply side: the transition from steam engine to electricity used the same primary fuel but the power came from a different source (Fouquet, 2010. New producers, distributors and retailers as well as infrastructure investments in gas, rail and electricity networks were required for the transition to electricity.
- Changes on the demand side such as the demands of particular localities or situations. Ex steam engines in Cornwall replacing coal (O'Connor & Cleveland, 2014)
- Changes in energy end use: In the US, although they were more expensive, electric lamps replaced kerosene in oil lamps because they were safer and had better light quality. (O'Connor & Cleveland, 2014). Cheaper or better energy services brought about transition in the manufacturing industry. As energy-end use capacity generally outstrips generation capacity, energy services are able to lead the energy supply transitions. Steam engines drove demand for coal and the internal combustion engine drove demand for fossil fuel. Similarly, sustainable energy would require the development of new technological combinations such large scale battery technology and electrification to drive demand (Grubler, 2012).
- The scaling up of technological solutions (Grubler, 2012): Scale can be at the individual technology level or at the level of whole industries. The key is to allow time for experimentation and learning and not scale up too quickly.

Further debates about energy transition center around the following:

- Picking the appropriate technology: some forms of energy production such as nuclear energy arouse strong reactions from certain parts of society
- Reshaping societal behaviour towards sustainable consumption
- Rising energy costs

- Reducing energy demand: Switzerland's 2000 watt society project aims to reduce per capita energy consumption from 4700 watts to 2000 watts per annum, which would ensure a high quality of life while reducing carbon emissions and preventing overconsumption of energy. This goal would be achieved by becoming more energy efficient, using renewable energy resources and environmentally friendly technologies, reducing, reusing and recycling (Morrow & Smith-Morrow, 2008).
- The importance of institutions as social and political rules of the game.

Significant investments in renewable energy infrastructure, energy storage systems, and grid upgrades will be required and financing these investments can be challenging in developing countries or regions with limited financial resources. Replacing the existing infrastructure built around fossil fuel-based energy systems will be costly and require careful planning. The wind, water, solar (WWS) strategy proposes that all end uses such as heating and transportation utilize electricity which would be produced by renewables. The strategy also incorporates energy storage and increased hydropower capacity. (Jacobson & Delucchi, 2009). The integration of intermittent renewable energy sources into existing energy systems poses challenges for grid stability and reliability. As the share of renewables increases, ensuring a balance between electricity generation and demand becomes more complex. Advanced grid management systems, energy storage technologies, and demand response mechanisms are needed to address the variability of renewable energy generation and maintain grid stability.

Effective policies and regulations are essential to support the transition to sustainable energy. However, inconsistent or inadequate policies can create uncertainty and hinder investment in renewable energy projects. Policy frameworks need to provide clear and long-term signals, incentivize renewable energy deployment, and address barriers to market entry. Additionally, regulatory frameworks may need to be updated to accommodate new technologies and market structures associated with sustainable energy. At the same time, continued research and development in renewable energy technologies, energy storage, and grid integration are needed to improve the efficiency, cost-effectiveness, and scalability of renewable energy technologies. Additionally, innovation is required to address challenges related to energy storage, grid flexibility, and the electrification of sectors such as transportation and industry.

Achieving a sustainable energy transition requires social acceptance and engagement. Community concerns about the visual impact of renewable energy infrastructure, and potential disruptions to existing industries will require education, awareness-raising, and effective communication about the benefits of sustainable energy.

The speed of energy transitions depends on scale, market size, technological interrelatedness and infrastructure (Grubler, 2012). Countries with large complex infrastructure take longer. Industries such as iron and steel are energy intensive so those countries with a large energy-intensive industrial base might find it more difficult to transition to low-carbon energy than others. Countries with smaller population might find it easier while mass transit is more feasible in countries with dense population centres.

Table 2 below shows some key dates in the development of energy and climate change events.

Table 2: Timeline of climate change/energy events

Year	**Event**
2000BC	Chinese First to Use Coal as an Energy Source
200BC	Chinese Develop Natural Gas as an Energy Source
	Europeans Harness Water Energy to Power Mills
1st Century	Chinese First to Refine Oil for Use as an Energy Source
10th Century	Windmills Built in Persia to Grind Grain and Pump Water
1590s	Dutch Build Windmills for Multiple Uses
1600	Development of coal coke in England paves the way for the First Industrial Revolution
1712	Newcomen' steam engine kickstarts the First Industrial Revolution
1800	William Nicholson and Anthony Carlisle invent electrolysis and paves the way for the invention of the Hydrogen Fuel Cell
1838	First Hydrogen Fuel Cell (HFC) developed by William Robert Grove - The 'Grove cell,
1859	First Commercial Oil Well drilled by Edwin Drake in Pennsylvania
1860	First Solar Power System developed in France by Augustine Moucho to drive machinery

Year	Event
1870	John D. Rockefeller forms Standard Oil. Petrol becomes major energy source in the US
1870-1910	Second Industrial Revolution and the rise of fossil fuels
1876	William Grylls Adams generates electricity from sunlight with a selenium solar cell
Sep. 4, 1882	First Electric Plant Built by Thomas Edison in New York
Sep. 30, 1882	First Commercial Scale Hydroelectric Plant Goes into Operation in Appleton, Wisconsin
1888	First Windmill generates electricity in Cleveland, Ohio
1892	First Geothermal district heating system built in Boise, Idaho
1896	Svante Arhennius predicts burning fossil fuels will CO2 levels
1904	First geothermal plant built in Lardarello, Italy (Boechle et al., 2021)
1920-1925	Opening of Texas and Persian Gulf oil fields inaugurates era of cheap energy.
1927	First commercial wind turbines sold by Marcellus and Joe Jacobs generate electricity
1938	Guy Callendar links the artificial production of carbon dioxide with global warming
1951	First Nuclear Power Reactor to Generate Electricity Built in Idaho
1954	First Silicon Solar Cell Developed at Bell Laboratories
1956	M. King Hubbard Develops the "Hubberts Peak Theory" for measuring oil supply
1957	First commercial nuclear power plant begins operation in Pennsylvania
1958	First US satellite in orbit utilizes solar cells for power
	Charles Keeling provides the first evidence that CO2 levels are rising
1960	First Commercial Scale Geothermal Electric Plants in the US Built in California
	OPEC formed
1960s	GE develops HFCs to Generate Electricity for Apollo and Gemini Space Missions
1968	Dr John Mercer predicts melting ice caps
1969	Earth's temperature measured with satellites for first time

Year	Event
1973	Energy crisis
1979	Energy crisis
1980	World's first wind farm built in New Hampshire, US
1985	Discovery of the Ozone Hole
	The lithium-ion battery is invented
1986	Chernobyl nuclear accident kills plans to replace fossil fuels with nuclear power.
1987	Warmest year since records began (New Scientist) 1987
1988	(Intergovernmental Panel on Climate Change) IPCC established
	Vienna Convention for the protection of the Ozone Layer comes into effect
1992	Coral reefs at threat (UKRI)
1994	UNFCC comes into force
1996	The world's first commercial CO2 storage project begins operation in the North Sea (UKRI)
1997	Kyoto Protocol signed
	Mass market hybrid cars produced by Toyota
2002	Second hottest year since records began
2003	Scientist link extreme weather to climate change (UKRI)
2005	Kyoto Protocol comes into effect
2006	Al Gore's film "An Inconvenient Truth" becomes a box-office hit
2008	The Arctic is warming twice as fast as the rest of the planet (UKRI)
2015	Paris Agreement adopted to cut carbon (UKRI)
2019	Ice sheet collapse in Antarctica and Greenland irreversible according to IPCC report (UKRI)
	The UK becomes the first country to pass the net zero emissions law (UKRI)

Source: https://alternativeenergy.procon.org/view.timeline.php?timelineID=000015, UK Research and Innovation, https://history.aip.org/climate/timeline.htm

The complexity of energy transition requires the input from diverse disciplines such as environmental science, policy studies, political geography and other because a single theory of transition is insufficient. Energy transition requires the restructuring of the existing energy industry and building greener industry and infrastructure while ensuring the participation of the affected parts of society. These changes in individual energy technology use and are dependent on economic development, technological innovation, and policy change (Cherp et al., 2018).

Transition research takes a "systemic perspective to capture co-evolutionary complexity" leading to phenomena such as path-dependency and non-linear dynamics (Kohler, et al., 2019). Systems thinking (von Bertalanffy, 1972) involves thinking of the whole as more than the sum of its parts. Complex system thinking (Waldrop, 1992) involves thinking of many components interacting in different ways, leading to emergent system properties such as self-organisation and resulting in complex adaptive systems (CAS). As transitions represent long-term changes in energy use by society, they may be viewed as the **co-evolution of three systems: social, technological and political.** This view requires combining techno-economic perspectives of energy systems (see Table 3 below) with the sociology and politics of technology adoption as focussing on micro-level changes might miss more significant dynamics required at higher levels of the socio-technological system (Berkhout, 2002).

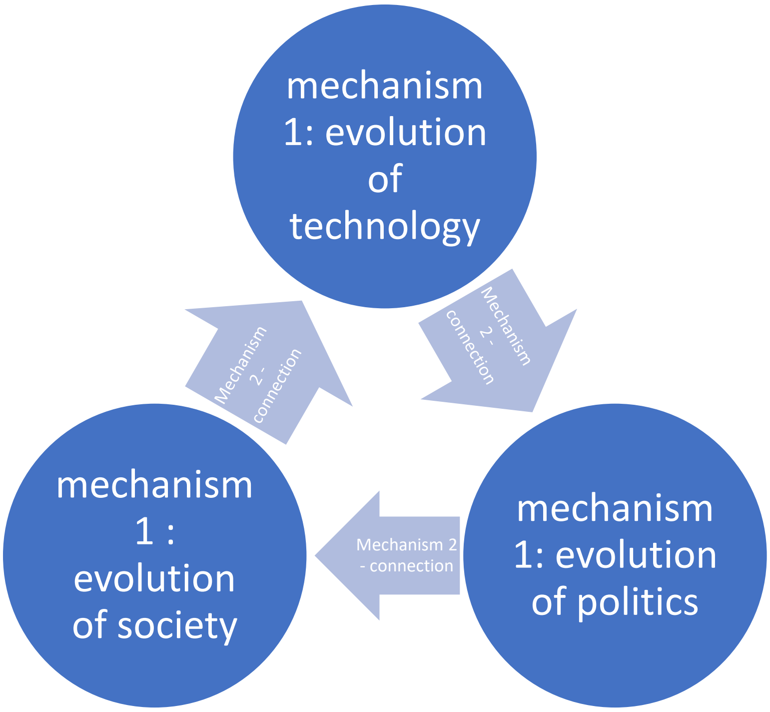
Table 3: Three perspectives on energy transition

Perspective	**Systemic focus**	**Concepts & variables**
Techno-economic	Energy flows & markets	Energy resources, energy demand, energy prices, etc
Socio-technical	Energy technologies embedded in socio-technical systems	Socio-technical regimes, niches, landscapes,innovation systems, etc
Political	Political actions and energy policies	National interests, policy paradigms, special interests, voters' preferences, etc

Source: Adapted from Cherp et al., 2018

This co-evolutionary process of energy transition involves a mechanism that explains the evolution of each subsystem and another mechanism that connects the subsystems as illustrated in Figure 4 below.

Figure 4: Co-evolutionary process of energy transition



Understanding these mechanisms involve studying the subsystem individually as well as they ways they interact together (Cherp et al., 2018). Political economist, Elinor Ostrom brought together sociologists, political scientists and economists to better understand what she called socio-ecological systems that had "relatively separable subsystems that are independent of each other in the accomplishment of many functions and development but eventually affect each other's performance," (Cherp et al., 2018). Transformative change will come about as the result of change at every level of this system. Similarly, energy transitions will be the result of decision making with culture and choice playing important roles (O'Connor & Cleveland, 2014).

2.3.1 Techno-economic systems

Techno-economic systems refer to the interconnected and interdependent relationship between technology and economics within a specific sector or industry. They encompass the technological components, economic structures, and market dynamics that shape and govern the production, distribution, and consumption of goods and services. Technological elements includes the physical infrastructure, machinery, equipment, and processes used in production, as well as the knowledge and expertise required to develop and operate these technologies. Changes in market conditions or consumer preferences can drive the need for new technologies, while technological developments can create new economic opportunities and business models. These interdependencies create complex feedback loops and dynamics within the system. The energy **techno-economic system** comprise of energy flows, conversion processes and uses co-ordinated by the energy market. These include fossil fuel deposits, transportation of fuels to power plants, petrol stations, electricity transmission and distribution, etc. Change in these systems can be explained by earth sciences such as climatology and engineering. The concept of demand and supply is used often but policies are exogenous rather than objects of analysis. The techno-economic perspective is not useful for studing inertia, path dependence and innovation in energy technologies. (Cherp et al., 2018). However, it is useful to understand technology and industry lifecyles to better understand the diffusion of technology.

Technology life cycles

The cyclical nature of economic activities follow wave-like patterns of technological change through time and have been generalised by means of the life cycle concept. Kondratief long wave cycles are caused by the growth of dominant technologies which "overwhelms the supply of natural resources upon which they are dependent" thereby raising commodity prices (Volland, 1987). This leads to the search for new sources in the medium term (10-20 years) while in the long term (40-60 years) "an exponential increase in demand causes resource-based technologies to become vulnerable to substitution by new technologies" (ibid). The cycle comes to an end as these technologies gain acceptance.

Dutch economicst Van Gelderen was the first to discover cyclical patterns of growth and decline in the economy (Ayres, 1990). Russian economist Kondratief popularised this idea with his long wave theory which identified cyclical patterns of economic booms and busts rooted in discoveries of gold, technological innovation, war, and investment cycles creating feedback processes (Ayres, 1990). Schumpeter introduced the role of innovation, R&D, entrepreneurs in creative destruction as the reason for structural change. Other researchers have posited reasons such as changes in supply of basic commodities (Rostow, 1978), the implementation of innovation (Mensch & Schnopp, 1980) innovation around transport and energy (Forrester, 1980). Perez (1983) attributes the technological aspect of long waves to socio-technical systems.

Innovations classified as General-purpose Technologies (Lipsey, Carlaw, & Bekar, 2005) such as cars, railroads and phone networks, generate waves of investments in related sectors such as shopping centres and suburban housing with respect to cars. The concepts of life cycles and of "new technology systems" have also been linked to Kondratieff s long waves. The upswing of these cycles of new technology systems increases economic growth rate and stimulates the rate of technological change as these periods tend to occur after a critical technological barrier has been overcome.

Vernon’s (1966) product life cycle hypothesis states that products go through market phases with innovation dominating the beginning, and price and marketing competition become more important as the product reaches maturity and obsolescence. Innovation comes about as a result of an opportunity or threat and is largely based on the needs of the home market. R&D investments are higher at this stage and the innovations of firms headquartered in a given market “tend to reflect the characteristics of that market” thus explaining the labour-saving features of US products, material-saving features of continental European firms and Japanese products that conserve material, capital and space (Vernon, 1979). The focus on technological innovation is associated with the availability of knowledge and skills. As the production process becomes standardised, the level of required skill decreases, and firms can set up production facilities in foreign locations on the basis of real or imagined monopolistic advantage. However, the development of the production process which takes place as the innovation itself develops, requires access to higher levels of skill as well as space and access to well-developed transportation networks.

The high levels of R&D investment required is a risk innovators are willing to take in the acquisition of competitive advantage. R&D investment is also required for process development. As the product design is standardised, products compete on price, leading firms to search for ways to reduce the unit cost of the product through process development or increasing the production scale.

The industry life cycles (ILC) literature examines patterns in the emergence and decline of industries and is closely related to product life cycles and technology life cycles in the sense that these patterns are driven by the move from product to process innovation and the advantages of spreading R&D costs over large quantities (Markard, 2020) Anderson and Tushman's (1990) technology evolution model incorporates the lifecycles of individual technologies. A "technological breakthrough, or discontinuity, initiates an era of intense technical variation and selection, culminating in a single dominant design" Anderson and Tushman's (1990). Gort and Klepper's (1982) ''life cycle of the market'' measures the diffusion of new products and innovations as well as the entry of new firms and provides insights into related markets and industries while describing how industries emerge and develop. Emerging markets feature ill-defined products, low volumes, high levels of uncertainty and few market entrants. According to Markard (2020), "This phase is followed by a period of rapid growth in which standards and value chains form, many new actors enter and sales take off. At some point, markets become saturated, growth slows down, competition increases and there is a shakeout with many firms leaving the industry. This leads to a final phase of stabilization."

The processes of technology emergence and decline are relevant to sustainability transitions to ensure sustainable technologies are nurtured while unsustainable ones are transitioned out. Technological decline in energy has been accelerated through the use of policies that phase-out coal and nuclear plants. System building during the formative phase leads to the emergence of the technological innovation system (TIS) which becomes rigid and path dependent as it grow in size. The TIS consists of networks of actors and institutions who contribute to the generation and diffusion of the relevant technology. Positive feedback effects are generated through interaction between elements of the system resulting in the emergence of formal and informal institutional structures that specifically support the development of the technology resulting in co-evolution of the TIS and the underlying focal technology. The growth phase of the TIS is develops as result of positive feedback and cumulative causation (Markard, 2020).

Technology can take many forms and can be used to refer to tools, products or processes as well as soft aspects such as knowledge and organisational capabilities. The many forms of technology that encompass knowledge as well as physical manifestations. Technological innovation towards a low-carbon transition fall into the following categories:

- Technology to reduce emissions
- Renewable energy technology

- Energy efficiency
- Technologies related to work and supply chains

Generally, improvements in mature technology are outpaced by innovations in emerging technology as evidenced by the case of electric lights where consumers switched from kerosene lamps to electric lamps for quality and safety reasons even through the electric lamps were more expensive (O'Connor & Cleveland, 2014). Focusing on newer better technology might ignore changes in better processes where incremental changes have a profound effect because of capital turnover rates (Berkhout, 2002). However, the direction of innovation needs to be changed from improving dirty technology to creating new clean technology and processes. Path dependence in technology decisions can impact present technological structure. In the UK, the manufacturing industry's transition from wood to coal took 150 years as the many sub-sectors had different technological requirements and institutions for the dissemination of knowledge and skills (Fouquet, 2010). Path dependent phenomena often lead to a multiplicity of equilibria leading to unique outcomes. The pathway selected is contingent on initial conditions and expectations about the future (Aghion et al., 2019, pg 71).

Adoption of new technology is also dependent on **local geographical and economic factors** such as watermills located on rivers. Similarly, windmills for grinding grain reduced the need for draft animals and labourers in counties where geographical conditions were favourable and a sufficient market existed for the products (Fouquet, 2010). Coal-intensive industries were located closed to coal reserves and inexpensive labour in France discouraged innovation in technology (Allen, 2009).

Similarly, the demands of particular localities or situation can encourage what Allen (2009) calls 'micro-invention' which is when a new technology goes through incremental innovation suited to a particular task or region. This can help diffuse new technologies to new areas or industries as highlighted by the diffusion of Newcomen's steam engine to Cornwall. Newcomen steam engine was highly inefficient and only cost effective when coal was cheap as in Newcastle. Many years later, engineers working in mines across Cornwall made several improvements that increased the steam engine's fuel efficiency to the point where it became cost-effective everywhere. These improvements were motivated by the higher price of coal in Cornwall (O'Connor & Cleveland, 2014).

Energy intensity and energy efficiency as drivers of transition

Energy intensity refers to the energy cost of producing an economy's aggregate economic output. It is calculated as energy use/real GDP measure the efficiency of an economy's energy use. Energy intensity generally increases with industrialisation and modernisation but declines as energy quality and energy efficiency increases. The substitution of lower quality fuels with higher quality fuel reduces energy intensity. Similarly, improvement in energy efficiency as a result of technological improvements also reduces energy intensity. In the US for example, energy efficiency in lighting increased dramatically as users moved from whale oil, candles, kerosene lamps and finally to electric lamps (O'Connor & Cleveland, 2014). A similar efficiency increase occurred with transition from steam engine, steam turbine, internal combustion engine and the gas turbine.

Energy intensive production processes can be improved through input substitution where energy is substituted by labour or capital or the development of new energy efficient production techniques. Industrialised countries have witnessed a decrease in energy intensity as a result of efficient energy use. Metals and machinery have seen green innovation however energy consuming industries such as food, beverages tobacco and rubber and plastics, have not seen similar progress. Japan, US, Germany and South Korea dominate the global share of green innovation (Wurlod & Noailly, 2018).

Commenting on the shift to renewable energy, Berkhout (2002) discusses the need for acceptance by a broad range of market actors as well as the removal of economic and political constraints. He also suggests that history suggests technological substitution may be the preference and that enabling a new regime "may involve the active closure of an existing regime." However, he also reminds us of the paradox of entrenchment in the case, where radical innovation requires substantial institutional commitment but might also mean becoming entrenched in inferior technology. He therefore suggests striking a balance between maintaining options as well as retaining the option to retreat.

Socio-technical systems

Socio-technical systems incorporate social as well as technical aspects of the system. This distinction is relevant because of the difference in nature of these elements. The socio-technical perspective deals with technological change and the emergence and diffusion of new technologies. Technology is a social phenomenon where knowledge and practices are embedded in infrastructure and artefacts. This is relevant for large technological systems, such as energy systems, which originated in the late 19th or early 20th century and incorporated technical components, such as power plants and utility companies and social components such behaviours and practices. The inventors and engineers who developed the technology were joined by financiers and managers who helped diffuse the technology through capital investments and management practices rooted in rationalisation and efficiency (Hughes, 1987). Human capital investments are associated with the changing inputs that have generated technological advances and the changing skill requirements of new technologies (Nelson & Sampat, 2001). However, as these systems extended over through time and geography, they gained inertia as well as distinguishing regional characteristics (Hughes, 1987). The socio-technical system is discussed in greater detail in section 3.3.

The political perspective

Governance of transitions and the politics of transition are two themes within the sustainability transitions literature. Transitions are considered a largely political process because "different individuals and groups will disagree about desirable directions of transitions, about appropriate ways to steer such processes and in the sense that transitions potentially lead to winners and losers. As incumbent industries might be threatened, they often exercise power to protect their vested interests and resist transformative innovation. At the same time, new entrants or actors in favor of alternative socio-technical configurations will lobby for public support" (Kohler, et al., 2019, p. 10). Therefore, the energy transition literature highlights the role of public policy in transition.

The state is the main unit of analysis in the political perspective on energy transitions and may be studied as an autonomous actor or how its policies reflect the interests of various competing groups which in turn affects the energy system. Political action systems also include the actions of voters and interest groups, regulations, laws etc (Cherp et al., 2018). Institutions also play an important role in the political perspective. The next section examines the policy mixes that impact transition.

2.4 Policy mixes for energy transition

Historical choices related to technology and infrastructure impact the current energy mix. Policies that focussed on security of supply without considering environmental impacts are unsuitable for the current landscape. However, policies like institutions are carriers of history and therefore it helps to understand how present policies related to energy came about.

2.4.1 Co-evolution of energy policy

The history of energy policy is complex and has evolved alongside the changing social and energy landscape. Examining the dominant carriers in the primary energy mix and their associated policies is one way of examining the evolution of energy policy. Coal was the predominant fuel of the late nineteenth and early twentieth centuries. As industrialization took hold, early energy policies emerged to address the exploitation of coals and concerns such as access to resources, safety regulations, and infrastructure development.

The emergence of oil as the dominant fuel in Western Europe and the United States occurred between the 1940s and 1970s (Melsted, O., & Pallua, I. 2018) and is closely tied to the evolution of US, UK and Western European energy policy. Although the rest of the world used little energy until 1960, the development of the global oil industry impacted the energy policies of countries around the world.

The beginning of the oil industry

The UK and Europe have a long history of oil technology. The first commercial oil wells in Europe were dug in Poland in 1853, Romania in 1857, Germany in 1859 and Italy in 1860. Despite the lack of significant levels of oil production, France, Germany and Italy have an important oil heritage contributing to the discovery and development of oil fields around the world. The UK played a leading role in the development of petroleum technology from the 1880s to the 1910s. However, interest for oil exploration in Britain diminished with the passage of the Petroleum Production Bill in 1918 which conferred landowners with the rights of ownership of any minerals found on their land (Craig, J et al., 23018). Prior to the North Sea discovery, British oil supply was dependent on imports from its colonies as well as America.

At the same time, drilling technologies developed in the US, made it the homeland of the oil industry producing more than half of the oil extracted worldwide between 1903 and 1962 (Graf & Skinner, 2018, p. 23). The first modern oil company is generally considered to be Standard Oil, founded by John D. Rockefeller in 1870. While there were various smaller oil companies and entrepreneurs involved in oil drilling, production, and refining activities at the beginning of the oil rush in the US, Standard Oil's emergence and subsequent dominance marked a significant milestone in the history of the oil industry.

Standard Oil achieved a near-monopoly in the oil industry, controlling a significant portion of oil production, refining, and distribution which allowed the company to exert influence over market prices, supply, and competition and shape US energy policies. The company was broken up into a number of smaller regional firms in 1911 following the Sherman Antitrust Act. However, the dissolution of Standard Oil sowed the seeds for the birth of five of the seven biggest oil companies of the 20^{th} century.

Post-war expansion

Oil use expanded after the Second World War making the US the world's biggest consumer in the 20th century. A similar increase was mirrored in Western Europe aided by the Marshall Plan which spent ten per cent of European Recovery Program (ERP) funds on oil supplied by the American oil industry (Graf & Skinner, 2018, p. 20-21). However, this increase was dwarfed by American demand. Between 1920 and 1960, oil and gas use increased from 17.7 to 73 per cent in the United States. Oil fueled the chemical industry and transformed agriculture creating further dependencies.

Western economies in the 1950s and 1960s underwent industrialization and mechanisation as a result of post-war reconstruction. The Marshall Plan which focussed on international trade among Western countries and the establishment of international institutions transformed Western society so that "unlike during the Interwar period, ordinary people did not need to fight to survive, but could concentrate on living - and, thus, consume energy. In short, energy was essential for the daily operation of society (Rudiger, 2014).

The production, transportation, and marketing of oil in the period after the Second World was controlled by the US, the UK and the “Seven Sisters”. The “Seven Sisters” was the name given to the seven leading oil companies of the early 20th century: Exxon, Mobil, Royal Dutch Shell, BP, Chevron, Gulf Oil and Texaco who can trace their development to the early days of oil exploration (Sampson, 1991). The complex web of relationships between these companies, 5 American and 2 British, and governments, shaped the oil industry, national development, geopolitics and controlled oil prices. After World War II, the Seven Sisters, experienced significant transformations and changes in their operations. They played a major role in developing oil fields in the Middle East, Latin America, and Africa, establishing long-term contracts and securing access to new oil sources. State power provided diplomatic and military assistance in defence of petroleum interests, while the "sisters” negotiated with governments over royalties, taxes, and posted prices (Keohane, 1982).

The close ties between oil and foreign policy is reflected in the three departments which handled oil policy in the UK – the Treasury, the Ministry of Power, and the Foreign and Commonwealth Office (FCO). The government maintained tight institutional connections to both firms; it was a shareholder in BP and had forged connections with Shell during the Second World War through the Shell-Treasury Agreement of 1946 which gave the Treasury control over the company’s access to foreign exchange. Decisions regarding oil matters were made on an ad-hoc basis with guidance from BP and Shell as government officials lacked the technical expertise. The British government provided strong support for the interests of BP and Shell in their foreign affairs as oil sales significantly helped the balance of payments (Kuiken, 2014). The North Sea discovery however, brought oil policy to the forefront of British politics.

The 1970’s oil crises and energy policy

In the 1970s, oil producing countries like Saudi Arabia, Iran, and Venezuela nationalized their oil assets, reducing the influence and control of the Seven Sisters. The 1970s oil crisis refers to a series of events in the 1970s beginning with the Organization of Petroleum Exporting Countries (OPEC) Oil Embargo of 1973 in response to the Yom Kippur War between Israel and a coalition of Arab nations. OPEC members, led by Saudi Arabia, imposed an oil embargo on countries perceived as supporting Israel, including the United States, Canada, and several European nations leading to a significant reduction in oil supplies and resulting in a sharp rise in oil prices. This was followed by the Iranian Revolution in 1979 which resulted in the overthrow of the Shah of Iran and the establishment of an Islamic republic. Iran's political instability and the disruption of Iranian oil exports contributed to a second oil crisis, causing oil prices to surge again. The oil price shocks pushed oil out of power generation which turned to coal and gas instead. Yet oil, continued to dominate the transportation sector.

The 1970s oil crises had profound effects on the global economy and energy policies. Governments around the world implemented measures to conserve energy and reduce dependence on oil, such as promoting energy efficiency and alternative energy sources. These events also led to a shift in geopolitical dynamics, with oil-producing nations gaining increased influence and control over global energy markets.

Although the British government anticipated changes in the structure of the international oil industry since the Iranian Nationalization Crisis of 1951, they were unable to formulate new policies to mitigate the risk because they were keen to move from their reliance on BP and Shell. At the same time, there was confusion over decision making authority with regards to oil as well as the discovery of newfound resources in the North Sea (Kuiken, 2014). At the same time, British political interests in the Middle East necessitated a separation of the commercial dealing of the oil companies and the state. The government's push for independent policy and the growing role of the state in the North Sea created a divergence between government and corporate policy with regards to oil causing BP and Shell to pursue the establishment of an international system of oil that transcended the State.

Over time, the original Seven Sisters underwent significant changes through mergers & acquisitions, and were reduced to the 5 oil majors of the present day. Some companies merged or were acquired by others, leading to the emergence of new entities in the energy sector. For example, Exxon and Mobil merged in 1999 to form ExxonMobil, while Chevron acquired Texaco in 2001. The energy landscape itself underwent significant changes with advancements in technology, the growth of renewable energy, and increasing concerns about

US energy policy

The evolution of US energy policy is closely tied to its foreign policy as well as the development of the oil industry. At the end of the nineteenth century, energy was produced either locally or regionally. This meant that decisions and policies were also developed at the local level. The absence of a comprehensive energy policy coordinating the development of energy resources led to the independent regulation of specific resources such as oil, coal, and natural gas. It was during this time that Standard Oil exerted significant influence on US energy policy through its dominance in the oil industry.

From its beginnings, the US was haunted by fears of oil shortage in economy making energy security and independence, important policy goals. According to Keohane (1982), "The 1940s were critical years for United States foreign oil policy." After unsuccessful attempts to implement governmental initiatives, ensuring the steady supply of oil was left largely with the major international firms. This meant that US energy policy related to oil was constrained by the political power of the oil companies. Further, American foreign economic policy in the 1940s was "shaped both by state initiatives and by industry influence, with the industry in a consistently strong position" (Keohane, 1982). According to Keohane (ibid), the 1940s sets the limits of state initiatives as "government officials' actions toward the industry then were more vigorous than they have ever been since."

The oil crises of the 1970s had a profound impact on U.S. energy policy, leading to significant shifts in energy priorities and strategies. The crises exposed the vulnerability of the United States to disruptions in global oil supply. As a response, energy policy focused on achieving energy independence and enhancing energy security. The U.S. government sought to reduce dependence on imported oil by increasing domestic oil production and diversifying energy source. It also led to the creation of the Strategic Petroleum Reserve aimed to build stockpiles of oil to mitigate the impact of future supply disruptions. The oil shocks also prompted increased interest in alternative energy sources and technologies. The establishment of agencies like the Department of Energy in 1977 reflected the growing focus on diversifying the energy mix and reducing reliance on fossil fuels. Prices of all energy sources were regulated and the first energy plan was presented in 1978 (Ryan, 1979). The objective was to control energy use and thereby achieve energy independence. Despite the importance of energy as a key intermediate input for the economy, policy initiatives focussed on short term issues such as supply shocks. The National Energy Act of 1978 represented a comprehensive overhaul of U.S. energy policy that included measures to promote energy conservation, encourage domestic energy production, and support the development of alternative energy sources.

While some countries developed policies to diversify energy sources to ensure energy security and indepence, US energy policy became intertwined with geopolitical considerations, particularly during times of conflict or international tensions such as the Cold War. According to Tomain's (1990) "dominant model of US energy policy", the prevailing US energy policy supports conventional fossil fuel and the "recognition that some segments of the energy industries possess market power requiring regulation." The policy has developed over decades of symbiotic relations between government and industry as well as the federal structure of the US. Since the Industrial Revolution, energy regulation has been used to control the production and distribution of energy.

The American public expect policies to reduce energy prices and politicians view support for price increases as detrimental to their careers (Joskow, 2003). With this prevailing view, energy policy debates have pitted Democrat vs Republican as well as a variety of special interests (industry vs consumer, energy producing vs consumers states,) against each other.

EU energy policy

Like the US, the need for a common energy policy was recognised only after the 1970's energy crisis. The European Coal and Steel Community established in 1951 and the European Atomic Energy Community established in 1957 were primarily focused on their own sectoral policy requirements. The first energy policy objectives focussed primarily on reducing energy dependence and consumption. Subsequent policy initiatives failed because of differences in resource endowments and energy policy was largely developed at the national level. The presence of the International Energy Agency in Paris also served as a deterrent to the development of a common energy policy.

Energy policy

Energy policies are derivative policies that reflect higher level policy objectives related to infrastructure, energy security, environment, industrial competition policies and the use of publicly owned resources (Joskow, 2003). They initially came out as a result of the 1970's energy crisis which raised concerns about the security of supply. The rise of consumer culture in Western economies created a difference in policies pursued by countries with their own (of access) to energy resources and countries that had to import them.

The primary aim of energy policy is to secure the supply of energy by stimulating investment in fossil fuel extraction, building power plants, transition and distribution grids. However, the oil shock of 1973 considerably expanded the scope of most national energy policies. Security of supply and diversification of energy sources and transportation routes then came to the forefront of energy-importing countries. At the same time, security-of-demand drives the depletion policies of energy-producing countries along with the rise (or fall) of resource nationalism. The environment initially did not feature in these policies.

Governments are one of many actors in the formulation of energy policy (Hughes & Lipscy, 2013). The challenge of setting energy policy arises because of different individual preferences with regards to environment, supply/demand security and economic competitiveness. The Arrow paradox (Arrow, 1951) has shown preferences related security of supply and concern for the environment are incompatible (Zweifel, Praktiknjo, & Erdmann, 2017) in societies with heterogenous preferences and explains why failures in energy markets are difficult to correct. One reason for that is attributed to self-interest decision making by politicians to correct these market failures. This idea is further explored in section 3.4.

Incoherent policy design and implementation create challenges when policies that require co-ordination across different institutions are implemented. For example, cantons and federal governing bodies in Switzerland, interpret the national energy strategy differently creating challenges in the policy implementation process.

Governments can stimulate innovation through policies that support low-carbon technological innovation and by fostering market demand. Similarly, governments and politicians can create barriers for those technologies that are deemed unfavourable. Nuclear power is an example of low-carbon technology that polarises opinions. Policies can induce technological change through the development of preventive technology that eliminates waste and reduces emissions as well as abatement (end of pipe) and clean (process innovation) technology related to pollution control and waste management. However, distinguishing between clean and dirty technology is difficult as definitions rest on claims made by producers. (Berkhout, 2002). Technological innovation requires finance for deployment. High upfront cost and unstable market situations act as barriers in the transition from large-scale centralised utilities to small-scale decentralised energy generation. Therefore, policies must create a favourable investment climate to encourage investment. Investment in risky renewable energy technology becomes less risky in the face of long-term energy contracts or FIT. Initiatives backed up by the government also help investors understand long-term market potential for new technology while time-limited programmes overcome deployment challenges.

Different fuel types have different environmental and national security externalities and cross national variation in energy demand supply management depends on which energy sources are prioritised. Development of alternative energy sources was the key focus in the 1980s followed by liberalisation of energy markets in the 1990s and sustainability. For this reason, understanding the political influence on technology selection is crucial for developing transition pathways.

The importance of oil to a country's economy means that most oil policy is shaped by energy security implications and becoming an oil producer depends on a country or company's ability to obtain ownership of fossil fuel reserves. As different fuel types have different scope (domestic vs international) a careful study of energy markets and the interests of the participants and the relative importance of the different fuel types is also necessary. The economic interests of producers and the consumers who use energy products in industrial processes are also relevant (Hughes & Lipscy, 2013). Therefore, countries such as France (nuclear) and Austria (renewable) have moved away from fossil fuels to ensure security of supply. However, the relationship between fuel import dependency and energy policy is not easily defined because of differing institutional capacities and the structure of energy markets which depends on fuel type. Further these markets change over time along with concerns over particular fuel sources (Hughes & Lipscy, 2013).

2.4.2 Renewable energy and transition policy

US energy policy recognised the interaction of environmental and energy policy as far back as the mid-1970s but found no conflict between increased energy consumption and improvement of environmental quality (Ryan, 1979). However, fossil fuels as we know have caused considerable damage to the environment and continue to do so as their price does not take account of externalities. Taxes are important for reducing emission, technology hedging and building technology portfolio strategies that can help balance technological uncertainty (Grubler & Gritsevskyi, 2002). Implementing an optimum environmental tax would be the most efficient solution to internalise environmental externalities as this would incentivise innovation and change consumer behaviour (Menanteau 2003). Instituting energy taxes can reduce energy demand, as evidenced in the Californian decoupling system, which rewarded energy companies for supplying less energy rather than more. However, as taxes are politically unpopular, policies are required to correct market failures caused by fossil fuels.

Environmental policies target air pollution (Nox, So2, Co2, etc.) caused by the combustion of fossil fuels and renewable energy (RE) policies encourage the development of the renewable energy industry. RE Policies must overcome the twin problems of uncertainty and discontinuity, as viewed by investors, to be successful. Further, as countries use a variety of policies to promote renewable energy, an appropriate policy mix must combine policies that reduce pollution and stimulate learning and innovation (Nicolli & Vona, 2019). Policies drive investment in new industries as they minimise risk, induce innovation and encourage knowledge complementarities or spillovers. Therefore, an optimal policy mix is required to resolve multiple issues as investors face high upfront costs, uncertainty, risks and long payback periods. Initially, market-opening policies may stimulate technical change and learning processes to help renewable energy prices become more competitive. At the same, time, voluntary approaches have a negative influence on RE growth (Aguirre & Ibikunle, 2014). The key, therefore, is to design a policy that considers the specific market conditions. Technology-specific policies that consider actual market conditions and the position in the technology life cycle are necessary for renewable energy investment(Polzin et al., 2014). For example, feed-in-tariffs (FIT) have successfully developed the solar PV industry as they provide strong positive signals to investors and have been successful in Germany and Italy.

Tradable permits and regulatory mechanisms such as codes and standards have been successful for the wind energy industry (Polzin et al., 2014).

In a developed market, the objective must be to integrate RE into the market while reducing the cost to society. Some policies impede growth simply because of uncertainty about the continuation of the policy. RE requires assistance with commercialisation and diffusion such as policies that accumulate experience in environmentally friendly technologies, early adoption and niche market and reduce "dead weight loss to society associated with the exploitation of FF" (Nakicenovic, 2002). The generation phase requires mitigation policies while the diffusion stage faces path dependency from fossil fuels, so it requires regulation to stimulate the market and dissolve path dependency. Fiscal and financial instruments are negatively linked to renewable energy growth as they are unlikely to be in place over the long term leading to investor uncertainty (Aguirre & Ibikunle, 2014). For example, the Production Tax Credit in the US created a boom-bust cycle in wind power investments damaging the industry's prospects. These instruments are further deemed uncertain during economic downturns such as the 2008 recession. 5-10 year policy incentives are generally viewed as appropriate by the industry. However, legislators hesitate to introduce long-term spending plans (Aguirre & Ibikunle, 2014).

As markets alone do not solve market failures, technology-push policy instruments, such as R&D and tax credits for R&D, foster technical change from the demand and supply side. This, however, depends on exploitable technology and a body of knowledge within each sector, which requires the support of other policies. Demand-pull policy instruments such as tax credits and rebates for new technology drive demand, which drives innovation and indicates that buyers are willing to pay for innovation. Systemic instruments target the system as a whole and not just parts of the innovation system and act as a platform for technology push and demand pull.

Policies that develop market incentive structures that encourage market growth and reduce prices have the potential to create a feedback loop through vicious cycles (Watanabe, Griffy-Brown, Zhu, & Nagamatsu, 2002). In Japan, the development of PV technology was embedded in a web of related technologies, such as semiconductors, to maximise the accumulation of knowledge stock. Public and private R&D was combined with spillover, learning effects, and economies of scale to maximise the benefits of network externalities arising from technological interrelatedness.

History matters in energy transition because of the capital-intensive nature of the energy industry and the long lead times to profitability. Historical technology and infrastructure choices impact the current energy mix, and traditional economic tools of cost-benefit analysis are insufficient to deal with the urgency of climate change effects. For Aghion et al. (2019, pg 68), climate models miss the deviations caused by compounded innovation that alter the economy's structure. Standard integrated assessment models are sensitive to arbitrary parameters. In contrast, Nordhaus's neoclassical DICE model hardwires trade-offs between lower consumption now for higher consumption later, leading to policy interventions at a slow or gradual level (Aghion et al., 2019, pg 68). This means that future energy policy must consider the environmental aspect of energy use while changing the current energy infrastructure. Recently, the Nordhaus' DICE model, which states that substitution is better than induced innovation in implementing climate-change policies, has been criticised by several experts for suggesting that no action on global warming would result in a temperature rise of 3°C, but an "optimal policy" would slow the rate of warming only marginally. Policies may focus on quantities or prices. Table 4 below provides examples of policies that support RE.

Table 4: Policy types

	Price	Quantity
Investment	Investment incentives Tax credits Low-interest loans	Tenders for grants
Generation	FIT	Tenders for extended-term contracts Tradable green certificates

Source: (Kilinc-Ata, 2016b)

Quantity-based renewable energy policies

Quantity-based approaches focus on national targets and setting up bidding or quota systems for green certificate trading. In competitive bidding processes, renewable energy producers bid to produce a pre-determined amount of renewable electricity for electric utilities, which are then obliged to purchase this electricity. The regulator generally organises the bidding competition. Producers are then awarded long-term contracts to supply electricity. Implicit subsidies correspond to the difference between the bid and wholesale market prices and are not borne by consumers (Menanteau et al., 2003). As the RPS is a quantity regulation instrument that comes under a command-and-control type policy, promoting low-cost technology as utilities are free to choose any RE technology.

In a Green Certificates scheme, a fixed amount of electricity has to be generated by renewable energy sources. The amount is decided for the country as a whole as in the bidding system. However, this system's marginal production costs are more efficient, and renewable energy generators are encouraged to enter the market (Menanteau et al., 2003). Although FIT would result in similar cost efficiencies, the overall amount generated might differ. Utilities can generate electricity or can be purchased using green certificates from renewable energy generators (Menanteau et al., 2003). Renewable electricity generators can sell electricity at market prices on the network or sell green certificates on the market.

Negotiated voluntary agreements involving multilateral partnerships within and between countries, such as the Global Methane Initiative (GMI) or the Kyoto Protocol, have been positively linked to renewables growth (Aguirre & Ibikunle, 2014) as they encourage technology transfer. However, other voluntary agreements have a negative relationship with renewable energy growth as they allow governments to appear to take environmental action but only serve to confirm the business-as-usual (BAU) scenario for companies. Voluntary agreements are best used as a transitional measure to inform the market before introducing mandatory policies.

Price-based renewable energy policies

Price-based incentives include feed-in tariffs (FIT). FIT is a price regulation instrument that stimulates RE investments by providing guaranteed prices for fixed periods, thus reducing risk and creating conditions for rapid market growth (Couture & Gagnon, 2010). These instruments can be differentiated by several factors such as technology, size and quality of installation, location of the project, etc. and are generally considered a challenge to utilities as they enable a variety of investors such as homeowners, farmers and municipalities (Couture & Gagnon, 2010; Jenner et al., 2012). FIT provides strong positive signals to investors, particularly for solar and has been successful in Germany and Italy (Polzin et al., 2014). FIT policies can be structured in several ways, each with strengths and weaknesses.

Market-dependent FIT offers a fixed or minimum price for renewable electricity delivered to the grid, allowing RE developers to compete with suppliers to meet market demand. A **premium price policy** offers a bonus above average retail price and can consider environmental, social or generation costs. The premium price option generally operates in deregulated electricity markets and is better suited for larger producers than homeowners or community producers who offer electricity on the spot market. To avoid windfall profits due to rising retail prices, a **variable premium FIT policy** implements a cap and floor to ensure reasonable overall remuneration. The cap and floor have the dual advantage of reducing risk for investors and reducing societal costs (Couture & Gagnon, 2010).

The **percentage of retail price model** sets a fixed percentage of the retail price for electricity purchases. It is the riskiest policy from a producer’s perspective and is integral to the policy learning process. However, their high-risk and cost factors make them unlikely to be used in the future (Couture & Gagnon, 2010). Market-dependent policies have been criticised for higher per-kWh costs for RE and are considered lower cost-efficiency (Couture & Gagnon, 2010).

Market-independent fixed-price FIT “offer a guaranteed minimum payment level based on the specific development cost of the technology for every kWh of electricity sold to the grid” and are more commonly used. These policies are usually tied to a purchase guarantee with payment levels set to cover project costs so that solar PV systems pay more than onshore wind power. They may also have inflation adjustment guards to protect the real value of the revenue (Couture & Gagnon, 2010). This may be relevant only for jurisdictions where inflation rates are high. However, they have been criticised for distorting electricity prices and ignoring prevailing demand. Front-end loaded FIT models offer higher payment in the early years of the project’s life and can be fine-tuned to consider project location and balancing costs. Although they make a project more expensive during the early years, they also provide additional financing when loan payments are higher (Couture & Gagnon, 2010).

In the spot market gap model, the government pays the difference between the spot market price and the required FIT price. This stops additional costs from being borne by taxpayers as ratepayers usually integrate these costs into the electricity rate base. Although this model is subject to the vagaries of budget allocations, it increases the market participation of renewable energy (Couture & Gagnon, 2010).

Transition policy

Transition policy offers another way of creating diverse options for complex adaptive systems such as the energy sector. Policies and institutions are viewed differently in transition policy which blends the fields of environment, energy and technology and includes policy, the development of knowledge and societal, institutional and behavioural change (Constantini & Crespi, 2013). When viewed through the lens of transition policy, public policy must focus on improving variety selection instead of results. As policies are influenced by resource availability, consumer behaviour, production capabilities and other factors, having various options increases the possibility of achieving transition objectives in the face of changing conditions. Flexibility helps navigate complex systems and facilitates the diffusion of low-carbon energy among consumers and producers in different socio-economic systems at the micro and macro levels. Adopting a transition policy framework could combat the challenges of gradually adapting a complex social-technical system such as the energy sector.

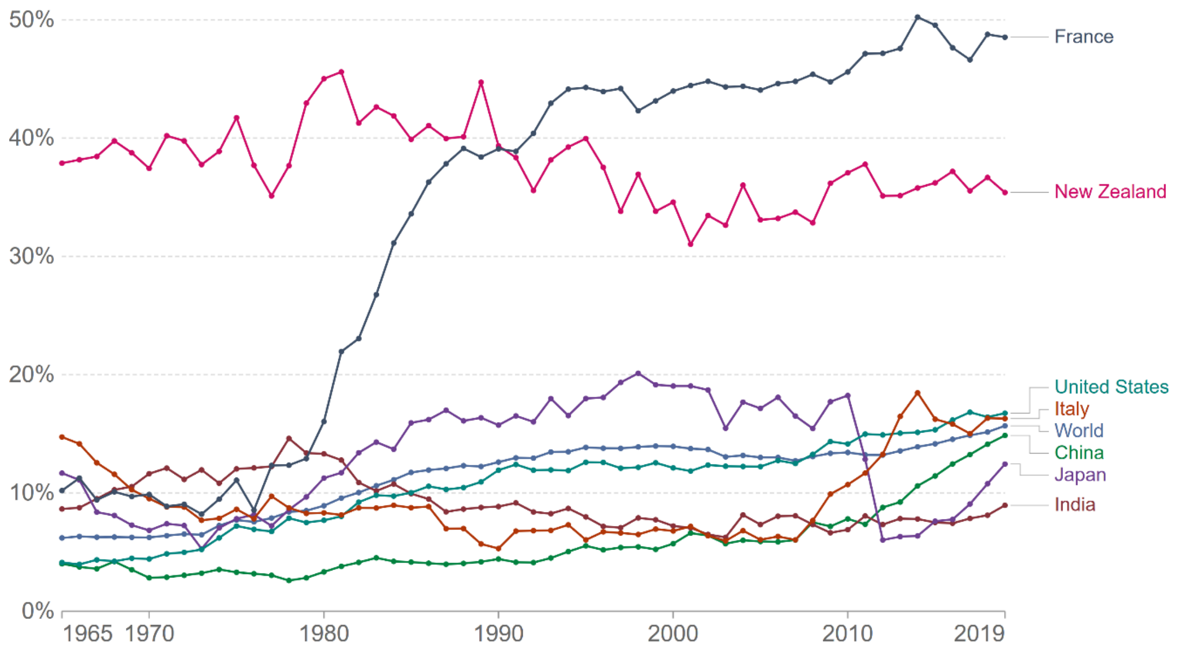
2.5 Sustainable energy transition case studies

This section examines the transition from fossil fuel to low-carbon energy in Iceland, Norway, France and Denmark. As shown in Table 5 below, these four countries were the world leaders in 4 different types of low-carbon energy; geothermal, hydropower, nuclear and wind energy, respectively, in 2019. Low carbon energy refers to renewable energy, nuclear and hydropower. It does not include traditional biofuels. Primary energy is calculated using the substitution method.

Table 5: Share of low carbon in primary energy sources in 2019

Country	Share of low-carbon sources	Largest low-carbon primary energy source
Iceland	79.08%	Geothermal
Sweden	68.89%	Nuclear, hydro
Norway	66.18%	Hydro
France	48.52%	Nuclear
Brazil	46.18%	Hydro
Finland	44.77%	Nuclear
Canada	33.94%	Hydro
Austria	33.7%	Hydro
Denmark	30.16%	Wind

Figure 5: Share of primary energy from low-carbon sources by country upto 2019



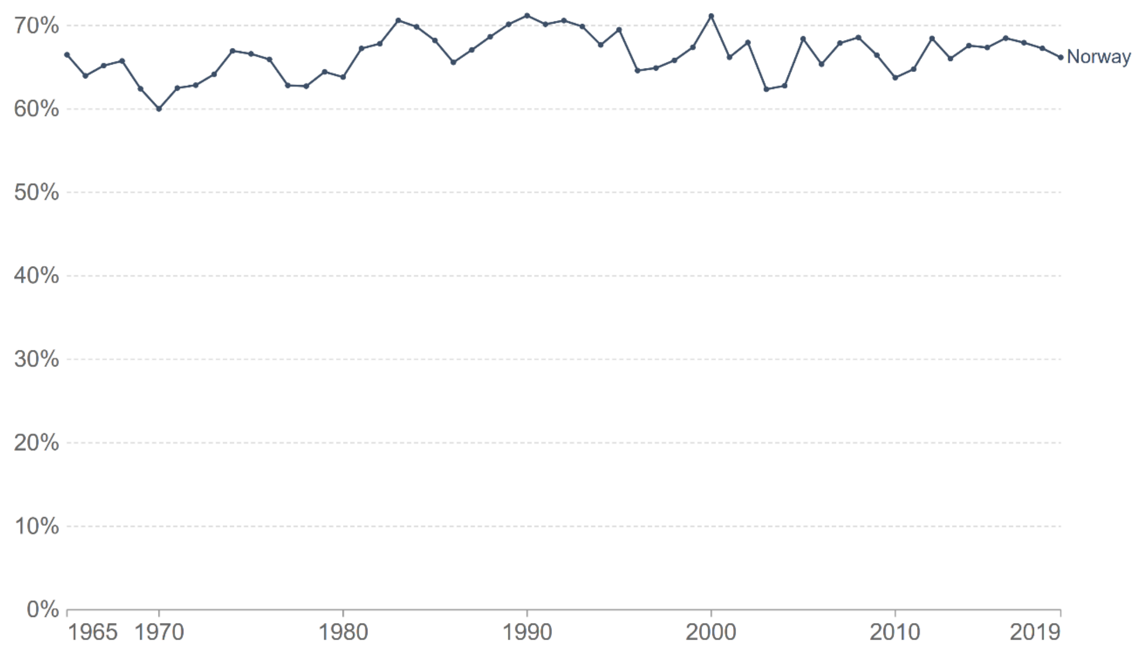
Source: Our World in Data, BP Statistical Review of World Energy

2.5.1 Norway: bountiful energy resources and a focus on sustainability

Norway benefits from various energy sources; oil and gas, hydro and wind power. Figure 6 below shows Norway's share of primary energy from low-carbon sources up to 2019.

Norway's energy history begins with hydropower development in the late 1800s (*Renewable Energy Production in Norway*, 2016). The diffusion of electricity and the electric motor between 1895 and 1920 led to the development of an industrial system based on exploiting large waterfalls (Venneslan, 2009). Initial small run-of-river projects powering local grain mills gave way to larger manufacturing plants and, eventually, large-scale plants for electrochemical and electrometallurgical production processes. By 1925 Norway produced 12 per cent of the global share of aluminium and had begun "substantial production of fertilisers, ferrous alloys and magnesium" (Tonne, 1983). Renewable energy production was thus tied to manufacturing.

Figure 6: Norway - share of primary energy from low-carbon sources



Source: Our World in Data, BP Statistical Review of World Energy

Norwegian law permits the private ownership of rivers, lakes and waterfalls. As foreign interest in Norway's hydroelectric resources and the establishment of power-intensive industries like fertilisers and aluminium began to increase, the Norwegian government passed the 'panic act' that required a concession from public authorities before acquiring a waterfall. The Nordic model of combining economic and social policies was adopted after the two World Wars leading to a large public sector and evenly distributed wealth and resources. The post-war reconstruction era created the "hydropower complex" that promoted close ties between energy and industry policies and implemented comprehensive programmes for hydropower construction and raising of energy-intensive industries. Norway was motivated by "promising export markets, need for foreign currency and electrification of the remaining parts of the Norwegian countryside" (Midttun,1988).

The program continued throughout the 1970s and early 1980s despite fulfilling these goals. Most of Norway's hydropower capacity was built during 1960-90, leading to excess capacity within the electricity sector. Deregulation in 1991 created an energy market where electricity prices provide long-term investment signals and balance short-term supply, demand and transmission. The Nord Pool electricity market was created by Norway and Sweden in 1996 to trade electricity. Finland and Denmark joined the market shortly after. Market integration with neighbouring Nordic countries and connections to the Dutch, German, Polish, Russian and Baltic energy markets provides flexibility and reduces vulnerability to fluctuations in production. Since then, Norwegian hydropower has provided base load capacity for intermittent renewable energy production, and reservoirs act as an energy store during periods of low precipitation. Financial incentives are provided to energy producers to ensure the efficient management of water stored in reservoirs. A well-developed power grid distributes renewable energy produced in different regions of Norway over the year, or in some cases, over several years (*Renewable Energy Production in Norway*, 2016)

Despite considerable oil and gas resources, Norway's preference for using hydropower and renewable energy to meet its energy requirements is based on the country's significant experience with hydropower and a robust environmental consideration. Environmentalism moved from the regional to the global level in the late 1980s when Ms Brundland became the World Commission on Environment and Development chairperson and published the Brundtland report in 1987. The report focussed on climate change as a significant environmental issue (Andresen & Butenschon, 2001).

Norway's development and control of its energy resources have been linked to the country's industrialisation and economic growth. The government's policy ensures that "these resources provide maximum benefit to society as a whole" (Tonne, 1983). As the waterfalls had been given by nature, the Norwegians felt that the benefits of the energy produced by Norwegian waterfalls should accrue to society and not the individual (Ryggvik, 2010). As the Norwegian state lacked both technology and capital, the major waterfalls were exploited by foreign companies, primarily German and French, under the condition that all exploitation rights would return to the state after a certain period. This ensured the state acquired the technical knowledge to run and manage the resource. A similar system was applied to the exploration and discovery of oil resources in the 1960s. Despite having no independent oil expertise and limited financial resources, Norway's weak negotiation position was countered by the government's insistence on controlling the pipeline transport network (Ryggvik, 2010). However, the state-owned Statoil's insistence on controlling the pipeline network resulted from political battles between Norwegian bureaucrats and the head of the state-owned Statoil company. Statoil won this battle because the head of Statoil enjoyed considerable political support (Ryggvik, 2010). As hydropower provided more than enough energy to meet the country's energy requirements, oil was always viewed as a strategic resource to improve the Norwegian economy, develop a 'qualitatively better society' and establish a national oil industry. Further, the insistence on socially-oriented management of resources ensured that wasteful industry practices such as gas flaring were restricted (Ryggvik, 2010)

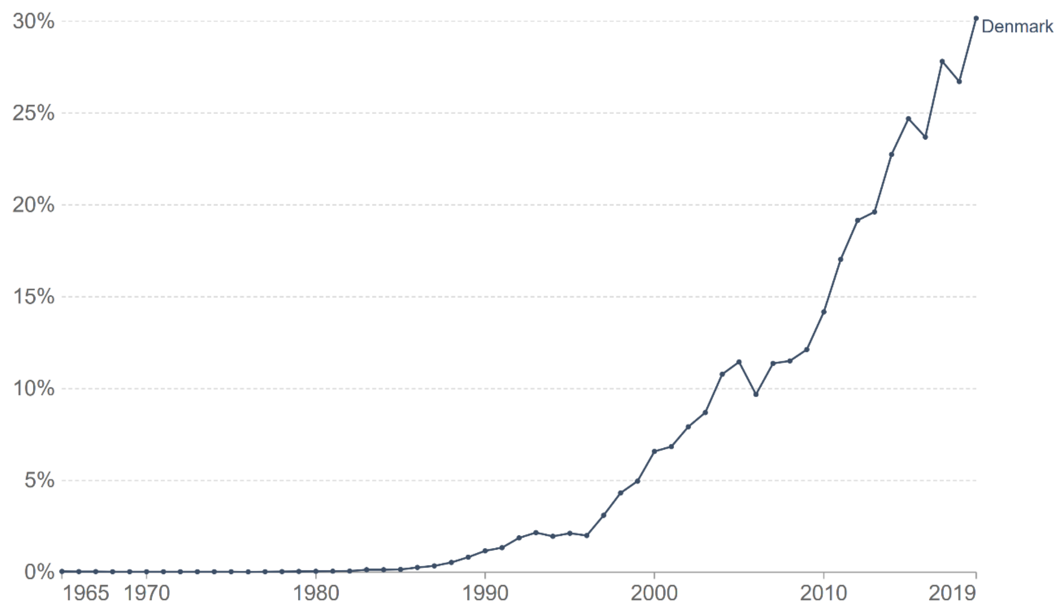
This included developing local competencies through the establishment of technical colleges. The development of technological capabilities to operate in harsh conditions offshore was built on related skills in the shipbuilding industry, which was the main driver of economic growth after World War II. Engineering and construction expertise was gathered during construction projects for hydroelectricity in 1960-1972 (Ryggvik H. , 2015). Prosperous and technically advanced trading partners such as England and Germany provided the means to build technical capabilities and export markets. This has enabled Norway to develop "a domestic market for nearly everything required to build and operate a comprehensive hydroelectric system" (Tonne, 1983). Further, "the Norwegian industry has developed the competence and capacity to construct and manage most elements of an integrated hydroelectricity and power intensive industrial system - for not only Norwegian needs but also for export" (Tonne, 1983).

Critics of Norway's energy policy have argued that hydropower's strong dominance and low carbon features have prevented the renewable energy industry from developing and led to path dependence in the energy system. Heating in Norway is primarily based on electricity and not water, as in other parts of Europe. The absence of infrastructure "to support water-carried heating systems thus effectively locks out many NRE sources that are inclined to produce heat rather than electricity, i.e. solar and bioenergy" (Christiansen, 2000). The Norwegian energy system has been locked into its present configuration because of the dominance of the hydropower and petroleum sectors in the Norwegian energy economy. Transmission and distribution capacity is based on centralised production and electrical heating.

2.5.2 Denmark: the success of CHP and wind energy as a result of political competition

The 1970s energy crises paved the way for Denmark's transformation from a country highly dependent on imported fossil fuel (90% in 1972) to one of the world's largest consumers of wind energy. Figure 7 below shows Denmark's share of primary energy from low-carbon sources.

Figure 7: Denmark – share of primary energy from low-carbon sources



Source: Our World in Data, BP Statistical Review of World Energy

The transition involved a switch from oil to coal as a fuel for electricity and from individual to district heating (Sovacool, 2016). However, this transition could only have come about with a strong environmental movement, a history of investment in knowledge and learning and community engagement. The success of Danish wind turbines has been attributed to the Danish Wind-Turbine Test Station, which unemployed engineers started with support from government funds to further innovation. The RISO National Laboratory for Sustainable Energy, established in 1956, has a turbine test centre used by turbine manufacturers worldwide. Just as in Norway, the publication of the Brundland report in 1987 (Brundtland, 1987) popularised the concept of sustainable development in Denmark. A strong R&D base in renewable energy provided windows of opportunity for environmentally conscious engineers and economists and NGOs to push through an alternative energy plan for Denmark. Intertwining energy and the environment was crucial for initiating the energy transition.

Following the energy crises in the 1970s, The Danish Energy Policy of 1976 focussed on reducing oil dependency and diversification of energy sources with a focus on coal and gas. Before the crisis, all heating in Denmark was provided by imported oil. However, the implementation of the Electricity Supply Act (1977) to improve energy efficiency and development of domestic energy sources, along with the Heat Supply Act (1979) to promote energy efficiency in generating heat for homes and buildings and the Construction of the Natural Gas Project Act (1979) initiated the diversification of energy sources. Domestic natural gas and coal-based supplies were used to expand District Heating and Combined Heat and Power (CHP) energy systems (Haselip, 2012). An energy-saving campaign was launched simultaneously, and heat generated from electricity production was used to expand district heating. At the same time, environmentally conscious engineers and economists presented an alternative energy plan. Nuclear power was also proposed but opposed by the public and electricity provider ELSAM, who wanted to avoid state intervention in the electricity section. These anti-nuclear sentiments were amplified by grassroots NGOs such as the OOA (Organisation for Information on Nuclear Power) and OVE (Organisation for Sustainable Energy), which promoted renewable energy. The OOA were particularly media savvy and focused on preventing Danish nuclear power plants from being built. Their considerable efforts influenced left-leaning politicians interested in job creation, export opportunities, and environmental benefits (Tranaes, 1997). The NGOs also instigated Danish debates on nuclear energy, and wind energy was driven from the bottom up. The Social Democrats were open to the nuclear argument but postponed plans to open atomic power stations between 1985-1993 (Kaijser & Meyer, 2018). Later, they preferred natural gas, while the Liberal party preferred nuclear power. However, the nuclear option was permanently removed when the Liberal Party fell out of power in 1986. This gave the alternative energy plan a boost.

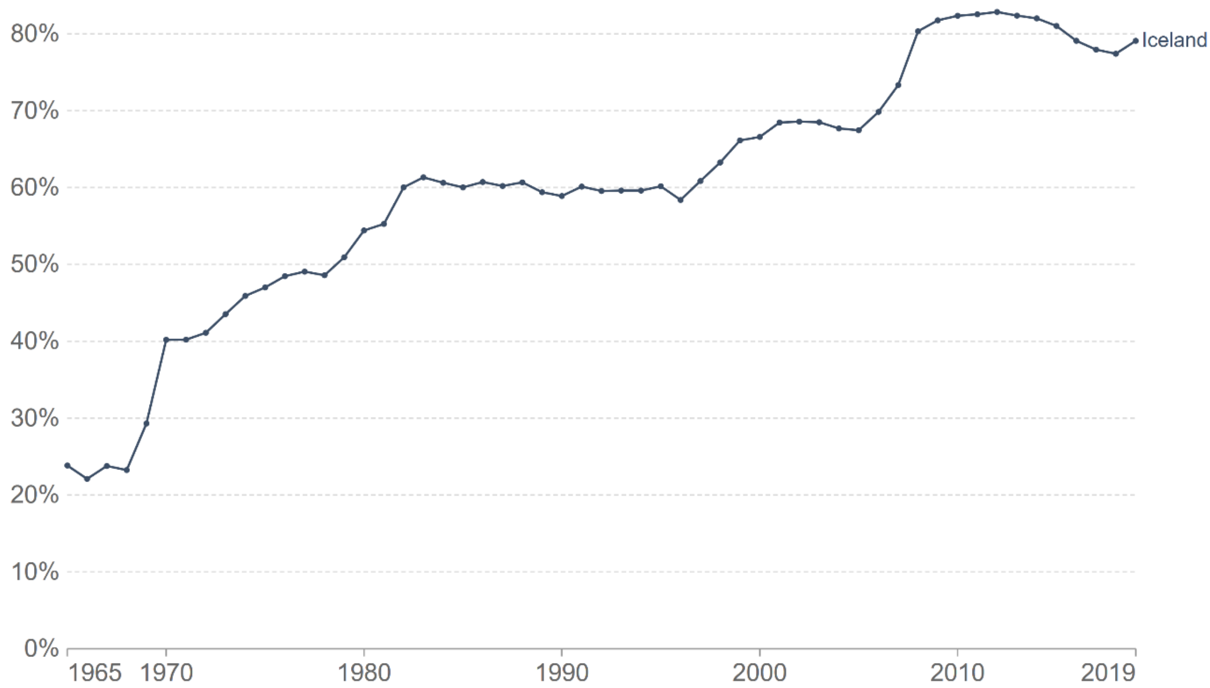
Political competition: Although wind power had the government's support in the late 1970s, the industry faced resistance from other governmental departments. It was only after installing a 'green majority' in parliament that wind power development got a boost (Tranaes, 1997). High energy taxes were introduced to incentivise the rational use of energy and continue to be used.

The transition to renewable energy in Denmark was the result of a struggle between the government and environmental groups. However, a history of distributed power generation and intense community-based action were crucial to wind energy development. Distributed power generation allowed the development of an energy paradigm that suited the characteristics of renewable energy generation – local production and consumption. Communities have a better incentive to provide public goods as they are motivated by the benefits, such as free energy input, better environmental effects, decentralised production, and the absence of government regulation. On the other hand, a utility company would factor in the cost of fossil fuel and the return on investment of a wind turbine which would not be feasible. This sentiment is echoed by Tranaes (1997), who believes that energy companies are only concerned with providing energy produced at the lowest price possible. He also believes that energy companies are preoccupied with politics to ensure they can continue supplying energy produced at the lowest price possible. The government's decision to invite environmental NGOs and utility companies to contribute to the energy plan was rooted in public sentiment. However, this decision would not have come if an alternative energy plan had not been prepared and the community actively engaged. Once this was done, the existing infrastructure of decentralised production, along with the accumulated knowledge stock and investment in R&D, set Denmark on a path of increasing returns from wind energy. The government aided this process by pushing energy efficiency mandates and taxes on fossil fuels and energy use. Energy taxes reduced the use of fossil fuels and created more demand for renewable energy creating a feedback effect.

2.5.3 Iceland: sustainable energy system

Geothermal energy has consistently featured in Iceland's energy mix. For centuries, Icelanders have used geothermal energy for bathing, washing clothes and cooking. Situated on the Mid-Atlantic Ridge, the country has frequent tectonic activity and geothermal energy in Iceland is primarily used for space heating and electricity generation.

Figure 8: Iceland's share of primary energy from low-carbon sources



Source: Our World in Data, BP Statistical Review of World Energy

Iceland is poorly endowed with fuel resources; however, its geology provides favourable conditions for geothermal exploration. Underground water is heated by hot magma and reaches 150–250°C. However, geothermal development did not take place until the 1930s. Before then, Icelanders relied on peat, animal dung and driftwood. Coal began to be imported for space heating around 1870 (Axelsson et al. 2010) and became the dominant fuel by the 1930s (Melsted, 2021). Oil started to be used for heating after the Second World War (Axelsson et al. 2010). Construction of the country's first urban geothermal heating system began in 1930 and finished after the Second World War in –1944. It gradually replaced coal in heating (Melsted, 2021). An economic boom followed Iceland's occupation by British and American groups during the Second World War and subsequent independence from Denmark in 1944. However, the country was still classified as a developing nation as late as 1974 (Valdimarsson, 2008).

In the late nineteenth century, Iceland was poor and lacked basic infrastructure, such as a sewage system. However, Icelandic entrepreneurs who had studied in other countries, usually Denmark, were keen to develop their country in a similar fashion. Like Denmark, the government did not drive the development of the renewable energy system in Iceland. Grassroots effort by farmers and entrepreneurs who wanted to harness the country's natural resources led to the develoment of an electricity system built from the bottom up through the collective action of farmers in rural areas and local governments. This fragmented system was later connected by the national government.

The geothermal heating system follows a slightly different development path where "local governments enabled access to geothermal heating and the national government assumed the risk of geothermal exploration, but where this was not possible, the national government provided subsidies for the use of electric energy for house heating" (Davidsdottir, 2022). Iceland's State Electricity Authority has promoted geothermal development since the 1940s through loans for exploration and research into uses for geothermal energy (Ketilsson et al., 2015). Establishing the Geothermal Fund in 1961 further encouraged geothermal development by providing grants for reconnaissance and exploration. In 1967, the fund was merged with the Electricity Fund and named the Energy Fund.

Despite this emphasis on geothermal energy, the 1970s oil crisis had a significant impact on Iceland which relied on imported coal to meet 75% of its energy requirements. At the same time, over 50% of the population depended on heat from oil. The crises spurred the government to reduce oil use and develop indigenous energy sources such as hydropower and geothermal energy sources (Ketilsson et al., 2015). This policy aimed to find new geothermal resources and build distribution networks to connect far-flung villages and farms. By 1990, the reference year for the Kyoto Agreement, the geothermal conversion for most buildings in the country was essentially complete (Valdimarsson, 2008).

Low summer temperatures mean that space heating is required year-round in Iceland. The local municipality runs district heating systems which are publicly owned. Iceland's decision to develop energy has saved the country millions of USD in imported oil (Davidsdottir, 2022). At the same time, the decision was made to reduce energy consumption. Controlled heating systems, better household insulation, increased energy awareness, and tariffs on the water used for heating have helped improve energy efficiency. Although transmission and distribution costs are high due to low population density, geothermal energy prices are competitive in Iceland and provide a reliable base load (Ketilsson, et al., 2015). As the technology is mature, it no longer receives government support, and utility companies now undertake exploration work. Their long operation history provides valuable knowledge about the long-term management of low-temperature geothermal resources.

Like Denmark, the development of geothermal energy in Iceland is a result of a mixture of individual efforts supported by government legislation. According to Davidsdottir (2022), "The absence of the national government from decision-making in the early days of harnessing renewable energy resources may have contributed to the strong programmatic performance as people around the country utilised what was at their disposal, the energy embedded in the country itself, rather than imported fossil fuels." Investment in R&D and financial assistance to encourage individual/non-utility development of alternative energy has positively impacted alternative energy development as a whole. The merging of the Geothermal Fund with the Electricity Fund shows how energy and environmental objectives were intertwined and led to sustainable outcomes. At the same time, the decisions made in the 1970s could not have come about without Iceland's prior experience with geothermal energy showing the path-dependent nature of energy development.

The presence of feedback processes in the development of the energy system is highlighted by Davidsdottir (2022), who says, "The development was gradual, with electrification based on hydropower taking place first, the build-up of domestic district heating second with electric heat in cold areas which was then used as a reason to continue hydropower development and the development of the electric grid. The consistency most likely resulted from the repeated comparative analysis of economic costs and benefits associated with different energy sources, the need for modern energy, and the continual reminders of not only the financial but the social and environmental benefits associated with the use of domestic renewable resources."

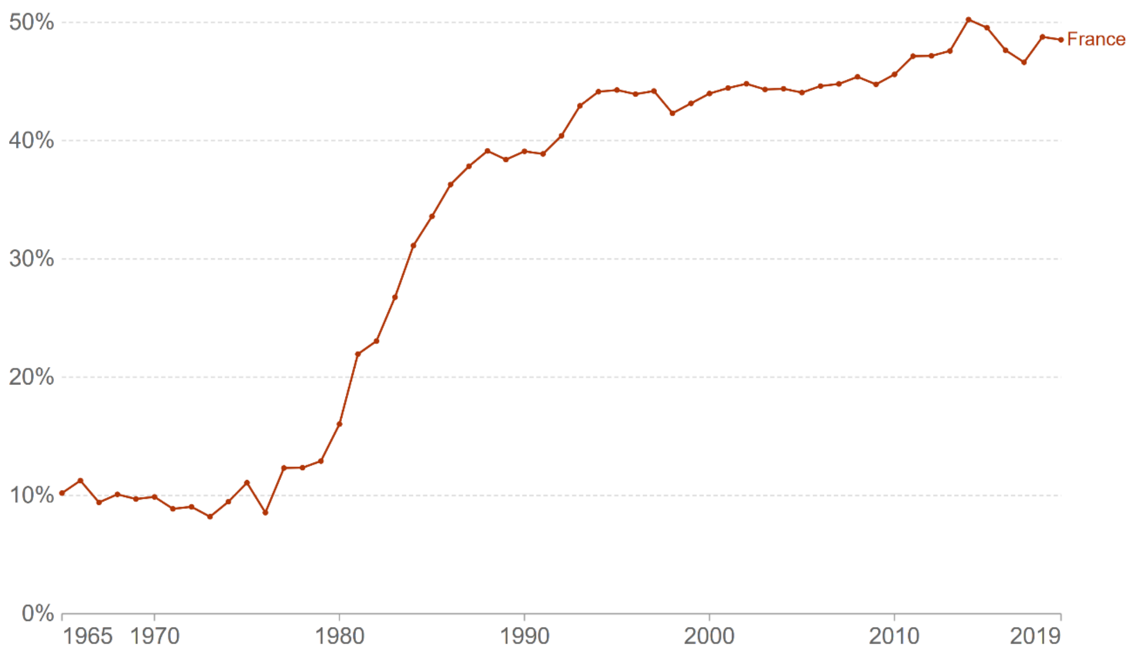
2.5.4 France – Nuclear energy with minimal opposition

The Commission for Atomic Energy (CEA) was created in 1945 to further nuclear research for military and civilian purposes and gain independence from the United States and the Soviet Union (Brouard & Guinaudeau, 2015). The first nuclear power plant was built in 1956, and the electricity production programme using CEA technology was promoted with the goal of energy independence and industrialisation. EDF, the electricity company, was nationalised in 1945 and was responsible for marketing electricity. The French transition to nuclear power began following the first oil crisis in 1973. A nuclear power program was initiated to replace France's dependence on imported oil. In 1969, EDF was allowed to use its preferred technology (American) based on the more efficient and robust pressurised water reactors, which led to the construction of 13 new plants by 1980 as part of the "Messmer Plan" for energy independence (Brouard & Guinaudeau, 2015). Eighty nuclear plants were constructed by 1985 and 170 by 2000 (Sovacool, 2016). The development of nuclear energy policy coupled with investments in nuclear research and development has allowed France to stabilise oil imports and triple energy production since the 1970s (Brouard & Guinaudeau, 2015).

The success of the French transition to nuclear power is due to the institutional setting that allows for centralised decision-making, regulatory stability and greater control during the expansion phase (Baumgartner, 1989). Nuclear power development was primarily left in the hands of technical experts and the government.

The early years of nuclear power development were kept separate from political partisanship as decisions about civil nuclear policy were considered a part of energy policy. At the same time, the usual left-right battles on nuclear power issues could not be generated as the Communist Party was a supporter and the Socialist Party was divided on the subject (Baumgartner, 1989). Consensus in the political areas has been nurtured by controlling the development of the issue. Policy making is carried out by state industries that manage every step of the nuclear power generating process from design and construction of plants, mining and manufacture of enriched uranium, waste deposal and marketing of electricity. Reactor and plant designs have been standardised to ensure safety, reduce costs, and simplify approvals. Tight control during the planning process and scarce public debate has helped the French concept of equal and universal access to electricity. At the same time, the technological advantage gained has fostered the emergence of world leaders, Areva and EDF, in the nuclear energy sector. Figure 9 below shows France's share of primary energy from low-carbon sources.

Figure 9: France: - Share of primary energy from low-carbon sources



Source: Our World in Data, BP Statistical Review of World Energy

2.5 Summary

History matters in energy transition because of the capital-intensive nature of the business and the long lead times to profitability. So historical technology and infrastructure choices impact the current energy mix. The wind industry's success in Denmark was possible because of the country's strong research and Development (R&D) record, which has led to the development of world-class wind energy and solid-oxide fuel cell technologies. Centralised decision-making coupled with regulatory stability has been cited as success factors in the case of France (Sovacool, 2016). Denmark, with its socialist communes and centrally planned France, share unique governance characteristics (Sovacool, 2016) that have helped the transition.

Smil (2017, p. 230) states that every energy transition is powered by “intensive deployment of existing energies and prime movers”. For example, the transition from wood to coal was powered by coal miners, while the transition to oil was powered by burning coal. This means that a transition to sustainable energy will also have to be powered by something, in this case, policy. Previous energy transitions came about because of the superiority of the new energy source in terms of cost and efficiency. Although the prices of the new energy declined as they became popular, these costs did not account for the variety of negative externalities. This is because there is no generally accepted measure for valuing the consequences to the climate and human health. Further, because of (their relevance to the economy), the fossil fuel industry has benefitted from government subsidies and tax breaks; the next energy transition therefore, needs to focus on environmental sustainability and not simply cost. This can only happen with the introduction of a carbon price. Energy sources such as oil, natural gas and uranium became valuable not when they were discovered hundreds of years ago but only when these energy sources were ‘invented’ or commercially exploited within society. This ‘social construction’ of the invention indicates the necessity of social support by financiers, politicians and the public for the success of an energy source. (Hogselius, 2019, pg 6). As different fuel types have different scopes (domestic vs international), a careful study of energy markets, the interests of the participants, and the relative importance of the different fuel types are also necessary. The economic interests of producers and consumers who use energy products in industrial processes are relevant.

Another point that came up repeatedly was the industry’s influence in promoting a particular energy source and the growth of supporting industries that either supplied or needed the energy source. This is why researchers talk about lock-in and co-evolution of industries. This process can happen organically, but when faced with climate mitigation's current challenge, sustainable energy's organic growth must be expedited through policy push. Deployment of new technologies stimulates learning by doing in manufacturing and increases efficiency. Productivity convergence is produced by mimicry and induced adapted invention (Evenson, 2002). This requires continuous investments in knowledge, and institutional support is needed as some level of tacit knowledge and engineering competence is necessary for mimicry. In the presence of knowledge stocks and the right institutions, countries can mimic the cost-reducing techniques used in developed countries. Country differences in prices, institutions or natural environment lead to production differences which can be minimised with adaptive invention. Adaptive invention entails modifying the developed country’s technology to suit the recipient country's environment but requires that the country have invention capacity in place (Evenson, 2002). This implies that energy and renewable energy policy must be designed bearing in mind the country's tacit knowledge. However, transaction costs and inadequate institutions such as property rights and bankruptcy law can lead to convergence failure.

The meso-level of environmental research focuses on institutions and the co-evolution of institutions and technology as well as technological systems to understand the total environmental consequences of a product. The research on systems innovations and technological regime shifts focuses more on goals and looks at the micro, meso and macro levels of change, albeit using different terminology, viz. niches, regimes and socio-technical landscapes. The emphasis on technological regimes over innovations highlights the slower rate of regime change than technology change. This is attributed to the buy-in required of a broader range of actors and institutions who seek stability and continuity. The concepts of path dependence, lock-in and lock-out have been used to explain processes of channelling technology. These processes arise because of learning effects, increasing returns to economic scale, technical interrelatedness and embedded institutional, political and financial commitments to a specific technology. The available knowledge and institutional and financial capabilities of the time bind further innovation. Although technological regime shifts have occurred in the past (canal by railway, horse and cart by car), it has been difficult to generalise the circumstances surrounding these regime shifts and how they can be managed. (Berkhout, 2002).

3.0 Understanding technological path dependence

As we saw in the previous chapter, energy transition is a lengthy process involving technology, policy and society. It is brought about by the commercialisation of technology and is dependent on policies and the institutional context. This chapter discusses the concept of path dependence and its relevance to technical change and energy systems. Neo-classical assumptions of economics are contrasted with evolutionary thinking in economics to explain how the processes of innovation, diffusion and technological change come about. These concepts are then examined within the context of energy systems to understand path dependence. The idea of socio-technical systems is then introduced to analyse how a transition away from a fossil fuel-based energy system may be accomplished.

3.1 Evolutionary theories of economic and technical change

Economic ideas can be divided into two categories: classical vs modern thinking. Classical economic ideas spanned 1600-1870 and were broadly concerned with production and distribution theory and the theory of value and price. It includes thinkers such as Thomas Mun (1571-1641), Richard Cantillon (1697-1734), David Hume 1711-76), Adam Smith (1723-90), Thomas Robert Malthus (1766-1834), David Ricardo (1772-1823) and Karl Marx (1818-83).

Modern economic thinking covers the 1850s to the early 1980s, emphasising markets, exchange, supply and demand and introducing micro and macroeconomic ideas. Beginning with John Stuart Mill, marginalism influenced the development of micro-economics and macro-economics and growth theory developments in the 1970s and 1980s (Vaggi & Groenewegen, 2003). The role of the environment in shaping economic ideas and the influence of previous thinkers is evident in Keynes' General Theory which was written during the Great Depression, deals mainly with employment. Similarly, the social consequences of the Industrial Revolution are apparent in Malthus' theory of population.

In general, mainstream economics focuses on the scarcity of resources and the need to choose between alternatives. The Neoclassical tradition within mainstream economics focuses on free markets with demand and supply as the driving forces behind the production, pricing, and consumption of goods and services. In this school of thought, agents are rational; resources are infinite or substitutable; growth is good and long-term effects should be discounted. However, the idea of the rational economic man and perfect competition has been challenged for decades (Gowdy & Erickson, 2005) and yet continues to be used in designing climate policies (Marechal & Lazaric, 2010). Policy making under these assumptions favours laissez-faire thinking, cheap energy and low carbon taxes. Innovation is difficult to incorporate into the neoclassical tradition as the outcome cannot be predicted (Faber & Frenken, 2009). As technological change is now viewed as the result of innovation and organisation (Van Den Bergh, 2007), economic concepts such as rationality, efficiency and optimisation are unsuitable for understanding these processes. Instead, patterns of change are better explained by Darwinian evolutionary theory based on variation, selection and replication, which have been applied to diverse disciplines such as sociology, psychology and technology studies.

Evolutionary thinking and innovation

Evolutionary economics is inspired by evolutionary thinking and examines “the change of economic knowledge as it applies to technology and production” (Dopfer, 2005, p. 3). The rational being in neo-classical economics is replaced with human beings with bounded rationality, which takes the form of routines, imitation and a limited time horizon. (Van Den Bergh, 2007). Diversity, selection processes, innovation and transferability play critical roles in evolutionary processes.

The mutation and crossover of genes in biological evolution have been used as the basis to study routines in technological evolution. Organisational routines produce technological artefacts efficiently and can be replicated vertically (within spin-off companies, for example) or horizontally (through imitation). R&D is viewed as a search to improve the quality of outputs or processes and is motivated by profit. Therefore, firms with better outputs have a higher survival rate.

Similarly, the concept of specific gene frequencies within a population is used to study technology diffusion within industries. Frequency-dependent selection means that the fitness of a particular technology explains its frequency in the population. The basic premise is that market-leading firms use the best available technology, similar to natural selection in evolution. Evolutionary arguments revolve around the causal mechanism that produces a variety of behaviour and the selection process that shapes these behaviours into emergent patterns of change. By examining political and interest group behaviour, evolutionary thinking in economics can explain the structural shift in energy systems over time or how national energy systems got to where they are at a particular moment in time.

3.1.1 Innovation as a cumulative and path-dependent process

Innovation involves change and is central to the energy transition. It is a systemic phenomenon involving individuals, firms, organisations and networks and is a continuous process featuring feedback and loops. Schumpeter defined technological change as new combinations related to production and exchange. The term 'innovation' is used in the sense of the economic exploitation of knowledge in this dissertation and not simply the creation of new ideas. Innovation is differentiated into the processes of invention, innovation and diffusion. In the Schumpeterian sense, innovation refers to new combinations of existing resources, with entrepreneurs and firms playing an essential role in the process. Expectations of increases in factor prices induce innovation. Knowledge and private profit incentive are the driving factors of firms' decisions to invest in innovation. Innovation costs include both R&D as well as investment in plants and equipment which leads to learning by doing and learning by using. Innovation is a cumulative process that builds on existing knowledge, innovation and inventions while providing a base for further innovation. This highlights the path-dependent nature of innovation.

Learning processes are crucial to innovation. However, when left to the private sector, innovation will be directed towards improving dirty technology. The private sector has the financial resources to buy expertise and influence policies that direct innovation. Further, differences between industries or technological fields give rise to characteristics of 'sectoral' innovation, such as the importance of intellectual property protection in the pharmaceutical industry compared to the construction industry. Growth or national innovation systems may determine innovation at the national level. The key idea is complementarity which can be explained using Kremer's O-Ring Theory (Kremer, 1993).

According to the O-Ring theory, a relatively minor aspect of economic development can be disastrous to the sustainability of a developing economy if it is not planned and executed correctly. Inspired by the devastating 1986 Shuttle Challenger disaster caused by a single rubber seal, Kremer's theory has implications for developing complementary products required when developing renewable energy systems. These products require local non-tradeable capabilities for product development. The presence and/or ability to increase these capabilities allows countries to diversify product development. Further, "the likelihood that a country develops a particular product depends on how "near" that product is in the "product space" to the products that the country produces. (Hidalgo & Hausmann, 2011). As products become more complex and require similarly complex capabilities, "they become less accessible from the point of view of local production. But as new capabilities become more tradable, manufacturing complexity can be addressed through the international division of the value chain" (Hidalgo & Hausmann, 2011). The O-ring theory explains why rich countries with high-skilled and educated workers specialise in complicated products (Kremer, 1993).

Path dependence in innovation processes

Aghion et al. (2019, pg 69) argue that research, knowledge and innovation processes are path dependent because 'scientists work in areas that are well-funded and where other good scientists work", i.e. socio-economic systems exhibit inertia because of interconnectedness. The energy transition will be slow when research directed towards advancing technological innovations that leverage existing infrastructure is more likely to be deployed. Technological and behavioural lock-in is why energy transition requires transforming our energy and economic systems. Technological lock-in occurs because historical choices impact the eventual outcome.

As knowledge is cumulative, incremental innovations appear during learning by doing due to previous knowledge generated. These innovations better performance and reduce costs. This implies that technological competence must be accumulated before technology transfer occurs. However, knowledge stocks also depreciate if it is not applied. The depreciation rate can be as high as 20% per year for technology knowledge stocks which have a short lifetime (Grubler & Gritsevskyi, 2002).

Information has similar properties to knowledge in that generation has high up-front costs, but subsequent use is free. Like knowledge, it is appropriable and provides incentives for investment. Learning by doing and timely investment in new technologies positively impact technological change. Increasing returns common in technology adoption creates problems not seen in evolution. Increasing returns in economics imply 'non-convex technologies' (Castaldi & Dosi, 2006, pg 101). The cumulativeness of knowledge and information has implications for increasing returns and path dependence. However, path-dependent learning faces a trade-off between exploiting what one already knows versus exploring new options.

Knowledge spillovers

Societies have an existing stock of knowledge, both general and industry-specific. Investments in improving the knowledge stock can improve overall resource productivity. New or different goods reduce costs and present new opportunities for other firms and industries. For example, the development of high-speed processors has implications for various industries. These knowledge spillovers are a positive externality of innovation (Grubler & Gritsevskyi, 2002). Knowledge spillovers come from licensing technology, patents, publications, employees and reverse engineering. They may be intrasectoral (between firms in an industry), intersectoral (between industries), local or international. Thus improved technological knowledge can exhibit increasing returns. International knowledge spillovers are also a source of positive feedback. However, institutional, political and cultural factors may prevent the spread of innovations, particularly in industries of national sensitivity, such as energy (Grubler & Gritsevskyi, 2002).

As a technological paradigm generally guides innovation activity**,** innovation generates expectations about a particular technology which in turn accelerates the development of that technology, creating a self-fulfilling prophecy (Faber & Frenken, 2009) which in turn leads to increasing returns. In the presence of increasing returns, technology adoption entails positive feedback making diffusion dependent not only on fitness but also frequency, meaning that the best technology is not guaranteed to win. The economy is then locked into a suboptimal Nash equilibrium, which requires collective action to unlock the economy to new technology (Faber & Frenken, 2009). Frequency however, can be boosted through policy to avoid or escape this outcome.

3.1.2 Co-evolution and technological change

Changes in knowledge and the institutional environment impact technological change the most. However, the current institution level and existing knowledge stocks determine their expansion. Mokyr (2002) finds that knowledge and institutions are necessary to induce technological change. He believes that “necessity is the mother of invention”, which can be observed in the countries examined earlier, that used the challenges presented by the 1970’s energy crises to diversify their energy supply in other ways, such as by developing their energy sources or geopolitical allies, etc. Grubler & Gritsevskyi (2002) divide technological evolution into four stages; invention, innovation, niche markets and diffusion. Invention represents the feasibility of a new solution and generates knowledge through R&D activity. Innovation refers to the regular production of technology and represents a discrete-time event along with invention. Knowledge is cumulative, and new knowledge often encounters resistance from existing forms with a vested interest in maintaining the status quo (Mokyr, 2002).

The niche market and diffusion stage of technology generally overlap. During these phases, technological change occurs in the form of plants, equipment and new products. Knowledge comes about as a result of applied R&D. The presence of multiple linkages and feedback processes means that these phases do not follow a linear trajectory, and the evolution of knowledge capacities is hard to predict. However, it important to maintain an innovation focussed environment through policy. Knowledge generation depends on various actors and is acquired from both internal and external sources. It is more complementary than substitutable and cannot be increased exclusively by internal efforts.

Policy-induced technological change

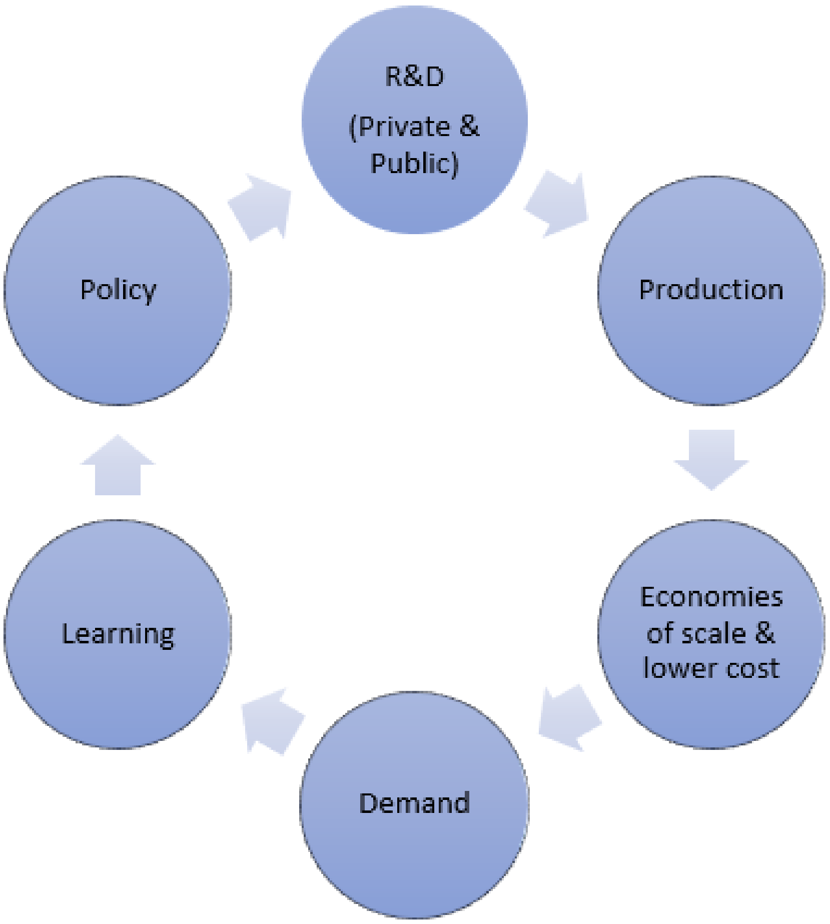
Effective technology development has been viewed as best developed by firms pursuing markets. Market-induced technology development leads to cost reduction and future opportunities that further determine private R&D efforts. Induced technological change views R&D efforts as the result of private sector decisions based on costs and potential rewards. However, private firms are generally reluctant to engage in long-run research such as renewable energy technology. Instead, firms tend to choose technologies that are close to the market or where they already have an interest.

Technological regimes in evolutionary economics refer to combinations of opportunity, appropriability and degree of cumulativeness. Evolutionary economics view environmental innovations as a means of temporary monopoly. It views technological transition as requiring specific policy related to unlocking current technology to create a new technological system and then further policy-making to avoid lock-in. Further policies are required to preserve flexibility, and the timing of policies is crucial (Faber & Frenken, 2009).

Induced technological change occurs when governments alter the rate and direction of technological innovation by changing the incentives. Price signals can act as a source of technological change. Increasing energy prices through energy taxes leads firms to produce less energy intensive products and accelerates the search for cost reductions in all energy sources (Newell, Jaffe, & Stavins, 2002). However, renewable energy cost reductions depend on learning, scale, and integration with networks. New knowledge is expensive to produce but inexpensive to assimilate. As benefits do not accrue to knowledge generators but to those who can apply it effectively, these knowledge externalities impact a firm's attitudes towards R&D investment. For these reasons, public research institutions best carry out this type of research. Public R&D funding coupled with private R&D funding, coordination mechanisms and price signals move innovation processes towards a declining cost for market growth (Watanabe, Griffy-Brown, Zhu, & Nagamatsu, 2002). The importance of learning based on market signals is highlighted in Japan's solar PV industry's growth.

As a mid-latitude country, incoming solar power in Japan varies considerably from season to season. However, learning effects and economies of scale have been critical to the success of PV development in Japan. The Sunshine Program was developed to encourage industrial participation across sectors and substantial industrial investment in PV R&D to increase Japan's knowledge stock on PV technology (Watanabe, Griffy-Brown, Zhu, & Nagamatsu, 2002). This, in turn, increased production and demand and resulted in further investment in R&D, creating a positive feedback loop. The learning/experience curve mechanism plays an important role in forming policy. Policy stimulates learning and technology spillover but is not the only channel for creating the feedback loop. Energy efficiency improvements due to technology spillovers enhance learning across industries leading to innovation in PV technology and economic growth. The loop between economic growth and technology spillovers and between technology spillovers and learning effects creates a positive feedback loop. Arthur's view of the economy is complex and process-dependent (Arthur, 1990). Positive feedback leads to non-deterministic and divergent outcomes and calls for non-linear physics and evolutionary thinking. Identifying states and times is necessary to create positive feedback in the right direction. The policy-induced feedback cycle is illustrated in Figure 10 below.

Figure 10: Policy-induced technological change



Co-evolution of demand and supply

Technological change requires a host of other technologies and infrastructures. Cars need roads and petrol stations. Research has shown that radical technological change is possible via the mechanism of increasing returns, R&D and niche market development (Grubler & Gritsevskyi, 2002). These mechanisms initiate continuous innovation and can stimulate a positive feedback effect. Technological change is path dependent because of its dependence on previous innovations, firm activities and existing capital and knowledge stocks.

3.2 Path Dependence in energy systems

3.2.1 What is path dependence?

The term path dependence conveys the idea that history influences present-day conditions. For David (2005), path dependence refers to non-ergodic processes, i.e. a dynamical system with an asymptotic distribution that evolves as a function of its own history (David, 2005) . Path dependence can also be found in stochastic systems with state-dependent transition probabilities and multiple absorbing states. In these circumstances, small events can set the system on a particular path and absorbing state. Identifying the critical structural characteristics of the process is useful for policy analysis. Path dependence can be used to study coordination problems created by externalities, bandwagons in public opinion formation and collusive oligopoly behaviour. David (2005) discusses the importance of **timing** in deciding whether to intervene in market allocation processes. If the existing energy paradigm faces pressure when alternative sources are not fully developed, the sustainable transition becomes even more difficult (Verbong & Geels, 2010). The network context, which may be economic, social, commercial or technological, provides the circumstances for feedback mechanisms.

David (2005) highlights the phenomenon of the ‘snow shovelling problem’ where a shopkeeper’s decision to shovel the snow from the pavement in front of his/her shop depends on the decisions of his/her neighbours on either side to do the same. Time limitations cause the shopkeeper to simplify decision-making to a rule depending on the actions of the less active neighbour. The evolution of the shopkeeper’s snow shovelling policy resembles a coordination game and can be examined using a Markov chain or process (Markov, 1906; Stewart, 1994, p. 4). Markov processes are stochastic processes for predictions about future outcomes based on the current state. An absorbing state is one which, once entered, cannot be left. An attractor is a set of states toward which a system tends to evolve. In the ‘snow shovelling problem’, the process's two attractor states are where everyone agrees on shovelling or not shovelling snow. Attainment of either of the two states means that no further changes in shovelling policy are required, and the pavement would be either free of or covered with snow. Neither of the two outcomes can be predicted in advance and depend on the timing of the decisions. When this behaviour is viewed at the macro-level, the collective behaviour "can be viewed as a stochastic process formed from additively interacting Markov processes or interdependent Markov chains with locally positive feedbacks" (David, 2005). It resembles a game involving coordination equilibria and appears in several economic areas, such as macroeconomics and oligopoly behaviour. These systems are prone to "convergence to an indefinitely persisting equilibrium" or lock-in if there is no change in the behavioural orientation of the individual agents.

For Buhanist (2015), path dependence is a process that includes technology and institutions. The process includes a preformation phase where initial conditions allow a variety of decisions, the formation phase of self-reinforcing processes, a lock-in phase with only one option and rarely an exit phase. In the preformation stage: decision-making is unconstrained, and although choices made at this stage are small, these choices or events lead to a bifurcation point where one choice dominates, leading to the formation stage. When re-inforcing processes such as increasing returns, the economy of scale and irreversibility of investments become irreversible, the process reaches lock-in that typically conforms to behaviour and paralyses decision-making. Typically self-reinforcing processes reinforce events. However, Mahoney (2000) discusses reactive processes that transform previous events.

Path dependence is useful for examining technological evolution which arises when "initial conditions and their historical antecedents matter for eventual outcomes" (Aghion et al., 2019, pg 69). Paul David defines path dependence as "A path-dependent stochastic process is one whose asymptotic distribution evolves as a consequence (function of) the process's own history." Instead of viewing it as a theory, David describes processes as having path-dependent characteristics. These processes are common in industries with network externalities and feedback phenomena. Energy systems have been characterised as socio-technical systems.

3.2.2 Path Dependence in energy systems

A continuous secure energy supply is a prerequisite for economic development. The fossil fuel-based energy paradigm consists of a centralised energy generation model where a large-scale power station burns fossil fuels to generate electricity. This electricity is then transmitted via a network to end users. This centralised model is reliable and benefits from economies of scale. Path dependence in energy systems arises for the same reasons they do in technology, viz.:

- Large setup, fixed and sunk costs
- Learning effects
- Coordination effects
- Adaptive expectations

Large setup or fixed costs

Energy markets have specific physical, geological, geographical and technical characteristics and depend on the political decision for various reasons. For example, fossil fuel reserves are concentrated in a few countries. The extraction of these reserves depends on the relationship between multinational companies, countries and politicians. Most energy markets are characterised by monopolies or oligopolies. Transmission and grid industries are natural monopolies and are usually regulated. The energy socio-technical system consists of existing technology and user practices, institutions such as markets, regulatory authorities, and knowledge stocks (Zweifel, Praktiknjo, & Erdmann, 2017). Quasi-irreversibility of investment means investors are inclined to run utilities for as long as possible.

Energy infrastructure is characterised by long-term heavy investment in power plants, cables and lines, transformer stations, etc., as energy demand is difficult to predict. These investments represent sunk costs making the sustainable transition difficult without policy intervention. Technological capital and R&D are expensive to redirect or replace. Sunk costs in old technologies slow the changeover to newer, more efficient technology. The intermittency challenges of renewable energy require upgrades to the existing ageing transmission and distribution infrastructure, and the utility business is no longer viewed as a growth industry.

Fossil-fuel-powered utilities derive their competency from centralised large-scale production. The inherent stability of fossil fuel-powered energy systems compared to intermittent energy sources provides additional reasoning for policymakers to stay with fossil fuels.

This paradigm has given rise to the following features that lead to lock-in

- Technical inter-relatedness, which gives rise to system compatibility.
- Economies of scale which makes fossil fuel-powered electricity cheaper than RE

An example of path dependence in the energy industry is the long-term oil-indexed agreement that forms the basis of gas company business models (Buhanist, 2015). The discovery of the Slochteren gas field led to the development of the Groningen marketing model, which was created when the gas market was in its infancy (Buhanist, 2015). The size of the Slochteren gas field meant that stakeholders could tailor a market design that benefited their commercialisation of the field. This was possible simply because of the infancy of the gas market, but it also formed the base for future oil and gas exploration projects.

Groningen agreements based on long-term fixed volumes and oil-indexed prices, are commonly used to commercialise newly discovered gas fields to provide security for investments. These agreements providing long-term commitments of up to 30 years for buyers and sellers, were seen as reducing transaction costs but can also be viewed as sunk costs. The price of gas in these agreements is typically like that of competing fuels such as fuel oil, and the prices are set at parity or a small discount. Although oil prices change daily, oil-indexed gas prices change quarterly and are based on oil prices of the previous 2 or 3 quarters. This lag reduces volatility and helps buyers forecast gas prices with greater accuracy. At the same time, although price renegotiation of the contract at regular intervals is permitted, the prices negotiated may be subject to floor or ceiling prices to mitigate risk from abnormal oil prices. The scarcity of liquid spot gas markets prevents the natural discovery of gas prices. Although gas markets have been transformed through deregulation and liberalisation, as companies are locked-in into long-term contracts, gas enters the energy market at uncompetitive costs.

Learning effects

Concerns about path dependence create obstacles to investment in alternative energy technologies. It is not possible to choose the optimal direction of energy system development 'a priori' (Grubler & Gritsevskyi, 2002). Learning and spillover effects have the greatest impact on emerging energy structures due to lock-in effects and increasing returns to adoption. In the long run, the optimum strategy would be to increase the capacity of all technologies, thereby reducing the risk associated with focusing on one or more technologies.

Learning processes act as a powerful driver of self-reinforcing dynamics. Castaldi & Dosi (2006, pg 101) found that knowing what they know today, actors would not go back to the previous day's beliefs and actions even under the previous day's circumstances. "Learning effects incentivise energy actors to affirm the institutions they are most familiar with. Many in the energy sector have been involved in the fossil fuel business for generations," making them reluctant to lose decades of institutional knowledge (Stein, 2016).

Another area impacted by learning effects is investments. Investors in energy infrastructure "are generally risk averse, and learning effects render innovative clean energy investments more expensive. Risk-averse lending institutions are less likely to invest in unknown technologies. Therefore, re-investment returns in existing technology create positive feedback that locks in existing technology and ultimately stifles innovation. Additionally, lock-in in one industry can result in lock-in in competitive and complementary industries, with each refusing to shift to a more efficient option without assurances that other potential users will follow" (Stein, 2016).

Complementarities arise 'when the payoff to the whole group from working together is greater than the sum of the payoffs of its parts' (Aghion et al., 2019, pg 70). Strategic complementarities arise when stakeholders make decisions that affect each other's welfare, and the individual's increased productivity makes all others more productive" (Aghion et al., 2019, pg 70). The interdependence of technologies required for technological change results in path dependence and lock-in phenomena. Brian Arthur discussed the notion of increasing returns in the economy that made the existence of multiple equilibria.

The potential for interaction and reinforcement in economic, social, commercial and technological networks provides the circumstances for feedback mechanisms resulting in multiple equilibria. In economics, history is relevant under non-convex technologies and the property is magnified in the case of information, knowledge, interdependencies, and dynamically increasing returns (Castaldi & Dosi, 2006).

Other sources of path dependence include conventions and standardisation. Coordination effects, similar to network effects, come from the interconnectedness of energy infrastructure. Networks of transmission providers enjoy economies of scale and efficiencies that come from having an interconnected network. Conventions such as industrial and technological standards and economic contracts are also sources of path dependence.

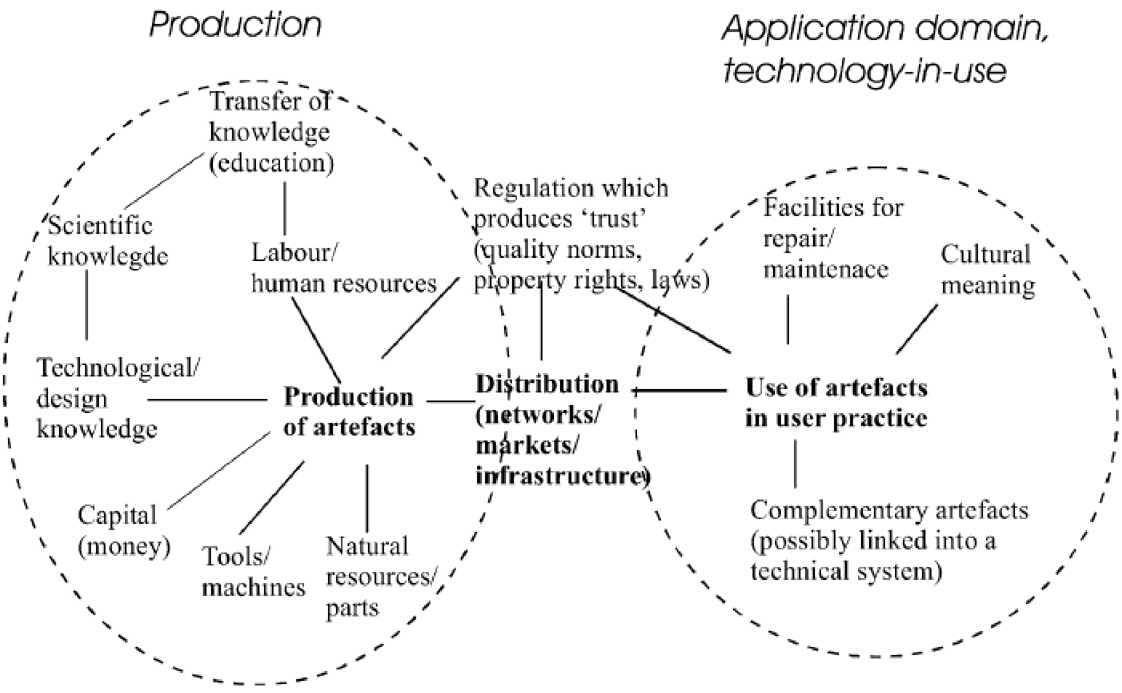
The development of the railway system highlights standardisation as a source of path dependence. The UK was the first country to develop the railway system and had a variety of gauges in use in railway systems in mining districts. This diversity was resolved as the railway system diffused and moved into new regions and markets. The demand for interregional and international transport speeded up the standardisation of the railway system gauge by incentivising cooperation and coordination (Puffert, 2002). These processes are sensitive to events that occur in the early stages, are hard to predict outcomes and therefore make forecasting difficult (Mahoney, 2000). However, once the 'shock' occurs, the resulting path-dependent sequences are deterministic and exhibit inertia. Sharing knowledge is crucial during the early stages of new technology as seen in our case studies of Denmark and Iceland.

Path dependence consists of three phases where the first and last phases are defined by "critical junctures," events that trigger a move toward or away from a particular path. The middle phase features positive feedback mechanisms reinforcing movement along the path (Stein, 2016). These phases are evident in the United States, where the second industrial revolution and the large-scale transition to fossil fuels began. The initial critical juncture "that set the country on the existing path was the discovery of cheap and abundant oil and gas (Stein, 2016). Since then, self-reinforcing mechanisms such as the development of roads and transportation, for example, have locked the US into carbon. While the US has invested in renewable energy, it has a long way to go before it moves to a low-carbon energy system.

3.3 Socio-technical transitions

Socio-technical systems refer to the interconnectedness between human beings, social structures and technology and the co-evolution of social and technological relationships, as illustrated in Figure 11 below. The three main sub-systems in a socio-technical system are market, technology and political institutions. These sub-systems interact on many levels, making transition challenging as the systems are stabilised by lock-in mechanisms related to infrastructure and investments, behavioural patterns and codes and vested interests. Therefore, the socio-technical transition requires understanding the causalities between these systems.

Figure 11: The Socio-technical system



Source: Geels 2004

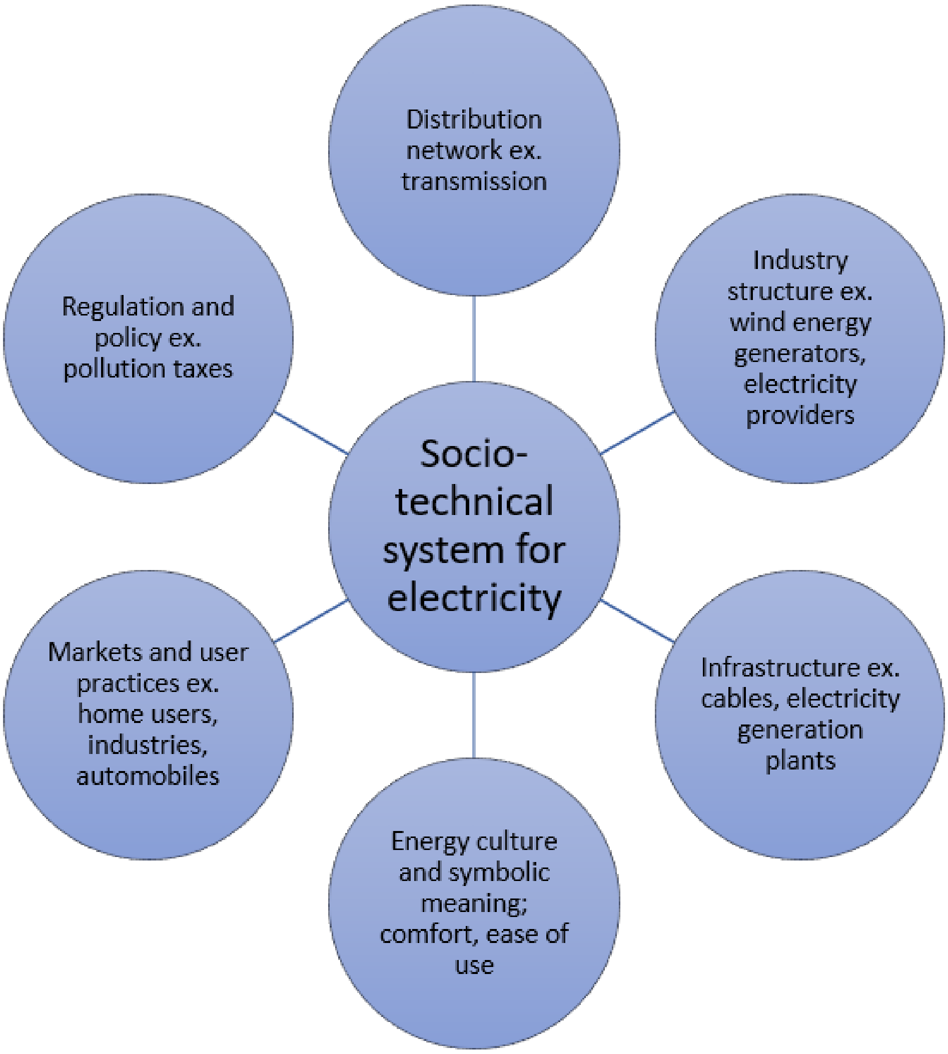
Socio-technical systems include networks of developers, manufacturers of wind turbines, car sharing, etc. Technological innovation systems (TIS) participate and spread new technology. Although, the socio-technical perspective explains technological change as a result of new innovations, it tends to overlook incremental innovation and change and the decline of old technology (Cherp et al., 2018). Hughes' (1987) inclusion of organisation and legal artefacts and Nelson and Sampat's (2001) inclusion of institutions as social technologies highlights the need to incorporate individual intentions and behaviour and complex social rules to bring about systemic change. Just as societies impact technologies, technologies also impact society. Regulators, customers and firms can act as sources of change from stakeholders (Berkhout, 2002). For example, the rebound effect where energy efficiency measures leads to increased energy use can be combatted with education and the use of technology that measure energy use. At the household level, the integration of PV with smart grids may encourage a change in behaviour as consumers become aware of their energy usage.

Social acceptance is particularly important for renewable technology because of their decentralised and geographically spread out nature. Switzerland closed down nuclear power plants due to low societal acceptance. Similarly, resistance to solar or wind farms have a negative impact on energy transition. Another source of resistance are socio-economic interests such as steel or coal which can become entrenched within a society and continue a country's pathway away from low-carbon transition. Austria's long tradition of high-quality steel manufacturing for example, has been important for jobs and prosperity. However, the industry recognises the need for innovation and a move towards low-carbon technology (Hanger-kopp et al., n.d.).

The study of socio-technical systems includes the user, systems, actors and the institutions which guide actor's perceptions and activities. Institutions and rules co-ordinate activities. Rules can be classified into regulative, normative and cognitive rules. Regulative rules refer to explicit formal rules that constrain behaviour as well as governmental regulations that structure the economic processes. Normative rules refers to values, norms and expectations that generally internalised through socialisation. Cognitive rules shape the meanings we attribute to objects and activities. These rules are generally linked together to form rule systems that make it difficult to change one rule without impacting another. The rule systems structure social transactions and different rules and regimes apply to different social groups. Members of social groups share rules that have come about as a result of previous interactions generating patterns of activity. These rules are not fixed and can vary between actors and different time periods (Geels, 2004).

Transitions are social transformation processes that structurally change energy systems over a period of time. These transitions can be viewed as developments on three levels: landscape, regime and niche. Fossil fuel energy technologies are better understood as large socio-technical systems that provide energy servies to users. Understanding how the system works requires recognition of the various physical and social components of the system and sub-systems and the linkages between them. Actors, institutions and infrastructure form the three basic interacting elements of the system. Actors exchange resources and form a network under an institutional regime that defines the rules for interaction. The infrastructure represents all the physical resources needed for the socio-technical system to function. For example, the transportation network consists of cars, roads, petrol station, road regulations, etc. Each of these components can be further broken down into numerous sub-systems. For ex: the car can be broken down into the engine, ignition system, etc which each have their own physical and social components that highly interconnected. The car industry consists of multiple supporting technologies and industries including physical compents such as petroleum, glass, rubber, etc with their own core competencies as well as networks such as motorways with their own related industries of asphalt, concrete, metals, aggregate and machinery. The interdependence between these components and systems create barriers to competing technologies (Unruh, 2000). Transitions involve disrupting the incumbent socio-technological system with an alternative socio-technical system that emerges from new technology. Re-orientation of incumbent energy firms is necessary to accelerate sustainability transitions because of multiple complementary assets necessary for commercialising renewable energy innovation. However, such re-orientation is unlikely until the existing energy paradigm destabilises. Figure 12 below illustrates the socio-technical system for electricity.

Figure 12: Socio-technical system for electricity



3.3.1 Institutional and socio-cultural Change

Our energy paradigm is deeply entrenched in how our institutions and societies run. The interplay between institutions, energy and technology forms the foundations of economic growth (Nielsen, 2017). The sections above emphasise the co-evolutionary and mutually reinforcing nature of technological change and changes in social practices. Social norms have a self-reinforcing character because of heuristics and rule-of-thumb. A socio-technical perspective on energy emphasises the importance of attending to the social practices that energy facilitates. The energy cultures framework studies the energy-related implications of habit and behaviour change (Stephenson, 2018). Energy consumption is 'embedded in cultural processes' according to Lutzenhise (1992).

The social dimension of energy transition

The socio-cultural aspects of energy consumption were first revealed in the Princeton Twin Rivers study, which showed that energy use in identical dwellings varied dramatically (Socolow, 1978). This was explained as “Behavioral anomalies” due to a lack of information or motivation to save energy (Frey, 1992). Social norm refers to behaviour deemed acceptable or unacceptable in society. The practices are generated by habits and are shaped through interactions. They help us understand how group values impact an individual’s decision-making. Policies focussed on institutional actors such as corporations and governments ignore the effect of changing the behaviour of individuals. A better understanding of everyday consumption practices such as heating, driving cars and where we go on holiday can help design better policies that motivate change in energy consumption practices.

Energy consumption depends on the building environment and “the choices delivered through systems of provision” (Horta et al., 2014). This means that the demand for energy-related services depends on cultural practices and social norms. Social structures like family and technology impact practices of consumption. As energy is now considered plentiful and cheap, energy practices are constructed over time and can vary depending on age. Children learn attitudes towards energy from their parents and integrate these attitudes into their way of life as they grow up.

The attitude towards energy consumption faces a ‘binary consumption/moderation relationship (Garabuau-Moussaoui, 2009). Current attitudes towards energy consumption are equated to comfort. However, older generations that have lived through war and experienced hardships may have a conservation attitude towards waste but may also value comfort more during easier times.

Households in fuel poverty, for example, typically live in uninsulated houses and inefficient heating and appliances. Wearing layers of clothing indoors and frugal use of heating were a part of everyday life and embedded in an energy culture that was hard to change (Stephenson, 2018). Other studies examined dominant forms of transport and found meanings associated with them, especially the idea of freedom (Stephenson, 2018). Prosumerism, where the consumer produces electricity, in New Zealand is impacting the country’s electricity network and the role of institutions in the electricity sector. These changes mean that cultural formations have an impact on sustainable outcomes. Prosumerism in Sweden, for example, has increased energy awareness but has also increased energy consumption by some households who justify this by their access to 'free electricity' (Palm et al., 2018). These examples highlight the need for better educational/informational support for responsible energy consumption.

Institutions enable governments to address long-term challenges like climate change by structuring the political environment and bringing about sociocultural change. Kinzig et al. (2013) found that "policies are needed when people's behaviours fail to deliver the public good. Those policies will be most effective if they stimulate long-term changes in beliefs and norms, creating and reinforcing the behaviours needed to solidify and extend the public good".

Institutional change refers to a change in the value structure of an institution. These changes can be organised into attitudes towards power and authority or meritocracy. Most institutions are in flux but are shaped by past choices leading to path-dependent outcomes. However, institutional persistence exists due to power. For Acemoglu et al. (2020), this happens because "groups that are empowered by current institutions benefit from these institutions and use their power in order to maintain them, in the process reproducing their own power over the future institutions" (Acemoglu et al., 2020). However, this reproduction depends on powerful groups wanting to maintain the current institutional arrangement. If the group wants a different institutional arrangement, change happens. This was evident in the reform in the Soviet Union, which was led by a sufficiently powerful group in the 1980s and led to the fall of the Soviet Union between 1989-1991 (Acemoglu et al., 2020). The desire for change can also be motivated by the political reactions of non-elites, specifically when the disempowered majority can organise and solve their collective action problem (Acemoglu et al., 2020) during temporary windows of opportunity.

Butler discusses how structure, agency and interconnectedness play into ideas of mobility and how they are tied to decisions about where we live, work and travel. Individuals motivated by sustainability may be forced to undertake unsustainable practices such as driving long distances because of family and work obligations. Others may not be motivated by sustainability per se but embrace sustainable practices as part of their spiritual or political beliefs. For example, their desire to be self-sufficient. (Butler et al., 2014)

Acemoglu et al. (2020) distinguish between two types of path-dependent change: intrinsic and extrinsic. Institutions can be designed for persistence and stability if the rules that determine policy and the rules that determine institutional change are distinct. Kingston and Caballero (2009), on the other hand, identify two broad categories of processes of institutional changes, design-based and evolutionary but acknowledge that both processes may be at work simultaneously and that a clear-cut separation of the two is difficult. Design-based change occurs in centralised institutions, either a single individual or group or with many individuals or groups interacting through collective-choice or political processes to arrive at decisions. Here, changes come about from changes in ***underlying beliefs or knowledge***. In the context of energy systems, the underlying belief that energy is cheap and plentiful (as in many developed countries) may be the guiding principle of change.

In evolutionary change, institutional forms periodically emerge at random or deliberately and compete against alternative institutions. Success depends on propagation by imitation or replication, while other institutions die out. Here, institutional change occurs through the uncoordinated choices of many agents to craft new rules rather than in a centralised and coordinated manner (Kingston & Caballero 2009). These researchers argue that the ideal model for studying institutional change depends on the context. Based on that, we feel that the model of collective choice and political interaction is the best model for studying institutional change in the context of path-dependence energy systems.

Institutions are formal and informal constraints that structure political, economic and social interaction. Informal constraints, such as taboos and customs or formal constraints, such as laws and property rights, came about with trade development. In the absence of information and cooperation, they solve problems of organisation and ease transaction costs by enforcing rules, reducing uncertainty and creating order (North, 1991).

In the political environment, institutions also reduce transaction costs in the political environment which generally impedes an economic transaction (Drazen, 2000). The existence of these costs is higher in politics because political promises are difficult to measure. Problems of information asymmetry and specification or enforcement of a political transaction are also present in politics. The exchange of votes for promises of policies or votes at a future date also presents problems of an intertemporal nature to political transactions. While contracts reduce transaction costs, these are difficult to produce in the political arena, where complexity and uncertainty prevail. In these situations, governance structures in institutional arrangements over space and time are more effective than contracts (Drazen, 2000).

North (1991) explains developmental differences in various countries worldwide with the evolution of their individual, institutional frameworks. Participants' success in early systems of exchange, such as bazaars and souks common in the Middle East, depended on the individual's exchange skills and access to information and suppliers. The central feature of this system was to "raise the cost of transacting to the other party to exchange." Innovation in this system would threaten the livelihood of successful market participants.

The system of exchange in early modern Europe, on the other hand, evolved from simple forms of exchange similar to bazaars to "sequentially more complex organisation" that lowered transaction costs and facilitated long-distance trade. This went hand in hand with curtailing the state's ability to confiscate assets. Financial innovations such as bills of exchange, discounting methods and the rise of banks and financial houses enhanced capital mobility. The printing of prices of commodities, information on weights, measures brokerage fees, etc., lowered information costs and increased the volume of international trade. This, in turn, led to the development of specific institutions to facilitate trade. The evolution of collaboration between the state and merchants is key to understanding trade growth. The growth of long-distance trade created problems related to contract negotiation, enforcement, and protection of goods and services en route. This, in turn, led to the creation of armed forces. According to North (1991), "The evolution of capital markets (which entails security of property rights) was critically influenced by the policies of the state since to the extent the state was bound by commitments that it would not confiscate assets or use its coercive power to increase uncertainty in exchange, it made possible the evolution of financial institutions and the creation of more efficient capital markets." In other words, the role of the state and institutions co-evolved.

The key difference between the two systems of exchange boiled down to the payoffs traders received from acquiring knowledge and skills. In the simple system of exchange, the payoffs accrued exclusively to the trader in question and did not impact the institutional framework. In the latter case, improved knowledge and skills motivated the trader to collaborate with fellow market participants on reducing transaction costs. However, North (1991) differentiates between the evolution of institutions in Western Europe and the "path-dependent nature of economic change that is a consequence of the increasing returns characteristics of an institutional framework."

Stability is a key requirement for institutions to be able to function. Special interest groups slow society's adoption of new technology and the reallocation of resources to changing circumstances. When institutions become efficient at generating growth, they may turn to protect vested interests and become obstacles to further economic development (Ruttan, 2002). Basic institutions, such as markets, change due to incremental innovation, such as boundary shifts between markets and non-markets.

Pressure from interest groups serves as another determinant of institutional change. However, this change is strongly influenced by the cost of achieving consensus (Ruttan, 2002). If transaction costs are high, non-market institutions such as private or public institutions can mediate between firms and individuals.

3.3.2 Path Dependency and behavioural lock-in

Behavioural lock-in occurs as a result of habits, learning or culture. Consumers and producer behaviours lock into inefficient or sub-optimal outcomes due to irreversibility. The decisions of others influence individual decisions in a variety of circumstances. Company-level processes and institutional behaviour can lead to sub-optimal outcomes (Buhanist, 2015). Organisations' structures, established work patterns, institutional pressure, the desire to maintain the status quo, or a reluctance to give up power and control all contribute to behavioural lock-in. Some types of training, for example, represent a source of power passed down from mentor to mentor. The allure of power and control discourages the adoption of new standards and practices, which may diminish professional autonomy or disseminate specialised knowledge. At other times, individuals resist learning new processes or technologies when they become too set in their ways (Barnes et al., 2004).

Conventions reduce transaction costs and resolve indeterminacy problems in interactions with multiple equilibria. Young (2013) discusses convention as “a pattern of behaviour that is customary, expected and self-enforcing” (Young, 2013). Conventions such as industrial and technological standards and economic contracts have direct economic implications. For Young (2013), “The main feature of a convention is that, out of a host of conceivable choices, only one is used.” Conventions come about as a decision by a central authority or through accumulation by precedent. Positive feedback loops are created when one way of doing things drives out the others simply because history gave it an early lead. As most economic and social institutions are governed by convention, it is easy to see how conventions affect path dependence. Using a simple model, Young (2013) shows that some norms are more likely to be observed than others simply because they are more stable in the long run.

Social conventions and formalised rule structures that govern organisations and institutions act as carriers of history, i.e., they came about to satisfy some purpose and evolved into their present form (David P. A., 1994). He finds that the following situations give rise to path dependence in economies:

- History forms mutually consistent expectations that ease coordination problems without a central decision. Socially established ‘conventions align individual expectations enabling “them to select one among a multiplicity of possible solutions to a coordination game.”
- Information channels and codes act as sunk organisational capital. Information in organisations must be processed for use in decision-making. To enhance efficiency in communication, a code is settled upon.
- Interrelatedness between organisations and their members coupled with constraints on choices of rules and procedures, which result from pressures to maintain consistency and compatibility within the larger structure. Finnegan (2019) found that institutions structure the political conditions necessary to drive variation in climate policies.

However, Levin et al. (2012) believe the properties of path dependence can generate policies that can ‘constrain our future collective selves’ by triggering sticking policy interventions and changing behaviour through progressively incremental policies. The time inconsistency of preferences refers to the tendency of individuals and societies to give greater weight to decisions that affect the immediate future. Levin et al. (2012) provide the example of a reformed smoker who can "pay someone on Monday to hide her cigarettes on Thursday when she knows that severe cravings will make her unable to trust her future self. The reformed smoker on Monday makes a rational decision, recognising she is subject to time-inconsistent preferences, to fight Thursday's cravings." Similar strategies can be employed to fight societal behavioural problems through policymaking that addresses this at the collective level (Levin et al., 2012).

3.4 The political aspect of the transition

This section examines the effect of politics on transition. It discusses the political nature of decision-making and how policies are selected in the face of conflicts of interest. Politics can be described as the study of power and authority. Lasswell (1936) defined politics as a competition about who gets what, when, and how. He argued that politics in developed democratic countries revolves around money in the form of tax rates and budgets. He believed politics resolved how these resources were used (Lasswell, 1936). In the case of the sustainable energy transition, heterogeneous interests of the green and brown industries present political constraints, and contributions, endorsements or lobbying by the relevant interest group may influence policy outcomes. **Resistance to climate policy** comes from well-organized actors who benefit from the continued use of fossil fuels. Political competition thus involves resolving competing interests and can be understood by studying how interest groups affect policy outcomes.

The green industry, for this dissertation, refers primarily to companies engaged in the production and development of renewable and low-carbon energy as well as related services such as R&D and firms that invest in green technology or low-carbon energy systems, etc. These companies "benefit from and therefore prefer government support for green technologies and renewable energies" (Cao, 2012).

The brown industry, on the other hand, refers to the companies involved in producing and distributing conventional energies, such as oil and gas, as well as energy-intensive industries. According to Cao (2012), "Companies producing and distributing conventional fossil fuel energy often compete directly with renewable energies for market shares and state support. For energy-intensive sectors, given the fact that renewable energies are on average more expensive than fossil fuels despite years of technological innovations, the preference is similar to those energy companies." These companies would prefer receiving a larger share of state support, thereby reducing their production costs (Cao, 2012).

Decision-making mechanisms to study interest group effects include:

- Pressure and influence: this depends on the size of the interest group and their spending on lobbying. The group's influence increases with its own size and spending and decreases with respect to the size and spending of other groups (Drazen, 2000)
- Campaign models where contributors hope to gain favour by contributing to candidates. As candidates understand that contributions will depend on their policy stance and engage in strategic behaviour.
- Electoral endorsements: Interest groups may try to influence policy outcomes by providing information to candidates and the electorate. This mechanism is particularly useful in affecting the behaviour of less informed votes (Drazen, 2000)
- Lobbying for influence via contributions or dissemination of information

Resolving competing interests

Public choice theory applies economic methods to the theory and practice of politics and government and provides insights into democratic decision-making (Butler, Parkhill, Shirani, Henwood, & Pidgeon, 2014). Self-interest forms the basis of people's private as well as public (political) choices. As people are motivated to maximise the outcome of their choices, economic tools such as profit and loss and efficiency can be used to analyse politics. The variety of competing public interests makes collective decision-making a struggle between varied personal and group interests.

As sustainability is a normative goal, the relative importance of environmental problems as compared to other more pressing economic issues is likely to be debated. Further, the uncertainty associated with new technology means that the choice between multiple transition pathways entails multiple criteria, for example, landscape pollution by wind turbines versus the risk of nuclear energy. The key is to understand how competing interests are resolved by the political process (Butler, Parkhill, Shirani, Henwood, & Pidgeon, 2014). Further, as sustainability is a public good associated with prisoner dilemmas and free rider issues, there is no incentive for agents to act immediately. Environmental problems such as climate change are global in nature as well as intangible. This makes it difficult to mobilise immediate action for a future invisible outcome.

Political decision-making is guided by rational choice theory, which assumes that individuals have “a coherent set of preferences, gather the necessary information to reach an informed decision, evaluate alternative actions and choose actions that are optimally related to their beliefs and values” (Staerkle, 2015). These decisions are assumed to further the individual’s self-interest and are therefore considered rational. However, research has shown that these assumptions are not always true for a variety of reasons, including lack of consistency, lack of correct information or knowledge, overconfidence in their choices, etc. (Staerkle, 2015). Therefore, bounded rationality models account for individual variation in decision-making. Bounded rationality proposes that rationality in decision-making is bounded by limits to thinking due to available information and time (Simon, 1990).

Another factor impacting political outcomes is the communication of political issues. Agenda setting by the media influence citizen’s concerns. Public opinion is affected by how policy issues are framed. Kingdon’s model of agenda setting describes when and how issues move from the government agenda to the decision-making agenda. Here, problems, policies and politics are connected by policy ‘windows’ that open up during ‘focussing’ events (Green-Pedersen, 2015), such as earthquakes or terrorist attacks.

On the other hand, the punctuated equilibrium model of agenda setting takes a long-term perspective and characterises attention and public policy with long periods of stability followed by short periods of change (True et al., 2019). Based on the concepts of political institutions and boundedly rational decision-making, stability and incrementalism in policymaking are contingent on how issues are perceived in the public domain. The periods of stability generate policy monopolies where a shared understanding of the problem develops between actors (Green-Pedersen, 2015). Positive feedback processes develop during periods of stability when challenges to monopolies become self-reinforcing. Negative feedback mechanisms develop during policy monopolies and help policy stability.

The institutional model of political decision-making views government as a collective of legislative and institutional groups such as political parties, bureaucrats, capitalist corporations, etc., each with their own objectives. These institutions influence groups and policies as well as the objectives of polluters. Institutional differences between countries may help understand the differences in policy instrument choice.

Government is the group of people with authority to govern the people of a selected region. It can be described as the way some seek to act upon the conduct of others to change or channel that conduct in a certain direction (Foucault, 1982). Governments are viewed as motivated to maximise social welfare.

A political party, on the other hand, is an organisation consisting of people united by common principles with the aim of acquiring and exercising political power. Political beliefs differentiate political parties, and organisation is key to achieving the party's goals. Political parties are guided by the party's principles which can be defined as "the durable convictions held in common by its members as to what the state should be and do" (Morse, 1896). Party policies are guided by party principles and seek to attain party goals.

Political parties are motivated by getting the votes needed to win power and position. Elections control a policymaker's performance. The possibility of re-election incentivises an incumbent to act in the interest of voters instead of him/herself. Assuming choices are made from a set of alternatives in a one-dimensional spectrum ex. Left-right, the median voter prefers the outcome of the majority vote. Political strategies may include pursuing the median voter, using policy actions to shape citizens' preferences, and designing policies to elicit feedback (Soss & Schram, 2007). Policies can be affected by influencing the behaviour of policymakers or voters. This effect comes about via elections. The demand and supply of policies are determined by policymakers or voters.

3.4.1 Path Dependence in Policy

Institutions incentivise behaviour that locks into particular paths of policy development. Policy-making processes are connected over time in patterns of continuity or discontinuity depending on the prevailing political and institutional sentiment (Skogstad, 2016). Long periods of institutional stability are punctuated by brief phases of "critical junctures" when policy choices that are made close off alternative options, thereby generating self-reinforcing path-dependent processes (Capoccia & Kelemen, 2007). Critical junctures are rare periods when economic, cultural, ideological and organisational influences on political action are significantly relaxed. They increase the range of plausible choices open to politicians allowing greater impact of policy decisions. These brief periods provide a brief phase; agents face a broader than the typical range of feasible options and the notion that their choices from among these options are likely to have a significant impact on subsequent outcomes. However, once a particular choice is made, they trigger a path-dependent process that constrains future choice making it progressively difficult to return to the point where when multiple alternatives are available. Power asymmetries, time horizons, units of analysis, and near misses. Institutional settings as such as political parties, public policies and political regimes provide ample opportunities to study this phenomenon in energy policy (Capoccia & Kelemen, 2007).

Network technology industries are subject to externalities that set in motion self-reinforcing dynamics that are a source of path dependence in the system (David, 2005). The existence of these feedback processes creates ‘windows’ for effective policy intervention. Policy intervention at the beginning of a new technology’s introduction has the greatest impact. However, the timing also poses uncertainties about the technology’s future trajectory. David (2005) suggests counteracting the strength of market giants by subsidising new technology.

Pollution taxes introduce negative feedback that counters the positive feedback of network externalities. Taxing dirty technologies and subsidising clean technology reduces the profit gap between the two and helps increase the share of clean technology by introducing negative feedback. When positive feedback is weak, environmental policy can increase the share of clean technology (Zeppini 2015).

3.4.2 The Politics of Energy and interest groups

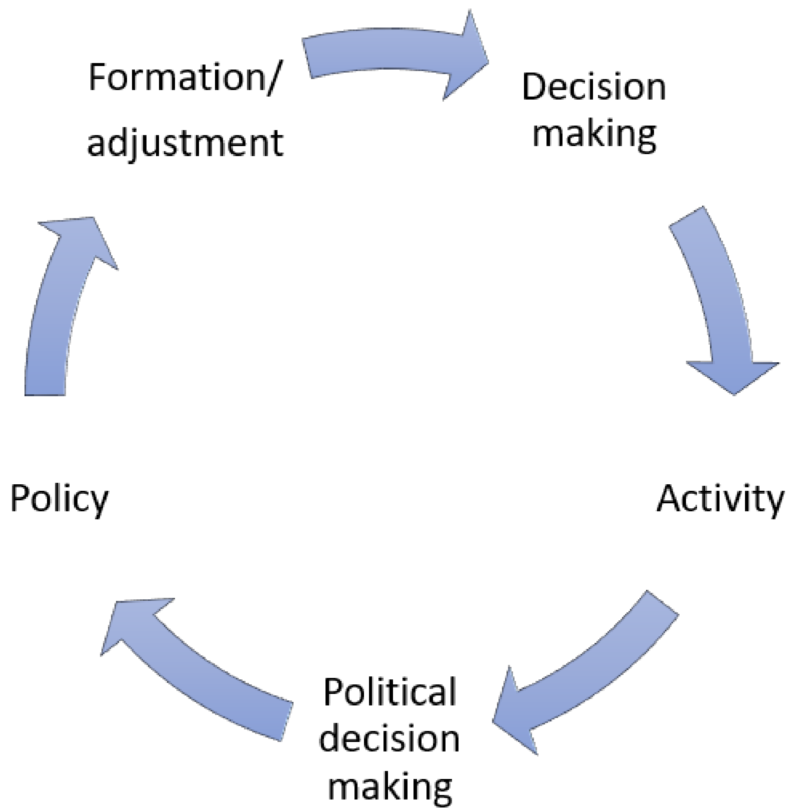
Structural change in energy systems is politically different because of the size and importance of the industry for economic growth. Therefore, governments take the interest of energy lobbies into account when setting policy (Geels, 2014). As we saw in Chapter 2, the influence of powerful corpoate interests often prevents “the formulation and execution of strong and consistent state policies” (Keohane, 1982). The creation of foundations, think tanks, political action committees, lobbying firms, and advisory committees funded by corporate interest has shaped government and public opinion in the US since the 1970s (Geels, 2014).

Policymakers and incumbent businesses form close alliances because of mutual dependencies. Industry depends on the government to establish property rights and rules of exchange, while governments provide support in the form of tariffs, tax concessions and grants. These alliances lead policymakers to internalise the interests of energy industries causing them to agree with the industry definition of the problem and desired solution.

The public-choice approach to economics stresses the importance of political and economic self-interest in the determination of policy (Aidt, 1998). Aidt (1998) uses a common agency model of politics to show that "competition between lobby groups is an important source of internalisation of economic externalities." Industrial influence in the political arena comes about through campaign financing and corruption. Energy groups mobilise against energy transition policies that threaten short-term profitability and long-term survival. These groups comprise the petroleum, coal and natural gas industries. In the US, they also comprise right-wing think tanks and conservative politicians who "frame the green energy transition as the improper government role in the economy" (Hess, 2014). On the other hand, green industry groups comprise green-energy industries. These groups must have the capacity to attract financial support, especially in the US. Interaction between policymakers and interest groups generally follows a circular chain of events (illustrated in Figure 13) viz:

- group formation/adjustment
- group decision making
- group activity
- political decision making
- government policies (van Winden, 2008, pp. 323-343)

Figure 13: Interaction between policymakers and interest groups



Source: van Winden, 2008

Conflict of interest is the essential ingredient to time-inconsistent problems. Majority preferences change over time, causing time-consistencies problems. The government's incentive toward time-inconsistent behaviour can be explained by the trade-off between commitment and flexibility. Reducing uncertainty by committing to a specific policy over the long term might leave it unable to respond to unforeseen events. The implementation of carbon taxes, acknowledged as the most effective policy for addressing climate change, has been irregular for this reason. Finnegan argues that the temporal nature of carbon taxation is to blame. Carbon taxes impose costs in the short term to accrue long-term unseen benefits. The politics of such long-term policy-making then depends on electoral competitiveness. Governments with a low risk of losing office can afford to engage in policies that induce long-term structural change as politicians are insulated from voter punishment. Finnegan (2018) argues that when electoral competition is high, politicians play to their voter's preferences. Taxes that have a high personal cost for a few, for example, because the majority of voters use public transportation, are less risky politically.

The negative impact of collusion, corruption and lobbying

Collusive industries with large profits have a greater incentive to form lobby groups and contribute to industry lobbying. Polluting industries have a similar motivation to lower pollution taxes ((Damania, Fredriksson, & List, 2003). Corruption and lobby group size have a similar effect on environmental outcomes. Corruption reduces energy policy stringency, especially in large sectors with greater coordination costs. ((Fredriksson, Vollebergh, & Djikgraaf, 2004). Environmental policy is also affected by the level of protectionism and/or corruption (Damania, Fredriksson, & List, 2003).

3.5 Summary

This chapter discussed the concept of path dependence and its relevance to technical change and energy systems. We argued that evolutionary concepts, with their ideas of bounded rationality and selection processes, might be more useful for understanding technological change and the evolution of systems than neo-classical economics. The distinction between these modes of thinking is necessary when designing policy to bring about regime change.

The events and policy choices by different countries made before and after the 1970s oil crises were contingency events as alternative choices for the security of energy supply could have been proposed in countries dependent on fossil fuel imports. Instead, self-reinforcing feedback processes facilitated removing energy alternatives in favour or against the renewable energy industry, depending on the country. These processes are better understood through the lens of path dependence and policy feedback.

Technological products and markets are complex and prone to path-dependent features for a variety of reasons. These features lead to technological lock-in, and while it may be difficult to predict the exact moment of lock-in, reviewing the history and understanding the moment of path bifurcation is useful for future policy development. The sustainable energy transition is essentially a societal transition and is therefore linked to technical, economic, environmental and cultural dimensions. Institutions are key to this change. The political obstacles to achieving sustainable energy transition largely involve tradeoffs between political self-interest and social welfare. However, one way of overcoming these obstacles is through policy design that captures the buy-in of a variety of stakeholders.

4.0 Perspectives on Feedback Processes and Models

How are policies designed, and do they achieve what they set out to achieve? This chapter examines the challenges, limitations and dynamics of public policymaking. The policy process is first discussed, followed by a discussion on path dependence. Next, we examine the concept of feedback and how feedback mechanisms may be used to bring about a transition to sustainable energy.

4.1 Theories of Policy Feedback

Policy feedback theory (PFT) is one of several theories in the field of policy processes, which integrates research on politics and government with a focus on policies (Weible, 2018, pp. 1-2). Public policies are defined as governmental decisions taken to achieve specific goals, such as statutes, laws and government programmes, but they also can include rules that structure behaviour or be understood by "identifying the institutions that constitute its design and content" (Weible, 2018, p. 2). PFT examines the effects of policy adoption with an emphasis on resource and interpretive effects.

4.1.1 The Policy Process

The policy process consists of agenda setting, policy formulation, policy adoption, implementation, evaluation and termination (Weible, Heikkila, deLeon, & Sabatier, 2012). Defining the problem and identifying economic, technological, political and institutional constraints form part of the policy feasibility analysis. Each of these areas offers influence opportunities by interest groups. Agenda setting and agenda control are essential because the ability to keep something off the governmental agenda is just as important as the power to choose between alternatives (Moran, Rein, & Goodin, 2006). In the 1970s, the US Congress did not consider imposing a high gasoline tax, considered the best way to reduce demand for imported oil, simply because they feared retribution by the voter (Moran, Rein, & Goodin, 2006).

Cultural studies argue that meaning arises from interpretation. As sense-making is an ongoing process, how issues are framed in the media influence how relevant audiences think and talk about these issues. **This, in turn, influences public support creating a**

feedback effect. Policy issues can be framed strategically to mobilise opinions in particular directions.

The political agenda refers to a set of issues considered and debated in a political system and can be classified into systemic and institutional agendas. The variety and diversity of problems in the political arena mean that attention is a scarce commodity. Mobilising bias, defining alternatives and keeping issues away from the agenda is one way of agenda setting.

The policy process involves complex interactions between various actors, such as interest groups, governmental agencies, researchers, journalists and judges with different values and policy preferences. These processes require decades to accumulate the appropriate knowledge about the situation and may involve different levels of government in areas such as air pollution control. Policy debates involve technical issues, the causes of the problems and the impact of policy solutions. They are also influenced by deeply held values and, often, large amounts of money, which may cause actors to misrepresent positions (Sabatier, 2007). Policy participants are goal-oriented but are limited by bounded rationality to process information. They are therefore affected by emotions such as fear and trust and rely on heuristics to aid in reasoning complex problems.

Policies are usually considered the result of political action. However, policies can also influence politics. Looking at policy from a feedback perspective requires examinations of the political web of governance relations. Policy analysis methods include puzzle-solving, critical listening, policy advice, for democracy, as critique (Moran, Rein, & Goodin, 2006). The advocacy coalition framework looks at processes that emerge through competition between groups over a period of time. Influencing and shaping policy requires developing knowledge, building networks and participating for extended periods of time (Weible, 2018). Cognitive factors such as bounded rationality and the use of heuristics such as ideology and beliefs to aid reasoning. Punctuated equilibrium describes policy behaviour of periods of stability followed by changes (Rubino, 2017). For Fowler, Neaves, Terman, & Cosby (2017), only events that bring about cultural change can overcome policy inertia. They find six historical events that have impacted US energy policy: The Suez Canal crisis in 1957, the Arab oil embargo in 1973, the 1973 and 1974 energy crises, the oil glut in the 1980s and the 1991 Gulf War.

The origins of policy feedback, with its emphasis on the temporal element of policy development, can be traced to three related bodies of literature (Beland, Campbell, & Weaver, 2022):

- Early literature on policy feedback originated within historical institutionalism (HI), making HI essential to understanding feedback. Punctuated equilibrium theory and social construction of target populations all contributed to our understanding.
- The next phase of the literature examines the effect of policies on public behaviour and attitudes. Specifically, they discuss how policies can increase or decrease participation or political equality and how they affect attitudes towards governments, parties and program recipients.
- The third strand of policy feedback focuses on prospects for policy change. Feedback mechanisms include economic returns, socio-political mechanisms, information and interpretive mechanisms, fiscal mechanisms and state capacity mechanisms. These mechanisms can be weak or strong, self-reinforcing or self-undermining. Each of these mechanisms can be used to further or hinder specific interests (Beland, Campbell, & Weaver, 2022).

Historical institutionalism examines the evolution of institutional processes over time. Comparative research is strongly emphasised as norms, rules, and policies vary from country to country. The key to understanding policy feedback with the HI framework is the distinction between the synchronic and diachronic effects of institutions. Synchronic effects refer to the "short-run effect of prevailing political-institutional arrangements on the relative political influence of political actors. Veto points are an example of a synchronic effect. Diachronic factors and processes analyse how changing political structures shape political capacities and change the actors involved. Policy feedback is an example of a diachronic effect (Beland, Campbell, & Weaver, 2022).

The early policy feedback literature focuses on the following:

- state capacities
- interest groups and
- lock-in effects.

State capacity refers to the government's ability to accomplish its policy goals. Expansion of state capacities is a form of policy feedback when newly established policies contribute to state building in a reinforcing manner. Skocpol (1992) demonstrated how the development of the Bureau of Pensions in the US for war veterans led to the gradual expansion of these benefits making the Bureau of Pensions "one of the largest and most active agencies of the federal government" (Skocpol, 1992). Similarly, the development of Social Security bureaucrats in charge of the Social Security program in the US promoted the expansion of the program (Beland, Campbell, & Weaver, 2022)

Theda Skocpol's "*Protecting Soldiers and Mothers: The Political Origins of Social Policy in the United States"* brought the idea of policy feedback into public focus with the idea that "policies, once enacted, restructure subsequent political processes" (Skocpol, 1992, p. 58). Her study focussed on social provisions for Civil War veterans' and mothers' pensions in the United States and their failure to develop into fully-fledged social programs because of the public perception that government programs were riddled with corruption and patronage. For Skocpol (1992), governmental institutions, electoral rules, political parties, public policies, and all their transformations over time create limits and opportunities. Institutional arrangements and electoral rules dictate "which of the society's groups become involved in politics" and largely depends on the fit between institutions and group goals (1992, p. 527). Changes in social groups and their political goals and capabilities are one source of policy feedback. At the same time, the transformation of state capacities is another source. The perception that non-contributory old-age pensions were subject to abuse prejudiced educated American opinion away from providing old-age pensions in the United States.

The development and expansion of interest groups is a second form of policy feedback in the early literature. This research focuses on how policies that confer economic and social benefits lead to the formation of interest groups by stimulating social identities or political capacities. Once formed, these interest groups are motivated to participate in debates to continue these policies. At the same time, policies may be used to strengthen or hinder specific groups by increasing or decreasing the size of their constituencies leading to a feedback effect Skocpol (1992). Larger constituencies are generally more resilient in the face of uncertainty. Yet even programs targeting politically disadvantaged people gain strength if they generate strong political allies.

Paul Pierson's seminal paper "When Effect Becomes Cause" (Pierson, 1993) expanded the investigation into policy feedback by creating a conceptual framework investigating how policies produce resources and incentives for political actors. For Pierson, "By virtue of their location within a political system, particular actors may have direct access to significant political assets" (1993), such access to authority or the capacity to issue commands. At the same time, political systems create incentive structures that influence the probability of particular outcomes and related payoffs. These incentives and resources facilitate the formation and expansion of interest groups by supporters and detractors/non-support and attract political entrepreneurs interested in helping 'latent groups'. Pierson's (1993) framework used two feedback mechanisms; resource/incentive effects and interpretive effects, and three sets of actors affected by these mechanisms; government elites, social groups, and mass publics; to show six "pathways of influence", as illustrated in Table 6 below. These mechanisms have the potential to initiate path-dependent processes that make it difficult to change course once initiated ((Mettler & Sorelle, 2018)

Table 6 Pierson's Dimensions of Policy Feedback

		Actors Affected by Feedback Mechanisms		
		Govt Elites	Interest Groups	Mass Publics
Type of Mechanism	Resource & incentive effects	Administrative capacities	"spoils" Organising niches Financing Access	"Lock-in" effects
	Interpretive effects	Policy learning	Policy learning Visibility/traceability	Visibility/traceability

Source: Pierson 1993

Ideational policy feedback refers to how ideas and symbols can shape the politics of policy reform. For example, 'welfare' has become a negatively connotated term. Feedback effects are best referred to as self-reinforcing or self-undermining (Beland, Campbell, & Weaver, 2022).

Feedback and mass politics

Political participation can increase or decrease depending on the attitudes of the target population. Policies convey messages which may be perceived as positive or negative, thus impacting attitudes towards political participation. Similarly, positively perceived groups such as senior citizens tend to receive "generous and efficiently administered" policies, while those for negatively perceived groups such as the poor or criminals suffer meagre policies. However, it is unclear whether it is the policies that create the group constructions or pre-existing conditions that lead to inefficient policy design (Beland, Campbell, & Weaver, 2022, p. 21).

Behaviour: Drivers of political participation resources, mobilisation and political engagement. Resources such as money, skills and free time increase participation. Citizens are also mobilised to participate when asked to do so. Similarly, program beneficiaries are more likely to participate, showing that political engagement results from political information and political interest. On the other hand, stigmatisation of programs such as social benefits that are means-tested has a negative effect on political engagement. These negative effects can be passed on through socialisation. For example, low levels of parental participation as a result of these negative effects are passed on to children. Threats to eliminate policies or increase the visibility of policy effects, such as draft policy, for example, are other reasons that encourage participation (Beland, Campbell, & Weaver, 2022, p. 17).

Attitudes: Policy feedback literature argues that policies affect the drivers of public attitudes. Individual attitudes are shaped in childhood through socialisation. Self-interest, personal experiences, class differences and the way political messages are framed all impact public attitudes. Trust in government, belief in markets and issue ownership, where citizens perceive that certain political parties are better at handling certain types of issues, are other factors that impact political attitudes (Beland, Campbell, & Weaver, 2022).

4.1.2 Path Dependency in Policy

Alesina and Tabellini (1990) show that policymakers use government debt as a tool to influence the choices of successors. In their model, benevolent social planners seek to minimise debt. The results of their model show that the equilibrium level of government debt is larger when the degree of polarisation between alternating governments is larger.

Previous policy choices may have a constraining or opportunity-enhancing effect on future policies such as the US health care system. Moving away from the current employer-finance health insurance for employees to state health care would entail additional costs to the employer to keep compensation at the same level while adding a budgetary burden on the public treasury. Thus the US is 'locked-in' to its current healthcare system, which does not incentivise either employers or the state to change/revise (Kay, 2006).

Another explanation for path dependence in policymaking is that it is easier to modify existing structures than build new ones, even if the new structure may be superior (Pierson, 2000). The co-evolution of government regulation, market structure, common law rules, and trade oversight is a specific form of path dependence in regulatory policy. Bardach (2011) cites the early regulation of milk and dairy products to protect consumers. The arrival of large supermarkets with milk in cartons and refrigerated displays reduced the need for government regulation. Regulation was later largely supplanted by the oversight of large milk producers with a vested interest in maintaining company reputations.

Unintended consequences

As policies can be used to yield advantages in future political electoral games, Soss & Schram (2007) believe that policymakers need to think two moves ahead like chess players. Unintended consequences are unplanned effects that could be beneficial, detrimental or controversial. These are difficult to identify at the outset because of various factors such as ignorance, greed, cognitive processes or complexity. Policies can have unintended consequences leading to feedback effects. Some unintended consequences are hard to predict, while others need to be accounted for in the policy planning process. For example, conservation plans to conserve old-growth habitats may spur landowners to pre-emptive habitat destruction (Polasky, 2006). Rising biofuel demand raised corn prices leading to riots in 2008 across the world. Similarly, draining Indonesian swamps to grow palm crops released large quantities of greenhouse gases into the atmosphere. Solar PV cells contain heavy metals that leach into groundwater when disposed of incorrectly. Further, the PV manufacturing industry is a leading emitter of greenhouse gases into the atmosphere.

Unintended consequences can be positive, negative, perverse (where the exact opposite of the desired effect is achieved) or controversial (where some view the results as positive and others not). Incentives to increase energy efficiency can lead to increased energy consumption.

4.2 Path-dependent processes

Antonelli (1997) defines path dependence as "the set of dynamic processes where small events have long-lasting consequences that economic action at each moment can modify yet only to a limited extent." These processes come about as a result of irreversibility, indivisibility and structural actions and make it possible for agents/individuals and their environments to affect each other behaviour creating a feedback effect. Agent's behaviour has an effect on their environment resulting in changes to the environment which impact the agent's learning and adaptation. The agent's behaviour is constrained by space and time. Path-dependent processes accommodate the consequences of actions at each point in time, but their outcomes cannot be predicted in advance. Time then becomes an important variable in the evolution of these processes because the consequence of each sequence of steps is irreversible and impacts future selection processes. The outcome of the process then depends on the characteristics of the initial conditions of the environment as well as the behaviour of agents. This is highlighted in the evolution of the Nordic energy systems. The Danish energy landscape had sufficient knowledge to employ wind energy. However, the eventual outcome came about as a cumulative result of decisions made at several key moments. These decisions did not come about harmoniously but were the result of conflict and decision-making at the political level.

Irreversibility is defined as the difficulty of changing a given behaviour or choice and is embodied in switching and sunk costs. Indivisibility of production factors leads to economies of scale as well as a scope which can cause lock-in. At the same inappropriability, especially of knowledge, leads to interdependence among users which leads to clustering and spillovers, which have feedback effects. At the same time, spillovers lead to technological recombination.

Structural action is the intentional change of technology or tastes, turning them into endogenous variables determined by the interaction of agents. In this case, it becomes the outcome of learning efforts as well as a change in conduct induced by other parties. Thus firms are able to manipulate the structure of the system. In the case of fossil fuels, lobbying by fossil fuel firms changes the structure of the system to suit their own purposes. For Antonelli (1997), "analysis of the interactions and combinations of the different specifications of irreversibility and indivisibility" helps us understand processes of change where time matters "instead of the factors of some well-circumscribed classes of market failures." Time becomes a source of uncertainty with regard to the consequences of each action, as each agent does not have a clear understanding or command of the sequence of stages. At the same time, as the sequence of steps cannot be reversed, irreversibility has important effects on selection processes leading to path dependence. In these situations, market dynamics are dependent on initial conditions and agents' behaviour. The diffusion of innovation exhibits increasing returns. As a new technology gains more users, information costs are lowered. As complementary products, technologies and skills diffuse alongside, sunk costs play into increasing returns. Increasing returns to adoption then stem from learning, network externalities, economies of scale and technological complementarities (Antonelli, 1997). These dynamic processes can be classified as excess momentum due to unexplained dynamic forces in the system or excess inertia when behaviours are retained despite incentives to change.

Complex Markov processes have been used to study systems with asymmetric relations between agents where behaviour changes the system due to local interactions through local positive feedback that reinforces agents' actions or unexplained fluctuations or the unexplained reduction in strength of force perturbating the system (Antonelli, 1997). The interaction of irreversibility, indivisibility and structural action implies positive feedback can be instigated and employed to induce sustainable energy transition.

Ergodic and non-ergodic processes

Ergodicity is the assumption that the time average of a variable equals its expected value. The ergodic hypothesis forms the basis of equilibrium theory in economics. According to Horst, the breakdown of ergodicity gives rise to path dependence because history matters (Horst, 2008). Horst (2008) describes a stochastic system as ergodic if "it tends in probability to a limiting form that is independent of the initial conditions." Ergodicity in stochastic systems is concerned with giving meaning to quantitative probability. This may be rooted in parallel universes or in time as long as there is no interaction between systems (Peters, 2011). However, Peters (2019) proposes a conceptual re-orientation of this basic assumption.

Probability theory originated in gambling and led to the development of expected value computed as an ensemble average using all possible outcomes. However, Daniel Bernoulli realised that this conclusion was based on the idea that all people are able to assume the same level of risk. He felt that this requires the use of parallel universes. Bernoulli came up with the "expected utility theory" to explain decision-making under uncertainty (Peters, 2019). This stated that people consider the expected changes in the usefulness (or utility) of wealth in addition to the expected changes in wealth when taking part in a gamble (Peters, 2019). "Expected utility theory predicts that people are insensitive to changes in dynamics" and encompasses high and low-risk-seeking individuals. However, ergodicity predicts something else (Peters, 2019). For Peter (2011), the prominence of Bernoulli's early arguments have contributed to economic attitudes towards risk impacting investment decisions and macro-economic processes. Poor risk assessments of modern financial products lead to market instability through the effect of credit and leverage. **The key observation is that ensemble averages converge while time averages diverge.** Utility functions represent risk preferences but cannot recommend appropriate levels of risk (Peters, 2011). However, other researchers have suggested that Peters's view that utility and attitudinal characteristics are unimportant is erroneous and that "no single paradigm is superior for answering all economic questions (Doctor et al., 2020)

Path-dependent stochastic processes are often non-ergodic, meaning that ensemble and time averages do not yield identical results. While ergodic and nonergodic processes coexist in some biological processes (Weigel et al., 2011), ergodicity and non-ergodicity in economics are dependent on complementarity. For Horst (2008), the breakdown of ergodicity plays a major role in social interaction. Historical choices based on specific circumstances can persist even after those circumstances change. This is illustrated in endogenous preferences, learning dynamics and non-market interactions. Stochastic growth models emphasise the convergence of economies with identical preferences and production functions. However, this convergence is absent from empirical studies. Durlauf (1993) uses technological externalities in production processes to explain these differences. Economies over low-production industries and move to high-production technology when "negative feedbacks from low production technology are weak." However, powerful negative complementarities can generate a non-ergodic growth path, according to Horst (20087). When complementaries are strong, industrial change fails, and economies become trapped in low productivity. Such processes may be observed in the utility industry. Strong complementarities between fossil-fuel-generated electricity prevent industrial change to renewable electricity.

In dynamic models of social interaction, Horst (2008) found that choices are influenced by past actions as well as anticipation of future actions by neighbours. These interactions result in spatial ergodicity for aggregate behaviour and temporal ergodicity for individual choices in the long run when the interaction is weak.

Polya urns and self-reinforcing systems

Polya processes are stochastic processes which are applicable to positive-feedback situations. These processes can be linear or non-linear and lead to a stable equilibrium. Polya urn models allow the study of self-reinforcing systems with explicit path dependence. A Polya urn contains x white and y black balls. One ball is drawn randomly from the urn and then returned. Then an additional ball of the same colour is added to the urn, and the process is repeated. Polya urn models help understand the evolution of the urn population and the sequence of colours drawn out. The random sampling with replacement scheme helps understand reinforcement as the history of the process tips the ratio towards one path or the other leading to a path-dependent equilibrium. The system is then locked into an equilibrium of one colour or the other. Reinforcement is weak when the number of balls added is lower than the number of balls in the urn and vice versa. Strong reinforcement changes the Polya urn behaviour and the Polya divergence. Weak reinforcements results in behaviour similar to Bernoulli processes (Ibe, 2014, p. 369; Hanel et al., 2017). Non-linear Polya processes result in an urn of one colour. Markets for non-linear Polya processes are typically found in knowledge-intensive industries and exhibit the following criteria:

- decreasing costs
- network effects
- product complementarity
- user knowledge

Markov processes

From Antonelli (1997), Markov chains (Markov, 1906; Seneta, 2006) describe processes where the current state impacts the state in the following period. The existence of multiple absorbing states makes Markov random fields interesting. If the energy state in period t determines the probability distribution of the energy state in the following period t+1 and the energy state in prior periods has no effect on the transition probabilities between t and t+1, the variation over time of the energy state can be determined by a Markov process according to Antonelli (1997). Simple Markov chains can be used when transitions from t to t+1 depend only on the state. The transition probability is not affected by features of the previous state, and the process is past-dependent but not path dependent. These processes are partly deterministic as agents' intentional behaviour does not affect the transition probability.

On the other hand, complex Markov processes are better suited to study processes where the probability transition is affected by states at time t, t-1, t-n, etc. These processes are non-ergodic and path-dependent as the state as well as the changes during the state, impact the probability transition. So path-dependent processes arise due to initial conditions as well as the behaviour of agents.

Markov chains are useful for analysing the evolution of a system through time or the evolution of agents' behaviour in the system through time. The parameters of the system are affected by the entry and exit of agents, connectivity and receptivity of agents. They also allow observation of small events that may have to activate chain reactions and change the parameters of the system (Antonelli, 1997), thereby changing the nature of path dependence through local action.

Percolation methodologies can be used to study agents' behaviour that is determined by the behaviour or decisions of neighbours (Antonelli, 1997). The outcome of the process at the global level depends on the distribution of agents' behaviour. Percolation systems are impacted by external pressure and connectivity, receptivity and density between agents. The dynamics of localised technological change and percolation processes are interdependent. The percolation probability is measured as a result of receptivity probability and connectivity probability and has been used to study technology adoption and spillover of the learning effect.

Increasing returns

In a model of increasing returns, the effects of small disturbances can be amplified by the agent's actions (Romer, 1986). In Romer's (1986) model of endogenous technological change, long-run growth is the result of the accumulation of knowledge by agents. Knowledge then becomes a basic form of capital, and new knowledge is the product of research technology. The creation of knowledge is assumed to have positive externalities on other firms as it cannot be kept secret.

4.2.1 Circular and cumulative causation

Initially developed by Veblen, cumulative causation (CCC) is a process where initial conditions are reinforced by subsequent occurrences (O'Hara, 2008). Interaction between variables magnifies and multiplies leading to feedback processes and cumulative causation, causing the system to move through time in a non-linear fashion. The concept is concerned with increasing returns, complementarity, disequilibrium and endogenous change. History, time, space, geography and regional differences play important roles in the concept alongside the accumulation of knowledge and technical skills.

Gunnar Myrdal and Nicholas Kaldor examined regional and industrial development, respectively, with the idea that "variables are interrelated and the general manner of interaction between variables in complex and manifold" (O'Hara, 2008). These interactions give rise to a positive feedback process which magnifies and multiplies "the combined impact of the interactions through historical time. The coefficients of interaction between variables will play some role here, as will the extent of any negative feedback (drawback) effects working in the opposite direction" (O'Hara, 2008). The cumulative effects of feedback amplify overall outcomes. Further, traverse, path dependence and hysteresis move through the system in a non-equilibrium fashion because innteraction between variables creates complex linkages and generates cumulative effects that result in large variations in outcome. Hysteresis refers to the condition that equilibria are path dependent. Persistence which has similar properties, implies that the original equilibrium will be re-established after a period of time. Hysteresis can be identified using univariate unit root tests, cointegration tests, Markov-switching and Kalman-filter.

While Myrdal examined the social economy and the role of ideology, assumption and social norms in cumulation and uneven development, Kaldor focussed on the narrower economic issue of technical demand-supply related to economies of scale and growth especially regimes of accumulation when norms become locked in. A cumulative growth mechanism has been developed using dynamic increasing returns to study differences in regional development. Culture forms the basis of the socioeconomic process in CCC. CCC dynamics encompass social and cultural aspects to explain differences in regional developments. This means that cultural, socioeconomic and technical factors must be examined to understand problems. Cumulative effects can be moderated by external forces such as “exogenous shocks, policy interference, negative externalities, industrial maturation, and floors/ceilings to the cycles” coupled with “changes in wages, population and enterprise profit” (O'Hara, 2008). At the same time, these cumulative effects may generate profound changes in the historical process that result in new phases of development and growth over time.

Zukowski (2004) found that the long-term persistence of regional differences in Poland was rooted in historical regional endowments that led to self-reinforcing cycles that widened interregional discrepancies and affected the regional transition to a market economy. For Zukowski (2004), “performance in a systemic transformation is a path-dependent process, partly governed by the long-run historical legacies. These processes have “3 defining properties:

- causal processes highly sensitive to early events. These self-inforcing processes exhibit increasing returns.
- early historical events are contingent occurrences that cannot be explained by the past. Each step is a reaction to the previous, making outcomes unpredictable.
- path dependent sequences are characterised by relatively deterministic patterns of causality

Zukowski (2004) found that the outcome of a shock depended on the response to them, which in turn depended on the economic and institutional structures of the region. He says, “Exogenous shocks might reinforce or weaken the internal effects of a reactive sequence. Nonetheless, the chain of occurrences also contains some sequences, which are self-reinforcing in nature.” These processes may be useful in explaining the accumulation of particular types of knowledge in certain areas. These areas or groups advance as a result of technological and skills accumulation, which impacts norms and psychological effects

(O'Hara, 2008). Individuals thus develop habits and behaviours that are conditioned by experience. The concept of cumulative causation helps explain the emergence of new intentional and unintentional behaviour as well as their coevolution with the environment.

4.3 Feedback models

Bardach (2006) describes systems as a set of interconnected elements where changes in some elements produce changes in other elements. The properties of the system differ from those of the individual elements. Systems consist of:

- Elements
- Rules that govern interactions between the elements
- Information to apply the rules

Feedback loops occur when elements in a system are connected in a cyclical way such that the process is regulated directly or indirectly by its own consequences, i.e. certain system outputs influence certain system inputs. This makes cause and effect detection difficult and therefore requires analysis of the system as a whole. Closed systems respond to changes within the system, while open systems respond to changes within as well as outside the system. A dynamical system is a system whose behaviour changes over time in response to external stimulation, but the effects are not immediately discernible (Astrom & Murray, 2008).

Growth-inducing feedback loops are positive, while negative feedback loops have a balancing effect (Bardach, 2006). Simple causal reasoning about a feedback system is difficult because the first system influences the second, and the second system influences the first, leading to a circular argument. Feedback properties can be exploited to make systems more resilient toward external influences.

Although feedback loops occur in diverse fields such as biology, electronics and economics, their structures are the same. Feedback loops may create emergent properties and generate multiple states. These can be analysed by understanding the structure of the system. Complex systems with many elements and interdependencies can be reduced to smaller systems to ease study. Negative feedback loops are particularly interesting in the study of lobbying effects of the green and brown industries. Bardach (2006) identifies two types of negative feedback processes:

- Oscillations that occur within certain limits, and
- Efforts to maintain a monopolistic equilibrium. In this case, reformation success would be a disequilibrating process.

Oscillating processes are balancing processes that preserve power balances; countervailing coalitions rise to challenge emerging coalitions. Coalition formation, in this case, is fluid, and the system "oscillates between relative peach and near-war" (Bardach, 2006). The oscillation of regulation policy is an example of negative feedback. In the US, the Environmental Protection Agency is more aggressive when the Democrats are in power (Bardach, 2006) indicating the Left-Right dimension of environmental policy. These oscillating processes are also relevant to managing risky policies related to the development of new technology if heuristics such as "If it didn't seem to work in x months, cancel it" are followed to avoid sub-optimal results. Public spending is another oscillating process where the public acts as a thermostat to counteract excess or under budgetary spending (Wlezien, 1995). Bardach (2006) finds party positions during elections and reforms are also prone to oscillating processes.

Monopolistic control of an issue in the policy agenda arises when established interests such as interest groups and policy committees agree on policy, creating a monopolistic equilibrium which can only be disrupted by the creation of new policies and institutions, or 'mobilisation of criticism' both of which require strong media attention (Bardach, 2006).

Positive feedback processes, on the other hand, come about through momentum-building processes such as legislative coalition building, social movements, innovation diffusion, etc. These processes encourage movement towards a goal and also stimulate others to move towards the same goal. Compensating feedback mechanisms in complex systems have the ability to beat policy interventions (Bardach, 2006).

4.3.1 Dynamic feedback

Barlas (2002) defines a system as a "collection of interrelated elements" forming a whole. The structure of the system describes the relationship between variables and creates the behaviour. In system dynamics, feedback and dynamics in variables arise out of the internal structure of the system (Barlas, 2002), which is not able to cope with unfavourable external conditions. This means that the dynamics are generated internally and not due to external forces. Common dynamic behaviour can be described as constant, growth, decline, growth-then-decline, decline-then-growth and oscillatory (Barlas, 2002). For Barlas (2002), "dynamic problems are characterised by variables that undergo significant changes in time." This dynamic behaviour can be managed, controlled and even reversed. Understanding the cause and mechanism of the dynamics is required to ameliorate them. Models in system dynamics consist of causal relations. A simple cause-effect relationship implies that a change in the cause variable will result in a change in the effect variable. Identifying a feedback look involves identifying the dynamic circular causality. Feedback loops between two variables generally involve other intervening variables. Feedback loops create additional dynamics that make it hard to predict eventual outcomes because of the path dependence. According to Barlas (2002), this happens because "the evolution path unfolds gradually and continuously determines its own path into the future." The dynamic system approach argues that dynamic problems are characterised by undesirable behaviour and not events. The events are usually the result of reaching threshold levels over time and require examination of the causal behaviour (Barlas, 2002). Dynamic processes such as policy feedback are persistent and recurring and must be managed and monitored continuously depending on results. Dynamic feedback problems originate as interactions between system variables.

Multiple feedback loops exist in biological systems. Thomas (1986) studies positive feedback loops and multiple stationarities in complex systems. Negative loops, defined as a circuit with an odd number of negative interactions) in such systems is a necessary but insufficient condition of stable periodicity. Similarly, the presence of a positive loop, defined as a circuit with an even number of negative interactions, is a necessary but not sufficient condition for multistationarity. Adaptive recursive methodology can capture structural dynamics. Another approach would be to use a survival or duration approach, which uses an entropy process to study the duration of an event through time. A survival methodology evaluates a behaviour or event and its impact on agents and their behaviour through time. Dynamic structuralism is a useful framework for studying the interaction of agents and their behaviour.

4.3.2 Positive and Negative Feedback

Negative policy feedback arises when interest groups organise in opposition to policy change inducing stability and incremental change in policies (Schrad, 2010). Negative policy feedback also arises when policymakers only make marginal changes to policies. A third source of negative policy feedback occurs when the shared idea of the problem, usually the supporting policy image, does not change, thereby maintaining policy stability (Schrad, 2010). Another source of negative policy feedback arises when the state does not disrupt the flow of needed financial resources and turns the treasury into an additional veto player. Policy punctuations are marked by a switch from negative feedback processes to positive feedback processes and can compound forces for policy change (Schrad, 2010).

Watanabe (1995) demonstrates how a feedback loop between technological development and economic growth in Japan came about as a result of policy changes. Following the energy crises of the 1970s, Japan was determined to overcome energy constraints by improving the productivity of scarce resources. The Japanese manufacturing industry used innovation to substitute limited energy with unlimited technological innovation. Energy conservation technology, alternative energy and technologies for improving energy productivity were used along with energy conservation investments. The Ministry of International Trade and Industry (MITI) introduced National R&D programs to encourage academia, national laboratories and industries to build new technology paradigms. Investments in R&D lead to technological innovation and changes in GDP, better energy productivity and changes in the social and cultural environment, such as changes in consumer preferences, education, customs and traditions, which in turn led to further investments in R&D.

Chesser et al. (2018) found a positive feedback cycle in the electricity market where the adoption of residential solar PV systems leads to a decreased demand for residential electricity. This, in turn, led to an increase in utilities' fixed cost of transmission and distribution, which in turn required an increase in electricity prices. Increased electricity prices further increased demand for residential solar PV systems, thus creating a positive feedback cycle in the adoption of renewable energy.

Granger feedback theory

Understanding the relationship between time series is one way of establishing causality between variables. At the same time, there is no universally accepted definition of causality (Granger,1980**).** Granger causality, however, can be said to occur when time series y 'causes' another time series x, i.e. when one time series is predictive of another. In this situation, the probability of x depends on its own past history as well as the past history of y, i.e. "x_{t+1} is better to forecast if the information in y_{t-1} is used than if it is not used, where better means a smaller variance of forecast error" (Granger, 1988). However, certain conditions are necessary for causality to occur:

1. The past and present may cause the future. However, the future cannot cause the past. Further, "all causal relationships remain constant in direction throughout time" (Granger, 1980)
2. Causality between two variables can also be explained by the existence of an unobserved third variable. Theory and assumptions can be employed to disentangle the causal structure and would be relevant to the interpretation of empirical results.

The Granger causality test, however, must be used in conjunction with theory as test results may have different interpretations in the absence of prior knowledge about the phenomenon. Inappropriate sampling frequency, co-integration, rational expectations and nonlinear causal relationships are four reasons why test results may be erroneous (Maziarz, 2015).

4.4 Feedback Mechanisms for sustainable energy transition

Economic theory is based on the principle of diminishing returns in a resource-based economy. In this situation, equilibrium is viewed as the best possible outcome. In the presence of increasing returns which is prevalent in technology, network and knowledge industries, the effect of small shifts is magnified, leading to multiple equilibria. Large initial investments in these industries are followed by cheap production processes, which in turn leads to increased knowledge and innovation, which further reduces production costs. The phenomenon of increasing returns is a recent occurrence that has been largely ignored by traditional economists as it does not conform to the math behind traditional economics. However, the realities of our networked economies and the ever-increasing reliance on technology to innovate means that this phenomenon cannot be ignored. Seemingly small events bring about opportunities that lead to self-reinforcing processes that further lead to phenomena such as industrial concentration.

Negative feedback in this dissertation refers to an attempt by the brown industry to regulate the system by reacting to the introduction of RE policy in a way that decreases the effect of those disturbances. Positive feedback from policy to the industry plays an important role in growing the green industry which can lead to a destabilising effect on the brown industry. This positive feedback can be used to transition the energy industry to sustainable energy.

4.4.1 Policy as a Mechanism for Feedback

Moynihan & Soss (2014) stress the impact of administrators and administration in the policy process. Policies include administrative practices such as capacity, structure, routines and cultures (Moynihan & Soss, 2014). Administrators within governing networks implement policy but are also able to affect policy by acting on and transforming political relations. According to Moynihan & Soss (2014), "They can restructure authorities, alter routines, redistribute resources, and reframe culture, identify and motivation." Principal-agent theory suggests that bureaucrats may implement policies in ways that deviate from the policy's original intention. This means that pro-environment administrators have the power to influence or advance policies that are in line with their own ideals. Moynihan & Soss (2014) argue that "Political actors respond to policies after enactments just as they would have before passage: They take action or do not, they reward or publish public officials, and so on because, for reasons that are exogenous to the policy itself, they approve or disapprove of particular governmental actions."

At the same time, administrative organisations are also "sites of politics" (Moynihan & Soss, 2014) that administrators must navigate while serving multiple masters and political goals. Within this landscape, active engagement of stakeholders is necessary to acquire political support.

Reconfiguration of interest groups through policies

Policies reorganise power relations by redefining political conflict or producing new social identities or political interests. Census categories in the US, for example, structure and reinforce racial identities creating racial politics. At the same time, the delineation of a senior group has produced a formidable political group with its own interests and advocacy group, the American Association of Retired Persons (AARP).

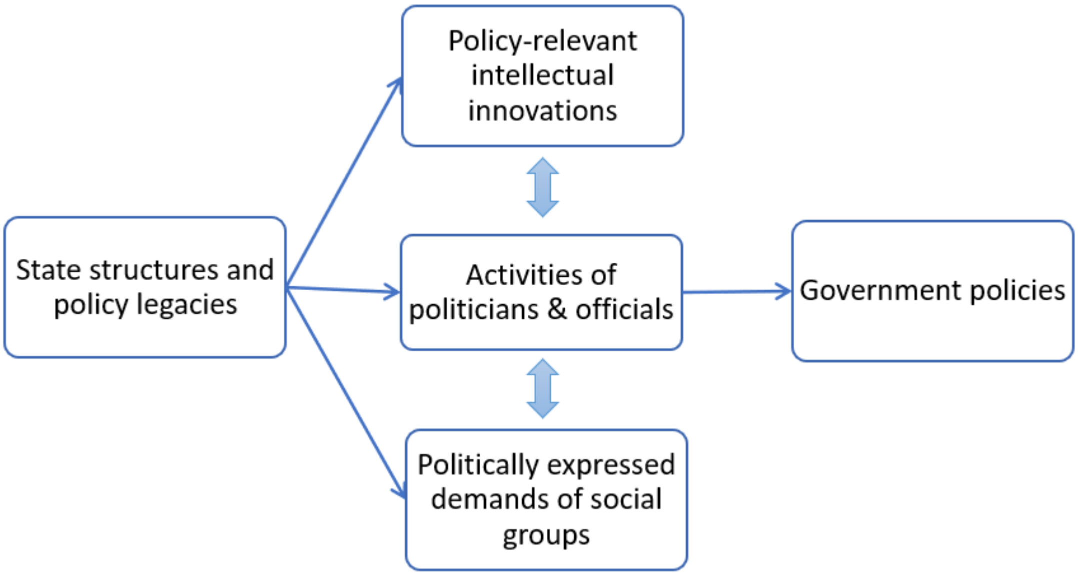
Policies that are distributive, redistributive or regulatory have the power to change political interaction as they affect the positions, capacities and beliefs of actors in interest groups Moynihan & Soss, 2014). Depending on how costs and benefits are distributed, policies can set path-dependent processes in motion that constrain possibilities and development.

The emergence of policy as a result of state structure and interest groups

Divergence outcomes to Keynesian macroeconomic policies implemented in Sweden, the US and the UK following the Great Depression were the result of state structure and policy legacies that influenced groups and affected the policy-making process within these countries. Sweden ended up with social Keynesianism, while the US ended up with commercial Keynesianism, and the UK failed to realise policy similar to the Swedish and American 'New Deal' (Weir & Skocpol, 1985).

Policy variation in countries has been explained using the relative strength of the working-class organisations in political class struggles. A strong working class that comes to power uses governmental authority to implement welfare-oriented policies. These policies come about because the workers are better organised and mobilised to use electoral democracy. A different theory focuses on the coalitional aspect where alliances based on the positions of industries and firms on labour, technology and market issues are identified. However, coalitions may be redefined in the face of new political realities. Further, patterns of state intervention or political initiatives may activate particular coalitions. For Weir & Skocpol (1985), "Institutional structures of state play a critical role in determining the access and weight of various interests and coalitions." States affect policy outcomes either through autonomous official action, which depends on existing judicial, fiscal, judicial and administrative capacities. If these capacities do not exist, new policy initiatives may not be taken, and on the other hand, if they do exist, policies may be initiated even before public demand. Policy making is a process where all actors prepare or react to state efforts for dealing with problems. Thus the potential for feedback exists as a bi-directional causal mechanism between state structure, politicians and interest groups, as illustrated in Figure 14 below.

Figure 14: Causal interrelationships between state structure, politicians and interest groups



Source: Weir & Skocpol 1985

At the same time, although a crisis provides an opportunity to apply innovative solutions to problems, political responses are influenced by earlier responses as a result of notions held by politicians or the time and resources required to create new capacities. Britain's response to the crisis was rooted in struggles over employment benefits as a solution to rising unemployment levels during the crisis, as the prevailing Labour government had limited experience with large-scale centrally managed public works expenditures. State aid for the unemployed was prioritised over providing employment. This response to the crisis made it difficult later on for Britain to introduce deficit-financed public works.

Sweden, on the other hand, focused on a response to the Great Depression that followed the existing administration by the National Unemployment Commission. In the absence of

unemployment insurance, localities were encouraged to require work in exchange for relief. The Unemployment Commission was replaced by a new agency administering public works for the unemployed. Sweden's long history as a bureaucratically centred monarchical regime meant that it had plenty of experience implementing centrally planned public works.
Thus, although both countries were motivated by similar ideas, they enacted policies based on their existing state capacities, which had completely different outcomes.

At the same time, in the US, although American workers voted sooner than European workers, their early engagement in the electoral process meant that their collective interest as a class was not directly represented in national politics. Workers were aligned with a variety of local groups in the absence of a strong National labour organisation. For Weir & Skocpol (1985), "America's distinctive complex of weak national administration, divided and fragmentary public authority, and nonprogrammatic political parties" meant that the American response married popular support with Federal regulation in the national interest resulting in an offer for individuals and groups in all classes.

During this difficult period, the State enacted social welfare policies as a result of power shifts to the labour and social coalitions. The support of industrial workers for America's New Deal and Sweden's new deal is explained by existing institutional structures. Although the UK was the first country to establish a 'new deal' with public social protection for the working class, the outcome was contrastingly different because of existing State structures. The British Labour Party and the Swedish Social Democratic parties were popular with moderately strong labour unions, yet neither could form majority governments throughout the 1920s and the early 1930s.

Co-existence of self-reinforcing and self-undermining processes in policy development

Skogstad (2017) found that the effects of early rationales in policymaking can generate self-reinforcing as well as self-undermining processes affecting policy continuity. The political and institutional context has a significant impact on these processes. Policies that solve multiple problems gain public support and provide momentum to self-reinforcing dynamics. Such policies find support in a broad coalition that rallies behind the legislation. Policies that encourage sunk investments or provide direct incentives and resources are more likely to generate self-reinforcing dynamics. These policies require the "emergence of supportive coalitions and institutions in the post-enactment phase" (Skogstad, 2016). Similarly, social policies delivered timely and whose effects are visible are also self-reinforcing.

However, political features of a democracy, such as the need for consensus-building across multiple decision-making bodies, may result in compromise politics and sub-optimal outcomes. Monitoring and review systems may also lead to self-undermining dynamics. This gives critics incentives to stay mobilised to press for policy reforms.

4.4.2 Information and Technology as feedback mechanisms

Learning and public opinion can be harnessed as feedback mechanisms. Policies are used to shape the preferences, behaviours and beliefs of the masses. Public policies embody the prevailing understanding of new technology. Policy designs can mobilise organised interests, and strategic politicians use policies to create pressure for further action.
Government policies affect public opinion through exposure, signalling and experience. The longer citizens interact with a particular policy or institution, the more comfortable they become with that policy. As the public is not knowledgeable on policy matters, past experiences have a greater impact than the policy itself on public attitudes (Gusmano et al., 2002). As new information about the potential negative effects of new technology comes to light over time, it weakens policy support and gains support from critics.

Similarly, the information flow of technological perceptions within neighbouring countries can be harnessed as a feedback mechanism. For example, the flow of information in migrant networks acts as a feedback mechanism in migration studies. Although the evolution of migration flows has been largely studied as a result of macroeconomic forces, Fonseca et al. (2016) study how positive or negative feedback of immigrant experiences in host countries influences the flow of immigrants to those countries. They found that when initial favourable perceptions are replaced by largely negative realities, the information flows through migrant networks contribute to declining migration flows creating negative feedback. Further, the experiences are influenced by the immigrant's economic standing and occupations. The experiences of Brazilian students who receive Government grants to study in Portugal are vastly different from Brazilian labourers who face negative labour market challenges.

The flow of information in this situation is comparable to information and learning diffusion of renewable technology. Rich countries who have to overhaul a central electricity system are more likely to respond to the challenges and negative experiences associated with renewable energy, while poorer countries who do not have established electricity systems are more like to focus on the positive aspects of renewable energy, particularly the distributed architecture and free resource inputs.

Creating technological momentum

Bottom-up decentralised flexible research pursued by Icelandic farmers along with entrepreneurs led to the development of the Icelandic geothermal industry. A similar bottom-up approach led to the development of the Danish wind turbine industry. Technical aspects of research must be combined with policy and regulation, ownership and profitability, information sharing and participation for successful market acceptance (Sovacool & Sawin, 2010). New technology must overcome technical, social, political and economic barriers to be successful. The American approach to developing wind energy focussed on designing large-scale turbines that would eventually be built by companies in heavy industries. There was little collaboration with other designers, producers and suppliers, as well as a weak link between the government and industry. The development and ownership of turbines in the US were concentrated among a few large firms. At the same time, US policies which were inconsistent and poorly designed, incentivised investment, not performance leading to investment in wind farms for tax credit instead of to produce electricity. In Denmark, wind turbine design was based on agricultural equipment and prioritised reliability. Collaborative networks resulted in frequent product modifications and improvements. Farmers, landowners and co-operatives owned the turbine and were vested in their development and usage. Regulators intertwined financial incentives with reports on wind power performance from operators. Decentralised ownership grew out of a long tradition of cooperatives and a vision of self-sufficiency. For Sovacool, "the Danish bottom-up strategy based on the dynamic principles of learning by doing, the accumulation of knowledge from multiple actors and the adoption of consistent policies" led to the creation of a strong domestic industry. For Sovacool (ref), a government's approach to technology development, especially creating momentum, is just as important as funding. Momentum can be created through transparency, information sharing, learning from mistakes, consistency and research (Sovacool & Sawin, 2010).

Positive feedback during the growth phase

As our economies are based on fossil fuels, the fossil fuel industry benefits from numerous positive feedback mechanisms such as fuel subsidies, complementarities, etc., making it difficult for the RE industry to gain a foothold. Policies should therefore be focused on creating and reinforcing positive feedback for the RE industry. As these industries develop and create new standards and paradigms, the fossil fuel industry will be pushed out.

Kleiman (1993) found that positive feedback during the growth phase acts as a mechanism for further growth. He illustrated this in the area of illicit activity and enforcement, where rapid response and targeted enforcement to growing drug markets is essential to controlling growth. He found that trends in rule-breaking can act as re-enforcing processes when the threat of punishment lags because the capacity to punish is saturated. This diminished deterrence generates more criminal activity, further burdening the punishment system and creating a feedback effect. Even though public demand for greater enforcement may be high, the system faces constraints due to court time and prison space. For Kleiman (1993), this positive feedback process remains as "the growth in enforcement costs due to greater enforcement productivity and increased enforcement resources is slower than the growth in physical drug volume", thereby creating a paradox where drug crime will continue to grow even as enforcement is increased making it seem as though enforcement is ineffective.

A similar response is required to increase efforts by the FF lobby. If positive feedback mechanisms are present during the growth phase of the RE industry, RE will be able to overcome the FF lobby. However, unequal lobby effects/size will have a detrimental effect on the growth of the RE industry and therefore, policies promoting RE must be coupled with policies limiting or decreasing the size of the fossil fuel industry.

For Moynihan & Soss (2014), the recursive relationship between policy and politics is complex, with endogenous explanatory variables that make it difficult to predict outcomes. They suggest using methodological tools "to build evidence that causal relations run in a particular direction, in a particular way, at a particular time." Longitudinal data can be used to construct ex-post and ex-ante policy observations to establish a policy's political effects.

Policy design must take into account feedback channels such as markets and distribution networks. Armsworth, Daily, Kareiva, & Sanchirico (2006) use a simple demand and supply model to show how biodiversity conservation planning policies face feedback effects through the land market. Purchasing land for conservation increases land prices making future investments difficult. Further, as areas surrounding reserves are attractive, this increases their development potential and further impacts conservation efforts.

Tesla Motors, on the other hand, shared their patents hoping to develop the market for electric cars and develop infrastructure. However, incumbent networks of independent car dealers employed by traditional car manufacturers prevent direct car sales as employed by Tesla and are thus preventing path-dependent feedback that could affect profits.

4.5 Summary

This chapter discusses the importance of history in feedback processes that lead to path dependence. The concepts of choice, intention and decision form the basis of policy analysis, as the policy is the result of government action to achieve a particular result. Preference, intention, action and consequences have different "temporal identifiers" that must be linked together. Otherwise, reducing policy to a choice implies the simplification of complex reality to a single variable. The success of a particular technology in the initial stages is governed by randomness. However, once a technology achieves path dependence and lock-in, it is very difficult to bring about technological change. The specific characteristics of fossil fuels have influenced the market paradigm for electricity. Apart from a couple of outlier countries like Denmark and Iceland, the early success of fossil fuel and the subsequently installed user base has made it difficult for renewable electricity to meaningfully penetrate the market. Policies should be aimed at inducing and reinforcing positive feedback and generating network effects for renewable energy. Further future expectations must be raised for the establishment of renewable electricity in the future economy. Public R&D support is required to generate knowledge transitions.

5.0 Empirical analysis

This chapter begins with a theoretical outline that explains the divergence of the sustainable energy transition due to policy feedback. The formal analysis is taken from Aklin & Urpelainen's model of government choice, which provides the basis of the empirical model and the selection of variables. We expand on the model by including the feedback aspect and investing the phenomena over a longer time period.

5.1 Formal analysis

Aklin & Urpelainen (2013) examine how exogenous shocks, such as changes in energy prices, lead to path dependence in sustainable energy transitions because of political competition. They find that governments can use positive reinforcement mechanisms to lock in policy commitments. The underlying assumption is that if a new energy technology becomes dominant, positive reinforcement may amplify diffusion, just as our societies have become locked-in to fossil fuel technology. Policy may make overcoming systemic obstacles possible, so 'green' governments promote renewable energy to achieve lock-in and strengthen their green political base. However, these actions may be overturned by future 'brown' governments that have a large support base in brown industries. Such 'brown governments' may withdraw support for leading sustainable energy transitions to diverge between countries. Aklin & Urpelainen (2013) find that transition success then depends on "the sequence of governments hostile to environmental regulation" who may choose "choose artificially low levels of public support to avoid the emergence of a renewables advocacy coalition."

This dissertation uses Aklin & Urpelainen's (2013) formal model of policy feedback to study sustainable energy transition. In the model, two governments formulate energy policies. One government is pro-sustainable energy (green), while the other is vested in the fossil fuel industry (brown). Each government strategically selects an energy policy that increases the strength of the respective industry interest group. The feedback mechanism works as follows:

1. Each period $t = [0, \infty)$ is indicated by subscripts
2. In each period t, the government chooses a green level of energy policy $Q_t \in [0, \infty)$ at time t: Q_t. The degree of support determines the size of the green coalition.

3. Policy increases the size of the green coalition G in the following period: t+1

4. The political-economic environment at time t is shaped by an exogenous state of the world Y_t. Yt measures external shocks that affect energy policy, such as policy changes and oil prices. As Y_t increases by 1, the government marginal benefit from increasing sustainable energy also increases by one, i.e. an increase in Y_t results in an increase in Q_t. If $Y_t > 0$, the time period is favourable for clean energy. If $Y_t < 0$, the time period is unfavourable for clean energy.

5. G denotes the size of the green interest group, and B is the size of the brown interest group where G, B >0. If G>B, the green interest group is stronger. As G increases, the government's incentive to increase Q increases. As B increases, the government's incentive to decrease Q increases.

6. To ensure both governments benefit marginally from clean energy, G or B-Y>0

7. When elections are held, the probability of a green government being in power has a probability of p ϵ (0, 1). The probability depends on the size of the green interest group.

8. The parameter δ measures the feedback effect of energy policy. When δ is positive, the green interest group grows and vice versa

9. Each government is forward-looking and tries to maximise its payoff in every period. The payoff to the government of type T ϵ {L, R} in Yt

a. $(T + \delta Q_t)\ Q_{t+1} – ½\ Q^2_t$

The payoff to the government in period Yt

b. $(T+Y)Q_{t+1} + TQ_t – ½\ Q^2_t – ½\ Q^2_{t+1}$

10. Equilibrium in the time period t+1: A government of type T maximises equation 9a such that:

$T + \delta Q_t – Q_{t+1} = 0$

so $Q^*_{t+1} = T + \delta Q_t$

Thus, the green energy policy level depends on the strength of the green interest group. If Q_t increases, the strength of the green coalition increases. The magnitude depends on the feedback parameter δ

11. Using equation 9 to work back to the strategic choice of green level of energy policy in period t, inserting Q^*_t in equation 9b, we get

$$(T+Y)Q_{t+1} + T(\delta Q_t + (1\text{-}p)G+pB) \text{ - } ½\ Q^2_t – ((1\text{-}p)/2)(G+ \delta Q_t)2 \text{ -}((p/2)(B+ \delta Q)2)$$

12. The green level of policy Qt is selected such that:

$$Q^*_t = ((A+p\delta(A\text{-}B)+Y))/(1+ \delta 2)$$

5.2 Variables

The political strength of an industry group is assumed to be a function of the sector's size. Large sectors, therefore, are assumed to have large interest groups with a considerable monetary contribution, expertise and the ability to mobilise large groups of voters.

Definitions of alternative energy

The terms Renewable energy, Sustainable energy, Clean energy and low-carbon energy are used extensively in the literature and require clarification. Renewable energy refers to the energy produced by natural resources that are naturally replenished (*Renewable Energy*, n.d.) The International Energy Agency (IEA) classifies solar, wind, geothermal, hydro and biomass as examples of renewable energy. At the same time, the European Union includes wind, solar, hydro and tidal power, geothermal energy, biofuels and the renewable part of waste as renewable energy in its statistical accounting (Harjanne & Korhonen, 2019) However, not all renewable energy is sustainable ex. biofuel, which sometimes takes away land from food crops.

Clean energy refers to energy that creates little or no greenhouse gases (National Grid, n.d.). Green energy refers to energy from natural sources. The terms 'Green energy' and 'renewable energy' are often used interchangeably. Still, it must be noted that while green energy sources are renewable, not all renewable energy sources are considered green. Hydropower which is sometimes generated as a result of deforestation and industrialisation, is not considered green (National Grid, n.d.).

Sustainable energy can be replenished within a human lifetime and does not cause long-term environmental damage. This is the energy source we will be considering. It includes all renewable energy sources, such as hydroelectricity, biomass, geothermal, wind, wave, tidal and solar energies.

Table 7 below classifies the different energy sources according to the above-mentioned definitions.

Table 7: Classification of Energy Sources

	Renewable	Sustainable	Clean	Green
Wind	x	x	x	x
Solar	x	x	x	x
Hydro	x	X	x	x
Tidal	x	x	x	x
Geothermal	x	x	x	x
Biomass	x	x		x
Biofuel	x			x
Wave	x	x	x	x
Nuclear		x	x	

Dependent variable: Green industry lobby

This dissertation's primary variable of interest is the strength of the green industry. Ideally, this variable would include all lobby groups interested in promoting renewable energy. In addition to the renewable industry lobby group, they may include environmental groups, firms involved in RE R&D, labour groups associated with renewable energy or green industry service providers, etc. Admittedly, data for this variable is difficult to obtain on a universal scale, and previous studies have used different proxies in the absence of data on the sizes of green lobby groups. Cheon and Urpelainen (2013) use the percentage of renewable energy in electricity as a proxy for the strength of the renewable energy industry.

Using the assumption that the strength of an environmental pressure group depends on their financial resources and membership base, Binder & Neumayer (2005) use environmental non-governmental organisations (ENGOs) as a proxy for the strength of the environmental pressure group. The number of ENGOs per capita is used as a proxy for the environmental pressure group's financial strength and membership support. Similarly, Fredriksson et al. (2007) uses the number of national environmental NGOs that are members of the World Conservation Union/International Union for the Conservation of Nature to show the strength of the environmental lobby in influencing environmental treaty ratification.

Vachon & Menz (2006) link the strength of the environmental lobby with a country's level of education and participation rate in environmental groups. Their study uses memberships per 1000 of the population in the Sierra Club, National Wildlife Federation, and Greenpeace in the US to explain the variation in green electricity policy adoption between US states. Cao

(2012) uses a negative function of the industrial sector’s contribution to GDP as a proxy for the relative strength of the green industry. Nicolli & Vona (2015) use the share of green deputies in parliament as a proxy for the green lobby as it “captures both people’s preferences for environmental quality and a political voice for environmental issues.”

This dissertation uses the following two proxies as measures of green industry are limited:

- Share of renewable energy in electricity measured as a percentage of overall electricity
- Share of green deputies in parliament measured as a percentage

Brown lobby

The Brown Group or the brown lobby group represents the brown industry which is defined in this dissertation as energy-intensive industries and industries involved in fossil fuel extraction. Fredriksson et al. (2007) use three proxies to capture the strength of the industry lobby group:

- the share of the labour force employed in energy-intensive industry
- a dummy variable for whether a country has a national committee group or group of the International Chamber of Commerce, as many green organisations view the ICC as opposed to climate change regulation.
- Share of fuel exports as a percentage of exports

Cadoret & Padovano’s (2016) study on the negative impact of industrial lobbying on RE deployment uses the value added of the manufactory sector as a proxy for the lobbying strength of the industrial sector. Cao (2012) uses energy production per unit of real GDP as a proxy for the relative strength of the brown sector. Other researchers use corruption as a proxy for the brown lobby’s ability to influence environmental policy (Nicolli & Vona, 2019)

To capture the political pressure of the brown industry, we use two alternative proxies:

- Size of energy-intensive industries such as basic metal, paper and paper products (Cao, 2012).
- Share of the labour force employed in the industrial sector (Fredriksson et al., 2007)

Policies

Policies are classified into four categories: Economic, Regulatory, R&D, Education and Support. Economic policies include financial incentives such as feed-in tariffs and quotas. Regulatory policies include standards and codes. As policies share the goal of increasing renewable energy contribution, this paper considers all types of policies instead of disaggregating by type. Where policies came under two or more classifications, each classification was coded with 1. For example, the Czech Republic's 2005 policy, "Promotion of Power Generated by Renewable Sources" was classified under Regulation and Economic. Therefore, both categories were coded with a dummy variable, i.e. both categories were coded with a 1. This was done to include the significance of the classification in principle components analysis.

Policies not classified by the IRENA database were classified according to their description. For example, the 2008 Australian policy titled "Australian Trade Commission (AUSTRADE) - Clean Energy Export Strategy" was classified as policy support. Other policies with missing classification, for example, the "Invest Chile Project", which came into force in 2005, were classified under "Economic" only in the 2019 download. However, the description further mentioned that it was R&D funding. Therefore this policy was classified under "Economic" and "R&D".

Policies superseded by another were considered in force until the year of the new policy ex. The Australian "National Greenhouse Response Strategy", which came into force in 1992, was considered in force until 1997 as in 1998, it was superseded by the National Greenhouse Strategy.

Where policy end dates were not specified, for example, the Czech Republic's 1994 policy titled "Renewable and Secondary Power Purchase Obligation" and supporting policy documents were missing or unavailable; the policy was considered in force for 1994 only.

Ideally, the policy variable should be continuous to allow for stringency (Johnstone et al., 2010). However, the variance in policy dimensionality across countries makes this difficult. Therefore, we have employed a simple dummy variable to ease comparability.

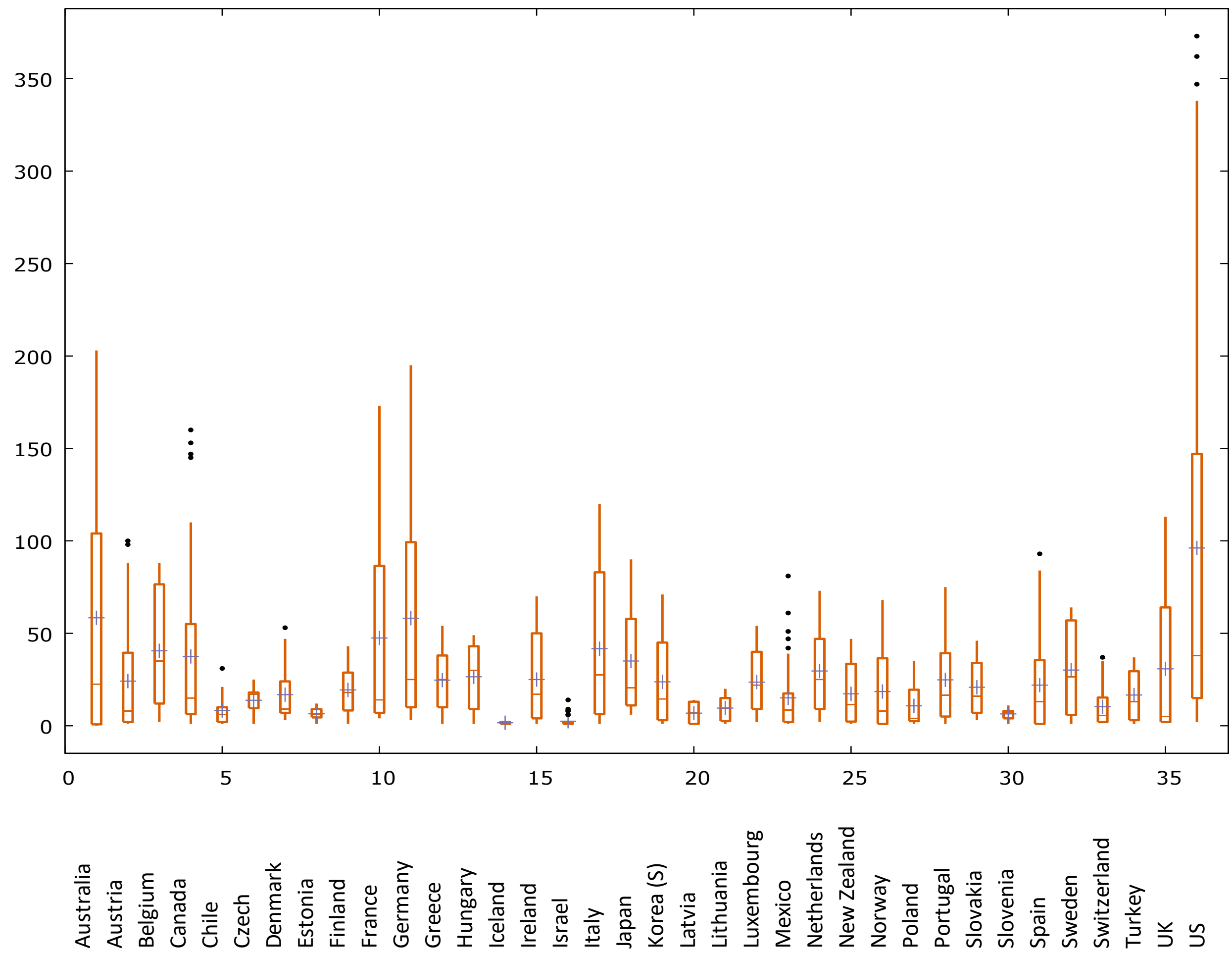
Following Zhao, Tang, & Wang (2013), we use dummy variables to record the implementation of different policy instruments as instrument type impacts RE investment (Polzin et al., 2015)(Yuan et al., 2014). The dummy variable takes on a value of 0 before implementation and one after. These dummy variables are then used to construct three aggregate measures of RE policy.

- **RE_Dum:** As per Kilinc-Ata (2016) and Zhao, Tang & Wang (2013), this variable is coded as one if any of the policy instruments was introduced during a particular year and 0 otherwise. This method ignores policy heterogeneity, ignoring whether countries adopt more than one policy in a particular year.
- **RE_Avg:** This variable is the average of all policy dummies. The total number of policies introduced in a year in a country was divided into four categories.
- **RE_PCA**: This variable uses the number of policies introduced in each of the four categories in a year and reduces them to a dataset with one dimension. The first component is the linear combination of the original variables that exhibits the greatest variance (Nicolli & Vona, 2015). Following (Zhao et al., 2013), only the first component is used as it accounts for 71% of the variance of its underlying variables.

Iceland was dropped from this regression as only one policy was introduced.

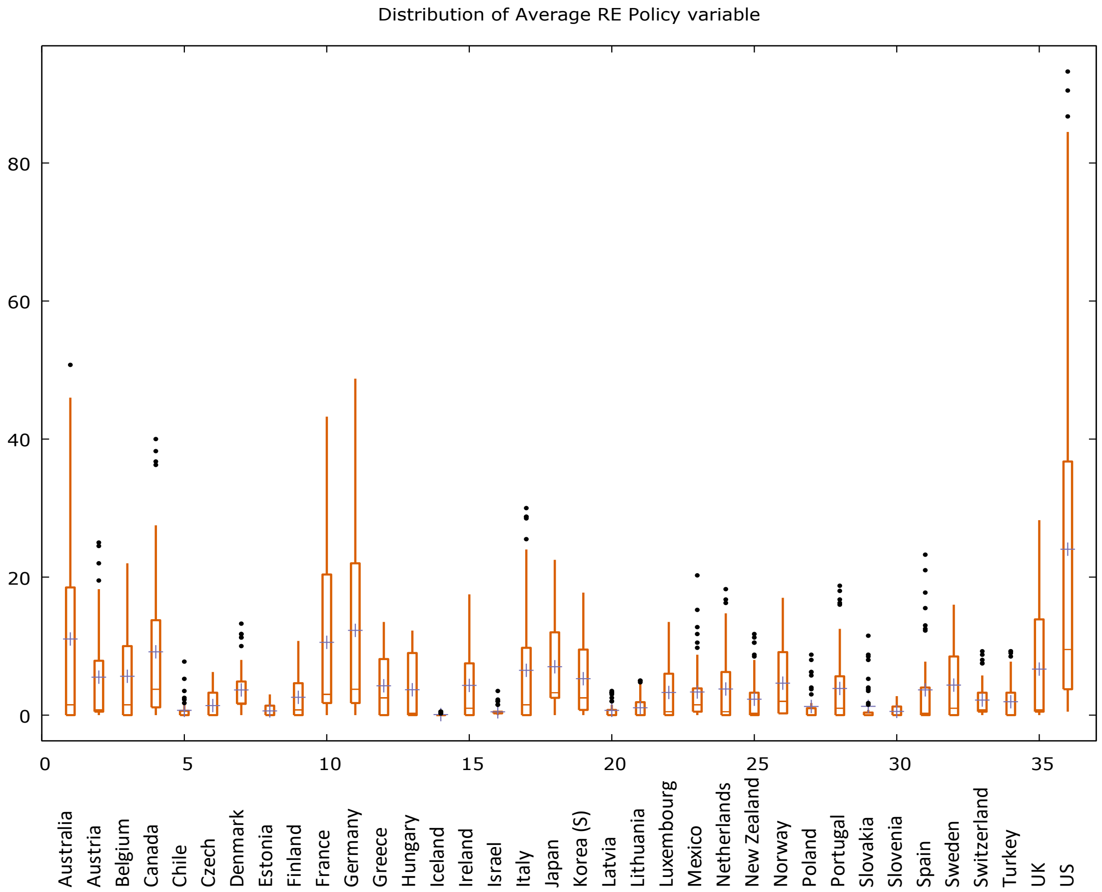
Figures 15 & 16 below show the total and average number of RE policies (respectively) implemented in each country. Countries such as Iceland, Chile and Estonia have implemented the least number of policies, while America, Germany and France have implemented the most. Figure 17 shows the frequency distribution of the percentage of sustainable energy used by the country.

Figure 15: Total number of RE policies implemented by the country



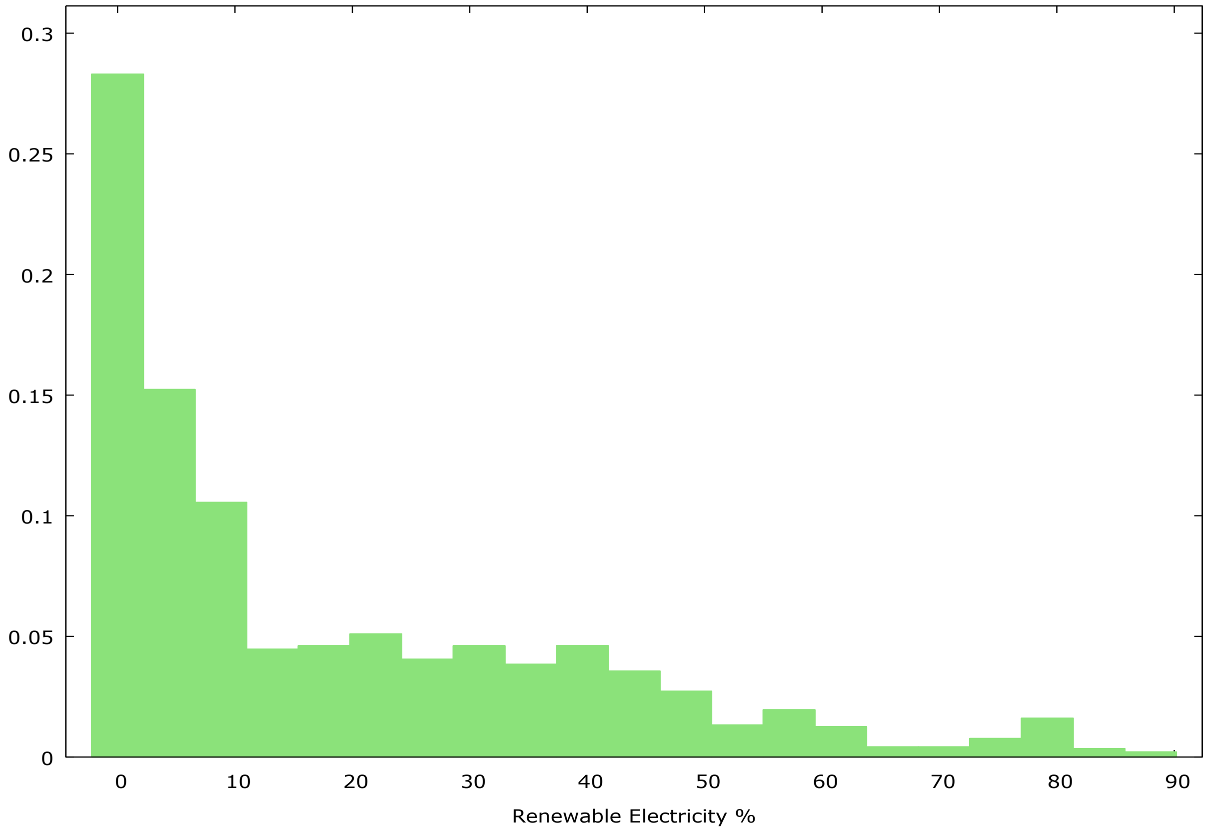
Data source: IEA policy database

Figure 16 Average number of policies implemented by the country



Data source: IEA policy database

Figure 17: Frequency distribution of the RE variable



Data source: OECD

Control variables

The following control variables are included:

GDP: The income effect on renewables is well documented. Richer countries are more able to support the development of expensive renewable energy. This variable is measured in per capita terms in 2018 USD.

Trade: Trade openness is documented as influencing renewable energy use. This variable is measured as trade as a percentage of GDP.

Oil price: Higher oil prices have a positive effect on renewable energy growth. This variable is expressed in 2018 USD.

Electricity consumption: Higher levels of electricity consumption are associated with lower usage of more expensive renewable energy. This variable is measured in kWh per capita.

Population growth: Countries with fast-growing populations generally have higher energy requirements. This variable is measured as a percentage.

Oil price: Higher oil prices are associated with greater interest in RE. This variable is measured as the price of crude oil per barrel in 2018 USD. Figure 18 shows the price chart for this variable.

Figure 18: Oil price 1970-2014

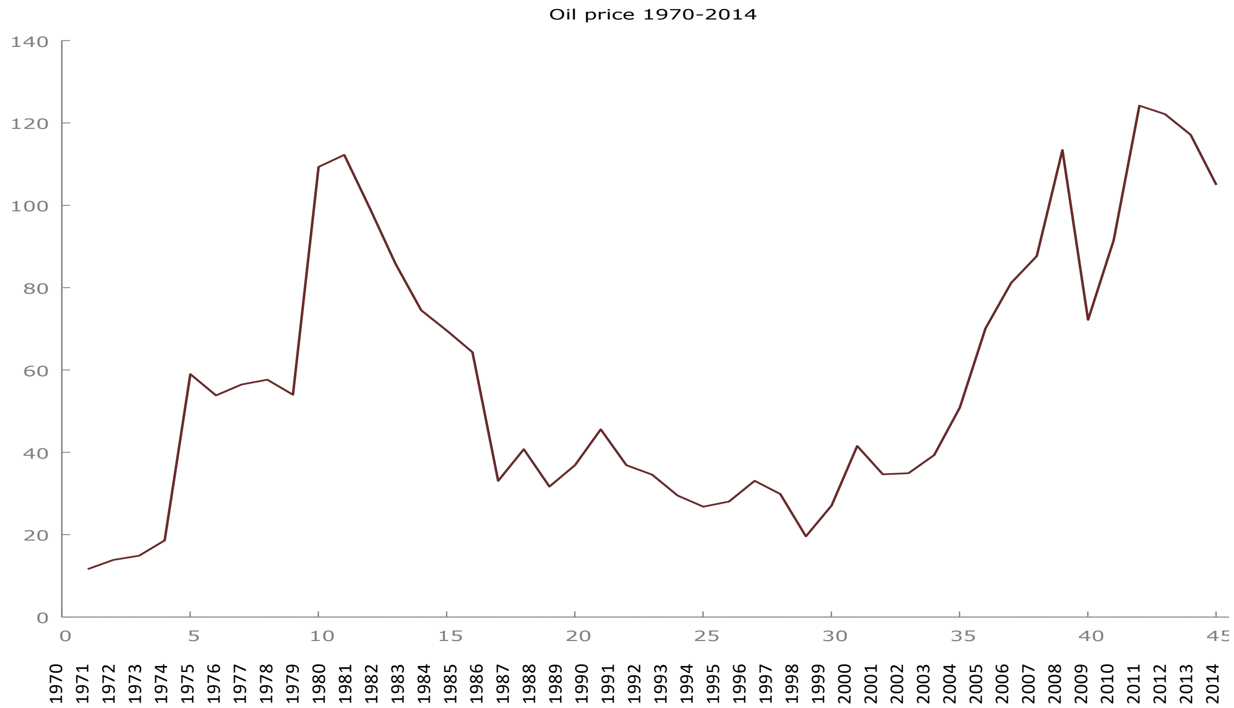


Table 8 below shows the definition of variables and sources.

Table 8: Definition of variables and their sources

Variable	Definition	Predicted sign	Source
1. Green	Green industry interest group proxied by:	+ for H1 + for H2	
	a. share of renewable energy in electricity and measured as a percentage of overall electricity		OECD
	b. Share of green deputies in parliament measured as a percentage		Comparative Political Data Set (Armingeon et al., 2019)
2. Brown	Brown industry interest group proxied by:	- for H2	
	a. the contribution of energy-intensive industries to GDP and measured as a percentage		OECD STAN database
	b. Share of the labour force in the industrial sector and measured as a percentage of the overall labour force		OECD
3. REpol	Energy related climate policy – composite variable ((Zhao et al., 2013)	+ for H1 + for H2	IEA Policy and Measures Database
REdum	The dummy variable takes a value of 1 if the country adopts any of the policy instruments.		
REavg	Average of the policy dummies recorded in the four categories in each year and normalised to like within the range of 0 and 1		
REpca	The variable is constructed using principle components to reduce dimensionality. Only the first component is used.		
4. I	Country. OECD and EU countries.		

5. T	Time period. 1970-2014	
6. X	Matrix of control variables	
	- GDP measured per capita in 2018 USD	Worldbank,
	- trade, measured as a percentage of GDP,	Worldbank
	- oil price measured as the price of crude oil per barrel in 2018 USD,	BP Statistical Review of World Energy
	- electricity consumption measured as kWh per capita	Worldbank
	- population growth measured as an annual percentage	Worldbank
7. υ	Country fixed effects	
8. ε	Error term	

The modelling framework allows for the inclusion of explanatory variables that may affect the dependent variables. The reasoning for this inclusion is summarised in Table 9 below.

Table 9: Arguments for the inclusion of control variables

Variable	Positive/negative	Argument
GDP	Positive	Richer countries have a higher percentage of RE due to more money available for investment.
Trade	Positive	Cross-border trade enables the exchange of ideas and knowledge, facilitating the diffusion of RE technology.
Oil price	Negative	Substitute for RE
Electricity consumption	Positive	Increasing electricity consumption is associated with increased use of all energy sources, including RE.

5.3 Data sources

The IEA/IRENA Global Renewable Energy Policies and Measures Database provides information on renewable energy policy information for all IEA and IRENA member countries. Policy data was first downloaded and copied into spreadsheet software. Policy data was downloaded in July and October 2019 and once again in October 2021. Each download revealed updates to policy information.

Policy classification

In the 2019 database, policies were classified into six categories: Economic, Regulatory, Policy support, R&D, Voluntary and Education. In the 2021 database, policies were classified into ten categories Payment, finance & taxation, Payment & transfer, Regulation, Codes & Standards, Targets, plans & framework legislation, Information & education, Framework legislation, Public Information, and Grants & Performance based policies. R&D policies in the 2021 database were classified under the title “Topic”. The policies were categorised into four classifications for this dissertation: Economic, Regulation, R&D, Information & Support.

Table 10 below shows how the 2019 and 2021 changes in policy classification were reclassified for this dissertation.

Table 10: Policy classifications

IEA policy database classification	Dissertation Classification
Payment, finance & taxation (2021)	Economic
Payment & transfers (2021)	
Grants (2021)	
Economic (2019)	
Regulation (2021)	Regulation
Regulatory (2019)	
Codes & Standards (2021)	
R&D (2019)	R&D
R&D mentioned in Policy Topic	
Targets, plans & framework legislation (2021)	Education & support
Framework legislation (2021)	
Education (2019)	
Information & education (2021)	
Policy support (2019)	
Voluntary (2019)	
Public information (2021)	
Performance-based policies (2021)	

Missing policies

In a few instances, policies mentioned in the 2019 database were not present in the 2021 database. However, many of these policies were mentioned on a third website, www.climatepolicydatabase.org. Therefore, the missing policies were included in the study. Policies that were clearly mentioned twice, such as the Italian policy titled "RES promotion - Decree Implementing Directive 2001/77/EC" implemented in 2004, were only included once in the study.

Missing categories

Many early policies that were included in the 2021 update were not classified on the IEA website. These policies were then classified for this dissertation based on the policy description. If the words R&D were mentioned, it was classified under R&D. Any mention of information campaigns or the establishment of Institutions meant that the policy was classified under "Support". The 2004 Italian policy titled "Methane to Markets Partnership" was classified under Support, while the 1982 Italian policy titled "Law 308/82", which was passed to establish regulations for the energy sector, was classified under "Regulation".

Other policies, such as Italy's National Energy Plan (PEN) implemented in 1988, which was neither enforced nor financed as originally planned, were included as it was acknowledged to have an impact on climate/energy policy objectives.

The present study uses an unbalanced panel of 36 OECD countries which includes 23 EU countries. 5 EU countries viz. Bulgaria, Croatia, Cyprus, Malta and Romania have been excluded due to insufficient data. The time period examined is 1970-2014. The dataset covers a period of 45 years and includes 9105 observations. Summary statistics of the variables used are presented in Table 11 below.

Table 11: Summary statistics

Variable		Mean	Median	Minimum	Maximum
Green Industry	Green Deputies	1.8001	0.00000	0.00000	22.200
	Green_RE	18.241	8.6902	0.00000	87.986
Brown industry	Brown_Ind	0.21177	0.19324	0.019099	1.2580
	Brown employment	26.751	25.770	10.983	50.072
Policy variables	REPol_Tot	28.345	13.000	0.00000	373.00
	REPol_Avg	4.5404	0.75000	0.00000	93.250
	REPca	-4.7581e-016	-9.1520	-17.670	187.80
Control variables	Trade	73.395	62.764	9.0997	392.80
	Population	0.66539	0.56574	-2.5743	6.0170
	ECons	6964.6	5494.0	222.39	54799.
	Oil	57.647	50.866	11.634	124.20
	GDP	19504.	13742.	273.54	1.1645e+005

Unbalanced panels are common in multi-country settings such as this dissertation. To test whether the effect of RE policies varies over time, the sample will be split into two periods, 1970-1990 and 1991-2014. The first period represents the period before and after the 1970s oil crisis, while the second period reflects trends in global action on climate change, including the adoption of the United Nations Framework on Climate Change Convention in Rio in 1992, the Kyoto Protocol in 1997 and the commencement of trading in the EU-ETS in 2005.

5.4 Methodology

The effect of policy

Panel models are useful when time-invariant regional characteristics (fixed effects), such as geographical factors (country/state level), may be correlated with the explanatory variables. Following (Kilinc-Ata, 2016), a fixed-effects panel regression is used to estimate the following equation for **H1: *Renewable energy policy has a positive effect on the green industry.***

$$Green_{i,t} = \alpha + \delta\ REpol_{it-1} + \gamma\ X_{i,t} + \upsilon_t + \varepsilon_{i,t} \quad (1)$$

where $Green_{i,t}$ measures the size of the green industry in country *i* at year *t*, $REpol_{it-1}$ measures RE policy instruments in country *i* at year *t*, $X_{i,t}$ denotes a matrix of control variables in country *i* at year *t*, υ_t captures country fixed effects at time t while $\varepsilon_{i,t}$ is the random error term that applies to country *i* at year *t*. Control variables to be included are GDP, trade, oil prices, electricity consumption and population growth. REpol is lagged one year to capture the delay of the policy effect.

The effect of lobbying

Interest group behaviour has been modelled using influence and vote function models, non-cooperative game theory and common agency models. Cooperative game models focus on coalitions and outcomes. Influence and vote function models examine the behaviour of policymakers and voters. Common agency models of contribution explain why influence occurs and is the model we have selected for this dissertation. In these models, the electorate is organised into interest groups or lobbies that offer contributions to policymakers contingent on policy outcomes. Policymakers are assumed to care about election outcomes and choose those policies that ensure re-election (van Winden, 2008, pp 118-129). Our second hypothesis states:

H2: Lobbying by the green and brown industries impacts RE policy.
H2a: The green industry has a positive effect on RE policy

H2b: The brown industry has a negative effect on RE policy

A fixed-effect panel specification will also be used to estimate the impact of lobbying on RE policies, **H2a & H2b.** Specifically, the following equation will be estimated:

$$REpol_{i,t} = \alpha + \beta\ Green_{it-1} + \eta\ Brown_{i,t-1} + \gamma\ X_{i,t} + \upsilon_t + \varepsilon_{i,t} \quad (2)$$

where $REpol_{it}$ measures RE policy instruments in country *i* at year ***t*,** $Green_{it-1}$ measures the size of the green industry in country *i* at year *t-1*, $Brown_{i,t-1}$ measures the size of the brown industry in country *i* at year *t-1*, $X_{i,t}$ denotes a matrix of control variables in country *i* at year *t*, υ_t captures country fixed effects at time t while $\varepsilon_{i,t}$ is the random error term that applies to country *i* at year *t*. Control variables to be included are GDP, trade, oil prices, electricity consumption and population growth. The Green and Brown variables are lagged one year to capture the delay of the lobbying effect.

Industry-policy causality

Studies on the causal relationship between policy and other variables are largely focused on monetary or other economic policies. Although the Granger test determines the ability of one variable to predict another, this relationship might be due to a third variable. Therefore, causality studies must be supplemented by other methods to understand the causal mechanism better. Panel Granger causality tests have been used to study causal relationships between foreign direct investment and economic growth (Kar et al., 2011). The energy growth nexus that investigates causal relationships between energy consumption and economic growth (Pearson, 2021) (Žiković et al., 2020) also has a large body of empirical literature. However, causality studies between renewable energy or climate policy and industry are scant.

Vector autoregressive (VAR) models were used frequently to test Granger causality relationships in time series data between two stationary variables. However, co-integrated variables are better studied using Vector Error Correction Model (VECM) once the order of integration has been determined. The autoregressive distributed lag model can be used on cointegrated variables with different orders of integration.

The models mentioned are best suited for time series data. Panel data requires different techniques, such as Panel Vector Autoregression (PVAR). However, these models are only suitable for homogeneous panels. Hurlin & Dumitrescu (HD) (Dumitrescu & Hurlin, 2012) have developed a panel non-causality test based on the Granger (Granger, 1969) test for heterogeneous panel data models. As the data used in this paper consist of heterogeneous panel data, the HD test will be used to specify the causal direction of the transmission mechanism between policy and industry.

The starting point for the DH test consists of the following heterogeneous autoregressive model:

$$y_{i,t} = \theta_i + \sum_{k=1}^{K} \gamma_i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \delta_i^{(k)} x_{i,t-k} + \epsilon_{i,t}$$

where x and y are two stationary variables observed on T periods for N countries. The individual effects are assumed to be fixed, and the lag-order K is identical for all cross-sections. $\gamma_i^{(k)}$ denotes the autoregressive parameters, and $\delta_i^{(k)}$ are the regression coefficients' slopes; both parameters differ across countries. By definition, x causes y if and only if the past values of the variable y observed on the i^{th} country help predict variable y for this i country only. The test is based on the null hypothesis of homogeneous non-causality; there is no causal relationship for any of the countries of the panel.

$$(\delta_i = \left(\delta_i^{(1)}, \ldots, \delta_i^{(K)}\right)' = 0,\ \forall i = 1, \ldots, N).$$

Under the alternative hypothesis, there exists a causal relationship from x to y for at least one country of the sample. The test statistic is based on the individual Wald statistics of Granger non-causality averaged across the cross-section units (Dumitrescu & Hurlin, 2012). Our third hypothesis states:

H3: Bi-directional causality between industry and policy creates a feedback effect
H3a: RE policy has a significant and positive impact on the Green Industry
H3b: The green industry has a significant and positive impact on RE Policy (positive feedback)

H3c: The brown industry has a significant and negative impact on RE Policy (negative feedback).

5.5 Results

The results of the three equations are summarised below and discussed in the following section. The results of the Hausman test on the baseline model indicate that while the Fixed Effects model is appropriate for most of the data, some sections would be better suited for a Random Effects model. Despite these results and the loss of efficiency, the fixed effects model was selected based on the rational that the variables being studied are largely time invariant. Further, the fixed effects model enables direct inference from estimated effects with fewer asymptotic results. Tables 12, 13 and 14 below present the results of the Hausman test on the baseline model.

Table 12: Hausman test results (baseline model)

Dependent variable	Independent variable	Asymptotic test statistic	P.value	Conclusion
Grn_RE	RPAvgL1	11.533	0.0732	FE
	RPTotL1	10.133	0.1192	RE
	REpca	6.9738	0.323277	RE
Grn_Dep	RPAvgL1	11.0541	0.0867179	FE
	RPTotL1	29.758	0.0000	FE
	REpca	5.88202	0.436535	RE
REP_Tot	BrnEmpL1/GrnREL1	20.8675	0.00397129	FE
	BrnEmpL1/GrnDepL1	16.6081	0.0201059	FE
	BrnIndL1/GrnREL1	49.1567	0.0000	FE
	BrnIndL1/GrnDepL1	34.8678	0.0000	FE
REP_Avg	BrnEmpL1/GrnREL1	11.4776	0.119099	RE
	BrnEmpL1/GrnDepL1	8.2096	0.314475	RE
	BrnIndL1/GrnREL1	12.1109	0.0969705	RE
	BrnIndL1/GrnDepL1	17.3959	0.015014	FE
REpca	BrnEmpL1/GrnREL1	25.6883	0.0005	FE
	BrnEmpL1/GrnDepL1	21.575	0.00279734	FE
	BrnIndL1/GrnREL1	66.4685	0.0000	FE
	BrnIndL1/GrnDepL1	93.6335	0.0000	FE

Table 13: Hausman test results – 1991-2014

Dependent variable	Independent variable	Asymptotic test statistic	P.value	Conclusion
Grn_RE	RPAvgL1	7.9502	0.2418	RE
	RPTotL1	9.8744	0.1300	RE
	REPCA	10.3702	0.1100	RE
Grn_Dep	RPAvgL1	4.8788	0.5595	RE
	RPTotL1	3.6149	0.7286	RE
	REPCA	1.8022	0.9370	RE
REP_Tot	BrnEmpL1/GrnREL1	20.8675	0.0040	FE
	BrnEmpL1/GrnDepL1	16.6081	0.0201	FE
	BrnIndL1/GrnREL1	15.1629	0.0340	FE
	BrnIndL1/GrnDepL1	17.9845	0.0120	FE
REP_Avg	BrnEmpL1/GrnREL1	11.4776	0.1191	RE
	BrnEmpL1/GrnDepL1	8.2096	0.3145	RE
	BrnIndL1/GrnREL1	15.3216	0.0320	FE
	BrnIndL1/GrnDepL1	18.0407	0.0118	FE
REPCA	BrnEmpL1/GrnREL1	25.6883	0.0006	FE
	BrnEmpL1/GrnDepL1	21.757	0.0028	FE
	BrnIndL1/GrnREL1	19.7757	0.0061	FE
	BrnIndL1/GrnDepL1	20.7121	0.0042	FE

Table 14: Hausman test results – 1970-1990

Dependent variable	Independent variable	Asymptotic test statistic	P.value	Conclusion
Grn_RE	RPAvgL1	41.0153	0.0000	FE
	RPTotL1	12.7773	0.0467	FE
	REPCA	13.1727	0.0404	FE
Grn_Dep	RPAvgL1	29.4495	0.0000	FE
	RPTotL1	10.3977	0.1089	RE
	REPCA	8.0334	0.2357	RE
REP_Tot	BrnEmpL1/GrnREL1	NA		-
	BrnEmpL1/GrnDepL1	NA		-
	BrnIndL1/GrnREL1	80.857	0.0000	FE
	BrnIndL1/GrnDepL1	50.0965	0.0000	FE
REP_Avg	BrnEmpL1/GrnREL1	NA		-
	BrnEmpL1/GrnDepL1	NA		-
	BrnIndL1/GrnREL1	35.0651	0.0000	FE
	BrnIndL1/GrnDepL1	18.4196	0.0102	FE
REPCA	BrnEmpL1/GrnREL1	NA		-
	BrnEmpL1/GrnDepL1	NA		-
	BrnIndL1/GrnREL1	90.7193	0.0000	FE
	BrnIndL1/GrnDepL1	91.4167	0.0000	FE

5.5.1 Baseline results

The policy effect

Table 15 presents the baseline results of the fixed effects panel regression results for the period 1970-2014 from Equation 1 with all control variables.

Using our first proxy for the green industry variable, renewable energy, the coefficients for the policy variables are positive and statistically significant, indicating that policies have a **positive impact on the development of the green industry**. Apart from trade and population, all other control variables are significant and have consistent results confirming their inclusion in the regression. Oil price has a **negative relationship** with the development of the green industry, as was expected. Energy consumption and GDP have a positive effect on the green industry. The first wave of policies in the 1970s in the EU15, US, Australia, New Zealand and Turkey focussed on R&D but were discontinued in the 1980s as oil prices fell (Nicolli & Vona, 2015). A second wave of policies was implemented in the 1990s to mitigate climate change. Despite these changes, the results of this regression show the positive impact of policy on green industry development.

Table 15: The policy effect: baseline results (GreenRE)

Dependent variable: Green RE		(1)	(2)	(3)
Policy variable	REavg	0.1206*** (0.0430)		
	Retot		0.0298*** (0.0101)	
	REpca			0.0631*** (0.0631)
Control variable	Trade	0.0152 (0.0183)	0.0049 (0.0198)	0.0123 (0.0216)
	Population	-2.3083*** (0.6829)	-1.3321 (0.8274)	-1.2085 (0.9267)
	Econs	0.0008*** (0.0000)	0.0008*** (0.0003)	0.0005 (0.0003)
	Oil	-0.0376*** (0.0094)	-0.0496*** (0.0106)	-0.0520*** (0.0116)
	GDP	0.0003*** (0.0000)	0.0002*** (0.0000)	0.0002*** (0.0000)
Constant		9.5625*** (1.3240)	12.2811** (2.1424)	14.9384*** (2.5953)
R2		0.8052	0.8683	0.8699
Observations		1306	955	851

Table 16 below presents the base regression results from equation 1 using the second proxy for the green industry, Green Deputies. All control variables have been included. The coefficients for the policy variables are not significant and surprisingly have a negative sign. Trade, oil price and GDP are significant and have the expected signs. Trade and GDP have a positive effect on green industry development, while the oil price has a negative effect.

Table 16: The policy effect: baseline results (green deputies)

Dependent variable: Green deputies		(4)	(5)	(6)
Policy variable	REavg	-0.0152*		
		(0.0090)		
	Retot		-0.0005	
			(0.0023)	
	REpca			-0.0013
				(0.0044)
Control variable	Trade	0.0231***	0.0218***	0.0167***
		(0.0004)	(0.0044)	(0.0049)
	Population	0.4522***	-0.1605	-0.0547
		(0.1488)	(0.1943)	(0.2080)
	Econs	0.0003***	-0.0001**	0.0000
		(0.0000)	(0.0000)	(0.0000)
	Oil	-0.0091***	-0.0090***	-0.0082***
		(0.0021)	(0.0026)	(0.0029)
	GDP	0.0000***	0.0000***	0.0000***
		(0.0000)	(0.0000)	(0.0000)
Constant		-3.1752***	0.6839	-0.1327
		(0.2828)	(0.5405)	(0.7539)
R2		0.6981	0.7787	0.7898
Observations		1171	853	749

The lobbying effect

Tables 17, 18 & 19 present the baseline regression results from Equation 2 with all control variables. The coefficients of the control variables are significant, indicating that these variables are relevant and have an impact on RE policy. GDP and oil prices are positive and significant. Higher oil prices are correlated with the adoption of RE policy, while population and trade have a negative effect. The effect of energy consumption appears to be mixed.

The coefficients for brown industry variables for all but one are negative and statistically significant, indicating that **lobbying by the brown industry has a negative effect on RE**

policy. The coefficients for green industry variables are not statistically significant. Green deputies appear to have a negative effect on RE policy adoption while the effect of the Green RE variable is mixed.

Table 17: The lobbying effect: baseline results (REavg)

Policy variable: RE avg		(7)	(8)	(9)	(10)
Green Industry	Green Dep	-0.1576	0.0069		
		(0.1371)	(0.1468)		
	Green RE			-0.0134	0.0656***
				(0.0358)	(0.0254)
Brown industry	Brown Ind	-5.5054*			-3.4871
		(3.2260)			(3.0014)
	Brown Emp		-0.8764***	-0.8296***	
			(0.1425)	(0.1218)	
Control variable	Trade	-0.0245	-0.1138***	-0.1032***	-0.0399**
		(0.0200)	(0.0177)	(0.0165)	(0.0190)
	Population	-3.1935***	-1.8455**	-1.8421**	-3.2678***
		(0.7215)	(0.7847)	(0.7386)	(0.6678)
	Econs	0.0000	-0.0004***	-0.0004***	0.0000
		(0.0001)	(0.0001)	(0.0000)	(0.0000)
	Oil	0.0714***	0.1265***	0.1187***	0.0706***
		(0.0097)	(0.0132)	(0.0112)	(0.0092)
	GDP	0.0004***	0.0001***	0.0002***	0.0004***
		(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant		-1.6222	35.3147***	32.5442	-2.5164*
		(1.7400)	(5.0229)	(4.3567)	(1.5183)
R2		0.6406	0.7719	0.7720	0.6550
Observations		880	671	769	937

Table 18: The lobbying effect: baseline results (REtot)

Policy variable: RE tot		(11)	(12)	(13)	(14)
Green Industry	Green Dep	-0.5358 (0.6470)	-0.7004 (0.6276)		
	Green RE			-0.0633 (0.1494)	0.2939** (0.1192)
Brown industry	Brown Ind	-50.5413** (21.1868)			-33.3231 (0.1192)
	Brown Emp		-4.8318*** (0.6478)	-4.4142*** (0.5536)	
Control variable	Trade	-0.1184 (0.0898)	-0.5337*** (0.0770)	-0.4853*** (0.0717)	-0.2643*** (0.0853)
	Population	-14.7088*** (3.6603)	-3.0441 (3.3827)	-4.0307 (3.1608)	-12.8963*** (3.3251)
	Econs	0.0033*** (0.0010)	0.00014 (0.0013)	0.0002 (0.0011)	0.0050*** (0.0009)
	Oil	0.3771*** (0.0480)	0.4817*** (0.0554)	0.4690*** (0.0470)	0.3730*** (0.0443)
	GDP	0.0012*** (0.0001)	0.0005*** (0.0002)	0.0006*** (0.0001)	0.0013*** (0.0001)
Constant		-25.9697** (10.8364)	159.145*** (23.9787)	150.995*** (21.2344)	-39.1699*** (8.8882)
R2		0.6415	0.7749	0.7745	0.6668
Observations		749	631	721	807

Table 19: The lobbying effect: baseline results (REpca)

Policy variable: REpca		(15)	(16)	(17)	(18)
Green Industry	Green Dep	-0.2336 (0.3767)	-0.1961 (0.3627)		
	Green RE			-0.0293 (0.0853)	0.1775** (0.0689)
Brown industry	Brown Ind	8.0479 (12.3507)			-9.4910 (11.0262)
	Brown Emp		-2.6755*** (0.3665)	-2.4486*** (0.3126)	
Control variable	Trade	-0.1866*** (0.0522)	-0.3125*** (0.0447)	-0.2768*** (0.0412)	-0.1692*** (0.0495)
	Population	-9.8813*** (2.0622)	-1.8396 (1.9394)	-2.2964 (1.8123)	-8.5671*** (1.9422)
	Econs	0.0067*** (0.0008)	0.0020** (0.0010)	0.0006 (0.0008)	0.0040*** (0.0006)
	Oil	0.2439*** (0.0276)	0.2845*** (0.0314)	0.2759*** (0.0266)	0.2299*** (0.0256)
	GDP	0.0007*** (0.0000)	0.0003*** (0.0000)	0.0003*** (0.0000)	0.0007*** (0.0000)
Constant		-73.8122*** (7.9224)	61.1951*** (14.6365)	62.6240*** (12.5920)	-49.4468*** (5.6621)
R2		0.6719	0.7745	0.7735	0.6702
Observations		696	607	694	764

5.5.3 Results for the period 1991-2014

The policy effect for the period 1991-2014

Equation 1 was analysed for the period 1991-2014, representing the period of global action on climate change. The results are presented in Tables 20 and 21 below. The policy coefficients have a positive effect on the development of the green industry showing the impact of the second wave of policies implemented in the 1990s. Trade and energy consumption has a negative effect, while population, oil price and GDP have a positive effect. The change in the effect of prices on RE policy adoption may be explained by growing energy needs coupled with rising concern for environmental issues. As seen before, **RE policies have a negative effect on the green deputy variable.**

Table 20: The policy effect 1991-2014 (Green_RE)

Dependent variable: Green_RE		(19)	(20)	(21)
Policy variable	REavg	0.0275		
		(0.0388)		
	Retot		0.0102	
			(0.0098)	
	REpca			0.0155
				(0.0183)
Control variable	Trade	-0.0082	-0.0007	0.0112
		(0.0161)	(0.0176)	(0.0186)
	Population	0.8097	0.0226	-0.4947
		(0.7505)	(0.8052)	(0.8345)
	Econs	0.0004***	-0.0011***	-0.0012**
		(0.0000)	(0.0004)	(0.0004)
	Oil	0.0347***	0.0418***	0.0455***
		(0.0125)	(0.0132)	(0.0137)
	GDP	0.0000*	0.0000	0.0000
		(0.0000)	(0.0000)	(0.0000)
Constant		16.2816***	0.0000	28.2552***
		(1.3053)	(0.0000)	(2.8384)
R2		0.9157	0.9176	0.9180
Observations		835	761	717

Table 21: 1991-2014 (Green deputies)

Dependent variable: Green deputies		(22)	(23)	(24)
Policy variable	REavg	-0.0022		
		(0.0104)		
	Retot		-0.0014	
			(0.0026)	
	REpca			-0.0015
				(0.0047)
Control variable	Trade	0.0046	0.0101**	0.01116**
		(0.0043)	(0.0047)	(0.0048)
	Population	-0.3475*	-0.3417	-0.1250
		(0.2006)	(0.2114)	(0.2139)
	Econs	0.0003***	0.0000	0.0002
		(0.0000)	(0.0001)	(0.0001)
	Oil	-0.0015	-0.0000	0.0000
		(0.0036)	(0.0037)	(0.0038)
	GDP	0.0000***	0.0000***	0.0000***
		(0.0000)	(0.0000)	(0.0000)
Constant		-1.4112***	-0.2309	-0.9328
		(0.3634)	(0.9208)	(0.9715)
R2		0.8295	0.8383	0.8411
Observations		727	667	629

The lobbying effect 1991-2014

The same period was also examined for equation 2. Tables 22, 23 & 24 present the regression results from Equation 2 for the period 1991-2014 with all control variables. The coefficients of the control variables are mostly significant. Again, GDP and oil price have a positive effect, while population and trade have a negative effect and the effect of energy consumption appears to be mixed.

The coefficients for brown industry variables clearly show the negative impact of **lobbying by the brown industry on RE polic**y. The coefficients for green industry variables appear to have a negative effect on RE policy adoption.

Table 22: The effect of lobbying 1991-2014 (REtot)

Dependent variable: RE tot		(25)	(26)	(27)	(28)
Green Industry	Green Dep	-0.4891	-0.7005		
		(0.6608)	(0.6276)		
	Green RE			-0.0633	0.0446
				(0.1494)	(0.1578)
Brown industry	Brown Ind	-75.1260*			-62.8273
		(44.7997)			(40.3494)
	Brown Emp		-4.8318***	-4.4142***	
			(0.6478)	(0.5536)	
Control variable	Trade	-0.2868***	-0.5337***	-0.4853***	-0.2762***
		(0.08557)	(0.0770)	(0.0717)	(0.0816)
	Population	-13.4045***	-3.00441	-4.0307	-13.7103***
		(3.4385)	(3.3827)	(3.1608)	(3.2820)
	Econs	0.0003	0.0014	0.0003	0.005
		(0.0014)	(0.0013)	(0.0001)	(0.0012)
	Oil	0.6424***	0.4817***	0.4690***	0.6143***
		(0.0587)	(0.0554)	0.0470	(0.0541)
	GDP	0.0005***	0.0005***	0.0005***	0.0006***
		(0.0002)	(0.0002)	0.0001	(0.0002
Constant		24.9359	159.145***	150.995***	18.4101
		(15.2552)	(23.9787)	(21.2344)	(13.0284)
R2		0.7508	0.7749	0.7745	0.7523
Observations		621	631	721	679

Table 23: The lobbying effect 1991-2014 (REavg)

Dependent variable: REavg		(29)	(30)	(31)	(32)
Green Industry	Green Dep	-0.07244	0.0069		
		(0.1580)	(0.1468)		
	Green RE			-0.0134	-0.0024
				(0.0358)	(0.0380)
Brown industry	Brown Ind	-19.0425*			-15.1451
		(10.6379)			(9.6650)
	Brown Emp		-0.8764***	-0.8296***	
			(0.1425)	(0.1218)	
Control variable	Trade	-0.0741***	-0.1138	-0.1032***	-0.0691***
		(0.0198)	(0.0177)	(0.0165)	(0.0190)
	Population	-3.6458***	-1.8455**	-1.8421**	-3.7798***
		(0.8049)	(0.7847)	(0.7386)	(0.7682)
	Econs	-0.0003*	-0.0004***	-0.0004***	-0.0003**
		(0.0002)	(0.0001)	(0.0000)	(0.0001)
	Oil	0.1592***	0.1265***	0.1187***	0.1541***
		(0.0140)	(0.0132)	(0.0112)	(0.0130)
	GDP	0.0001***	0.0001***	0.0002***	0.0001***
		(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant		9.6485***	35.3147***	32.5442***	8.3604***
		(2.4689)	(5.0229)	(4.3567)	(2.4014)
R2		0.7555	0.7719	0.7720	0.7562
Observations		651	671	769	709

Table 24: The lobbying effect 1991-2014 (REpca)

Dependent variable: REpca		(33)	(34)	(35)	(36)
Green Industry	Green Dep	-0.118 (0.3870)	-0.1961 (0.3627)		
	Green RE			0.0102 (0.0919)	-0.0293 (0.0854)
Brown industry	Brown Ind	-32.0044 (26.7249)		-32.1075 (23.1448)	
	Brown Emp		-2.6756 (0.3665)		-2.4486*** (0.3126)
Control variable	Trade	-0.1732*** (0.0498)	-0.3125*** (0.0447)	-0.16521*** (0.0471)	-0.2768*** (0.0412)
	Population	-7.7725*** (1.9713)	-1.8396 (1.9394)	-7.9804*** (1.8741)	-2.2964 (1.8123)
	Econs	0.0010 (0.0011)	0.0020** (0.0010)	0.0009 (0.0008)	0.0006 (0.0008)
	Oil	0.3739*** (0.0333)	0.2845*** (0.0314)	0.3567*** (0.3060)	0.2759*** (0.0266)
	GDP	0.0003 (0.0001)	0.0003*** (0.0000)	0.0003*** (0.0000)	0.0003*** (0.0000)
Constant		-12.1283 (11.7154)	61.1951*** (14.6365)	-11.8529 (8.4832)	62.6240*** (12.5920)
R2		0.7467	0.7745	0.7486	0.7735
Observations		599	607	657	694

5.5.3 Results for the period 1970-90

The policy effect for the period 1970-1990

Tables 25 & 26 present the regression results for the period 1970-2014 from Equation 1 with all control variables. As this period represents the birth of energy policy for most countries and grassroots alternative energy movements, it is not surprising to see that the coefficients of the policy variables are not significant. However, they are positive, **indicating their positive effect on the green industry.** Trade and GDP have a positive effect, while the oil price has a **negative relationship** with the development of green industry development as was expected.

Table 25: The policy effect 1970-1990 (Green RE)

Dependent variable: Green RE		(37)	(38)	(39)
Policy variable	REavg	2.8962***		
		(0.7813)		
	Retot		0.2473	
			(0.3061)	
	REpca			-0.1264
				(0.7753)
Control variable	Trade	0.3385***	0.1105	0.1527
		(0.0677)	(0.1840)	(0.2448)
	Population	-0.4395	-4.2307*	-4.4672
		(1.1367)	(2.4542)	(4.2897)
	Econs	0.0029	0.0037***	0.0043**
		(0.0005)	(0.0013)	(0.0017)
	Oil	-0.0376**	-0.1037***	-0.1104**
		(0.0152)	(0.0259)	(0.0401)
	GDP	0.0003**	0.0001	0.0002
		(0.0001)	(0.0002)	(0.0003)
Constant		-25.1388	-6.2895	-12.6557
		(4.0225)	(9.1025)	
R2		0.7219	0.7879	0.7888
Observations		471	194	134

Table 26: The policy effect 1970-1990 (green deputies)

Dependent variable: Green deputies		(40)	(41)	(42)
Policy variable	REavg	-0.2571**		
		(0.1042)		
	REtot		-0.0299	
			(0.0385)	
	REpca			0.0331
				(0.1188)
Control variable	Trade	0.0532***	0.0789***	0.0842*
		(0.0100))	(0.0291)	(0.0481)
	Population	0.7123***	0.4461	1.1042
		(0.1540)	(0.3721)	(0.6931)
	Econs	0.0001	-0.0002*	-0.0006**
		(0.0000)	(0.0001)	(0.0003)
	Oil	-0.0127***	-0.0142***	-0.0239***
		(0.0022)	(0.0039)	(0.0007)
	GDP	0.0001***	0.0001***	0.0001**
		(0.0000)	(0.0000)	(0.0000)
Constant		-4.3652***	-2.7499*	0.2891
		(0.6466)	(1.4826)	(3.7750)
R2		0.5431	0.5537	0.57936
Observations		444	186	120

The lobbying effect for the period 1970-90

As Brown Employment data only starts from 1991, this variable has been excluded from the regression. Tables 27, 28 & 29 present the regression results from Equation 2 for the period 1970-1990 with all control variables. The coefficients of the control variables are mostly significant. Again, GDP, trade, energy consumption and oil price have a positive effect, while the population has a negative effect. The positive effect of energy consumption appears to be mixed.

The coefficients for brown industry variables clearly show the negative impact of **lobbying by the brown industry on RE polic**y. The coefficients for green industry variables appear to have a negative effect on RE policy adoption.

Table 27: The lobbying effect 1970-1990 (REavg)

Policy variable: RE avg		(43)	(44)
Green Industry	Green Dep	-0.2045*** (0.0543)	
	Green RE		0.0120*** (0.0040)
Brown industry	Brown Ind	-0.1543 (0.3813)	-0.5205 (0.3706)
Control variable	Trade	0.0237** (0.0095)	0.0018 (0.0092)
	Population	-0.0025 (0.1319)	-0.1305 (0.1191)
	Econs	0.0000 0.0000	0.0001** (0.0000)
	Oil	0.0033* (0.0017)	0.00072*** (0.0017)
	GDP	0.0000*** (0.0000)	0.0000*** (0.0000)
Constant		-1.5475*** (0.5186)	-1.0552** (0.4753)
R2		0.7949	0.8098
Observations		229	228

Table 28: The lobbying effect 1970-1990 (REtot)

Policy variable: RE tot		(45)	(46)
Green Industry	Green Dep	-0.9802*** (0.3237)	
	Green RE		0.0028 (0.0190)
Brown industry	Brown Ind	8.7871** (4.2241)	5.4393 (3.8592)
Control variable	Trade	0.2972*** (0.0613)	0.0913 (0.0644)
	Population	-0.2436 (1.0417)	-0.8625 (0.8483)
	Econs	-0.0002 (0.0002)	0.0011*** (0.0003)
	Oil	0.0000 (0.0092)	0.0252*** (0.0088)
	GDP	0.0005*** (0.0000)	0.0003** (0.0000)
Constant		-15.2326*** (3.0402)	-12.1274*** (2.5208)
R2		0.8333	0.8556
Observations		128	128

Table 29: The lobbying effect 1970-1990 REpca

Policy variable: REPcov		(47)	(48)
Green Industry	Green Dep	-0.2246 (0.1592)	
	Green RE		-0.0111 (0.0095)
Brown industry	Brown Ind	4.2912* (2.1643)	4.9318** (2.0167)
Control variable	Trade	0.07414* (0.0412)	0.0676* (0.0345)
	Population	-1.4503** (0.7267)	-1.8604*** (0.6095)
	Econs	0.0006*** (0.0002)	0.0007*** (0.0002)
	Oil	0.0076 (0.0054)	0.0092* (0.0049)
	GDP	0.0001*** (0.0000)	0.0002 (0.0000)
Constant		-25.5544*** (1.5208)	-25.1521*** (1.4038)
R2		0.8672	0.8692
Observations		96	107

5.5.4 Industry-policy causality

Due to the large number of zeroes in the Green Deputy variable, it was dropped from the analysis. Causality analysis was done only for the Green RE variable. Tables 30 below presents the results of the causality tests.

Table 30: Industry-policy causality results

Period	Countries	Lags		P.value	Conclusion
1970-1990	11 countries: Austria, Canada, Denmark, France, Germany, Japan, Korea, Mexico, Switzerland, UK, US	1	Green RE→RPavg	0.0000	Bidirectional causality
			Rpavg→GreenRE	0.0131	
	Variables don't work.		GreenRE→RPTot		
	7 countries: Canada, Denmark, France, Japan, Korea, Norway, USA	1	Brown industry→RPAvg	0.0697	Unidirectional causality
			Rpavg→Brown industry	0.1020	
			BrownInd→RPTotal	0.9506	Unidirectional causality
			RPTotal→BrownInd	0.0000	
1970-2014	15 countries	1	Brown industry→RPAvg	0.0000	Bidirectional causality
			RPAvg→Brown industry	0.0000	
	28 countries	1	Green RE→RPavg	0.0000	Bidirectional causality
			Rpavg→GreenRE	0.0000	
			Green RE→RPTotal	0.1480	Unidirectional causality
			RPTotal→GreenRE	0.0000	
	7 countries: Canada, Denmark, France, Japan, Korea, Norway, USA	1	BrownInd→RPTotal	0.0000	Bidirectional causality
			RPTotal→BrownInd	0.0001	
			BrownInd→RPAvg	0.0000	Bidirectional causality
			RPAvg→BrownInd	0.0000	
1995-2014	All countries	1	Green RE→RPavg	0.2941	Unidirectional causality
			Rpavg→GreenRE	0.0000	
			Green RE→Rptot	0.5392	Unidirectional causality
			Rpavg→GreenRE	0.0000	
			BrownEmp→RPTotal	0.0061	Bidirectional causality
			RPTotal→BrownEmp	0.0000	
			BrownEmp→RPAvg	0.1554	Unidirectional causality
			RPAvg→BrownEmp	0.0000	
			BrownInd→RPTotal	0.0365	Bidirectional causality
			RPTotal→BrownInd	0.0001	
			BrownInd→RPAvg	0.0188	Bidirectional causality
			RPAvg→BrownInd	0.0000	

The 1970-1990 regresssion proved challenging due to insufficient data for all countries. Pair-wise regression was done on those countries that had sufficient data. A feedback effect is present during this period between policy and the green industry. Unidirectional causality from policy to the brown industry is weakly present. In the period 1970-2014, bidirectional causality between the brown industry and policy clearly indicates the presence of negative feedback. This is confirmed in the period 1995-2014.

Causality results for the green industry are mixed. Bidirectional causality or feedback is present between GreenRE and RPAvg during the period 1970-2014. However, there is unidirectional causality from Policy to GreenRE during this period suggesting that the green industry might not be powerful enough to combat lobbying by the brown industry. This is confirmed in the 1995-2014 period when causality runs from policy to the green industry. Table 31 below provides the summary of the causality tests.

Table 31: Summary of results

Hypothesis	**Period**	**Variables**	**Conclusion**
Effect of policy	1970-2014 1970-1990 1991-2014	Green RE, Policy	Policies have a positive effect on the green industry
	1970-2014, 1991-2014	Green Deputies, Policy	Policies have a negative effect on green deputies
	1970-1990	Green Deputies	Policies have a mixed effect on green deputies.
Effect of lobbying	1970-2014 1991-2014		Brown Lobbying has a negative effect on policy.
	1970-1990		Brown lobbying has a mixed effect on policy.
	1970-2014 1991-2014		Green Lobbying has mixed effects on policy.
	1970-1990		Green Lobbying has a largely negative effect on policy.
Policy-industry causality	1970-90	Green	Feedback between Green Industry and Policy
		Brown	Weak unidirectional causality from policy to brown industry.
	1995-2014	Green	Unidirectional causality from policy to green industry.
		Brown	Negative feedback
	1970-2014	Green	Weak positive feedback
		Brown	Negative feedback

5.6 Discussion

This dissertation aims to explain policy feedback as a mechanism for path dependence in a country's energy-related policy, contributing to the variation in different countries' energy transitions. The regression results confirm the policy's positive effect on green industry. Our hypothesis that the lobbying efforts of the green industry have a positive effect on policy is also confirmed. However, lobbying by the powerful incumbent brown industry hurts the development of policy. This lobbying creates negative feedback, which impacts the growth of the green industry.

There is a strong interrelation between socio-economic and technological dimensions within the energy sector. The lack of clear results may be attributed to the lack of strong coordination between public policies, leading to contrasting forces and impacts, thus reducing the overall benefit (Constantini & Crespi, 2013).

However, the analysis shows the highly persistent nature of path-dependent processes. Countries like Denmark and Iceland which have large amounts of renewable energy, did not become that way simply because they are environmentally friendly. These countries had a sufficient stock and existing knowledge of these technologies for them to slowly become a viable alternative to fossil fuel. Their dependence on fossil fuel imports, relative lack of financial resources, and smaller, more homogenous populations with a shared culture coupled with strong grassroots movements stimulated alternative energy debates and use in the 1970s and allowed them to move away from fossil fuel usage.

The government's role is to stimulate innovation and accelerate learning processes. R&D programs dominated the renewables policy framework in the 1970s, while the 2000s were dominated by Obligations and Tradable Certificates. Public support for energy R&D declined during the period 1985-95. The US, UK, Italy and Germany all reduced R&D expenditure on nuclear energy during the 1985-1995 time period and redirected funding towards non-energy related areas. R&D was largely carried out by nine countries in 1995: Canada, France, Germany, Italy, Japan, the Netherlands, Switzerland, the UK and the US (Dooley, 1998). R&D is difficult and slow in the early stages. Strategy development with regard to R&D is an emergent process. However, as time goes by and countries build knowledge and technology stocks, the process accelerates. As innovation diffuses, follower countries benefit from years of R&D conducted by championing countries leading to the leapfrog effect.

Energy systems are influenced by the cultural and institutional ecosystem they find themselves in. Zukowski (2004) showed us that interregional developmental differences that occurred as a result of exogenous shocks lead to divergent regional outcomes. These differences persist over time because of the path-dependent nature of technological development. When faced with an exogenous shock such as the 1970s oil crisis, countries made decisions and implemented policies based on their existing institutional capacity, technology and knowledge stocks and natural endowments and which led to diverging paths. But these decisions were also an outcome of their reaction to the shock. Responses to the shock depended on each individual nation's current state of development, culture and other socio-economic factors. The policy and technological choices made during this period have had a lasting impact and have led to divergent outcomes in the sustainable energy transition for different countries. Countries chose to move away from fossil fuels simply because they were too expensive or did not provide energy security

As Sovacool (2016) argues that the speed of energy transitions depends on the start date that is determined independently, he also mentions that countries such as France (nuclear), and Kuwait (oil), all had prior experience with the energy sources in question with pilot programmes that were implemented before the transition.

The negative effect of Green deputies

The negative effect of green deputies may be explained by the relatively late arrival of Green Parties, which have been achieving more significance since the 1990s, particularly in European democracies (Mourao, 2019). Despite this, the maximum number of Green Deputies in parliament has only been 22.2% (see summary statistics), with a mean of 1.8 and a median of 0, indicating the low values and, therefore, low strength of this variable. However, as their presence in Parliament involves coalitions, these parties tend to be indistinguishable from their major partners as they need to deal strategically with these groups (Mourao, 2019). When compared to Right-wing governments, Left-wing governments are generally more focused on environmental quality than the economy. However, when facing electoral pressure, both governments forego environmental goals for economic growth

(Mourao, 2019). The negative effect of green deputies suggests that there may exist a less pronounced impact on RE policy in these situations. Another explanation may also be the political focus of Green Parties and political parties in general, which have evolved over time.

The positive effect of green deputies on green industry development signifies the emergence of alternative energy movements. However, the negative coefficients for this variable in the 1991-2014 period might indicate that the growing green industry has a negative impact on RE policy adoption. Perhaps this is when economic and support policies are required, just as subsidies are handed out to the fossil fuel industry. It may also be hypothesised that during this period, green deputies were more concerned with other 'green' causes and their own political battles. Another point to consider is the inclusion of nuclear energy in the Green RE variable. Nuclear energy is not considered a green energy source and, therefore, might create a negative effect.

The relative strength of the brown industry

Left-Right partisanship might be another way to analyse the effect of the brown industry on the development of the green industry, particularly when studying levels of government support. Cao (2012) found that the brown sector strength is a good indicator of the level of state support it receives regardless of government partisanship. This is because governments trade industry aid for support from interest groups which means that stronger interest groups, such as the brown sector, receive more support.

As Sovacool (2016) argues, the objective of energy transition should not just be the promotion of renewable energy sources but also cease the use of fossil fuel energy. As we implement policies that encourage the growth of the renewable energy industry, we should also be implementing policies that curtail the fossil fuel industry. This means discouraging not just the use of fossil fuels as an energy source but also other fossil fuel products such as plastic and feedstocks for chemical processes. This would require a transition to a completely different way of running our economies and industries. One way of achieving this would be to mimic the Christmas effect (Sedgwick, 1983) where institutions, businesses and people come together and speak with 'one voice' for Christmas. Building a similar voice for climate change would require a massive effort on an international level but would help countries achieve carbon reduction goals. While the "Christmas effect" would help overcome the socio-technical inertia surrounding the sustainable energy transition, coordination of a global effort would require considerable resources and time.

Policy classification

As policies have evolved to correct negative externalities and stimulate innovation, they become harder to classify and evaluate across countries and time. This might explain some of the conflicting results in the analysis. This was apparent during the policy data collection process, where a number of policy descriptions had changed over the course of a couple of years. Further, the inclusion of certain policies as climate-related policies in certain countries that might be considered standard policies in other countries (need an example of the speed limit policy) adds to the challenge of correctly identifying climate and RE policy. This highlights the fact that policy descriptions can be changed to suit various purposes and therefore need to be carefully considered when included in the policy database. Nicolli & Vona (2015) express similar concerns about the difficulty of providing an aggregate measure of heterogeneous policies that capture the effort made by each country in favour of the transition to sustainable energy.

Another point to consider is that pollution taxes introduce negative feedback that counters the positive feedback of network externalities for fossil fuels. Taxing dirty technologies and subsidising clean technology reduces the profit gap between the two and helps increase the share of clean technology by introducing negative feedback. When positive feedback is weak, environmental policy can increase the share of clean technology (Zeppini 2015).

Renewable energy will achieve grid parity only when the cost of fossil fuel energy includes the price of externalities through the introduction of an emissions charge or carbon tax. It is evident that countries need to ensure a secure supply of energy for their economies. In this scenario, climate change faces problems associated with a common good. This means that waiting for the market to encourage the adoption of low-carbon technology will not happen until the introduction of a carbon tax. Using end-of-pipe solutions such as negative emissions technology is an attempt by fossil fuel companies to continue their monopoly on the world's energy system. Climate change mitigation requires the end of fossil fuel use which entails stopping the production of fossil fuel in its entirety.

Further, resolving climate change problems involves the coordination of multiple countries with vastly different energy objectives and needs. The problem is compounded by the fact that the largest portion of GHG emissions are emitted by a handful of countries while the effects of climate change are felt by other countries. At the recent COP26 summit, instead of phasing out coal power and fossil fuel subsidies in the Glasgow Climate Pact, India and China negotiated to reduce the use of these tools. COP21's Paris Agreement called for action to prevent temperatures from rising above 2 degrees Celsius, and ideally 1.5 degrees Celsius, above pre-industrial levels by the end of the century, which would require global emissions to be halved by 2030 (Percio, 2021). However, a report from the IPCC indicated that global temperatures have already risen by 1.1 degree Celsius on pre-industrial levels leaving very little room to achieve the 1.5 degrees Celsius. In the face of such an inability to achieve agreement on a global solution, the only solution may be the establishment of a global institution with the power to enforce international agreements related to climate change.

Limitations

Research challenges arising from this study principally include the measurement of the green industry. In the absence of data, the limitations of using a proxy variable suggest that our findings must be interpreted with caution. The data used in this dissertation was designed for a different study, so the variables provide only rough proxy measures of green industry growth. The challenges of using a proxy variable are evident in the selection of Green Deputies as a proxy for the strength of the Green Industry. Although proxy variables can reduce specification bias that arises when data are not available, there are risks involved. On the other hand, under-researched subjects such as policy-industry causality should not be ignored purely because of a lack of data. We hope that this area of research generates more data that will allow for better analysis.

Rates of RE industry growth vary over time and place. Attempts to measure feedback effects with cross-sectional data are challenging because of interdependencies between the green level of policy and the growth rate.

Finally, policies have been classified according to their descriptions. If the descriptions have changed over the period, then the classification will be erroneous.

6. Conclusion

In this dissertation, we tested an empirical model based on panel data to provide evidence of policy feedback. We model governmental policy choice as the result of political competition, with policy feedback contributing to the growth or underdevelopment of the green industry. Our results show that RE policy is positively correlated with the green industry. Our hypothesis that the lobbying efforts of the green industry have a positive effect on policy is also confirmed. However, lobbying by the brown industry harms the development of RE policy which creates negative feedback that impacts the growth of the green industry. We emphasise the role of policy feedback as a mechanism of path dependence.

Astrom & Murray (2008) describe feedback as a reactive process because an error must be made before corrective actions are taken. However, a ‘feedforward’ can be used as a control mechanism in some situations to take corrective action before the feedback occurs, thereby reducing the feedback effect. This can be done through anticipatory action when RE policy is introduced, in advance of a reaction by the brown industry.

An exploration of historical energy transitions revealed that transitions come about due to the crisis and/or superior technology and generally take several decades or longer. The current spotlight on extreme weather events in Europe and North America as a result of climate change, provide the ideal opportunity to bolster RE policy, provide support for complementary technologies and stop fossil fuel exploration. The support and co-evolution of industries is a common factor in transition. Policies to accelerate the deployment of new technologies must be coupled with policies to reduce fossil fuel use if systemic obstacles are to be overcome to set up a new energy system. Scaling up new technology drives transition, but it must have sufficient time for learning and experimentation. Sustainable energy sources, therefore, require support from various stakeholders, including financiers, politicians and the public. Perception of investment opportunities influences investor behaviour, so policies need to consider this and influence investor behaviour by inducing a better perception of investment opportunities, thus influencing investor behaviour (Polzin et al., 2015).

The price of fossil fuels does not account for the variety of negative externalities it produces. Renewable energy policy objectives have been defined without an explicit carbon tax, meaning the market will not respond to calls for reducing fossil fuel consumption without a carbon price (Menanteau, 2003). The notion of pricing negative externalities is problematic in the case of climate change as the problem is global in scope and has long-term implications, including intergenerational equity. Still, the sustainable energy transition will require introducing a carbon price to achieve the twin goals of decarbonisation and responsible energy use.

Aghion et al. (2019, pg 76) specify the need for research subsidies combined with carbon pricing and the combined effort of private and public market forces to overcome system inertia. These research subsidies must specifically target clean energy, mainly if gas is used to transition from coal to clean energy. They also stress the need to share clean energy technology with less developed countries while considering border carbon adjustments.

The sustainable energy transition is embedded in technological, social, institutional, and economic change, meaning societal behaviour must be reshaped alongside clean technology adoption. The impact of lobbying is clearly visible in policy outcomes in this dissertation. This shows the immense effect that the right policy could have. In addition to creating a new energy system, policies that educate might have little economic benefits but are necessary to change societal attitudes and behaviour. These policies would need to:

- **combat climate denialism** by understanding people's motivation to object to climate concerns. The internet quickly communicates fringe ideas, as witnessed in movements such as QAnon.
- **combat cheap energy populism** or the idea that energy should be cheap. By not responding to the concern of rising energy prices, societies face counter-mobilisation by vested interests such as fossil fuel companies. Market economies are only efficient when they factor all costs into the market price. This is not the case for energy. The Japanese energy transition in the 1950s aimed to reduce the demand for coal by regulating the oil demand. The idea was to increase coal production costs for producing small quantities, thereby making reducing coal prices by industries impossible. This would continue conversion to oil while shrinking the market for coal (Kobori, 2009)

- **change how we live:** technology companies are incentivised to back cheap energy as their products need so much. As society is mainly concerned about energy reliability rather than the type of energy source, behavioural change such as biking instead of driving or buying energy-efficient appliances can be encouraged through policy and education. Labelling and efficiency standards induce changes in energy efficiency. The efficiency principle was extended to district heating and led to the development of CHP plants in Denmark.

The Danish and Icelandic cases show that governments, citizens and industry must work together to find a sustainable solution. However, the initial steps have to be taken by the government or organised citizens to overcome the features of public goods. In Denmark and Iceland, citizens initially pushed for renewable energy. Sustainable solutions find an audience in communities concerned with their well-being. Visual intrusion also becomes less of an issue. Solutions provided by an external entity usually have a different motivation, primarily financial. The ‘built-in inertia’ of the energy sector leads to a reluctance to include new solutions. This makes creating a consistent renewable energy supply system challenging as different energy companies compete for the same customer.

The central theme of this dissertation is the explanation of international differences in the sustainable energy transition. As hydropower is an established technology, most research on the development of the renewable energy industry has focussed on the role of policy and other factors, such as innovation diffusion. However, the role of policy feedback and the strength of the fossil fuel industry and the effects of their lobbying has yet to be researched. Data on subsidies to the fossil fuel industry or lobbying activities remain scarce. Nonetheless, from our empirical analysis, it emerges that lobbying by the fossil fuel industry has a negative impact on implementing policies that foster the development of green industry and mitigate climate change. Despite the limitations of the data, this dissertation provides some valuable insights into the concept of policy industry feedback as a contributor to path dependence. Our findings have important implications for our understanding of energy transition and the continued support of fossil fuels. The existing literature on the impact of RE policy indicates that market mechanisms with little policy push would be insufficient for building a green industry and transitioning to renewable electricity.

Further, without a carbon price, a market mechanism will not develop sufficiently to discourage fossil fuels while promoting renewable energy. The findings show the considerable strength of the brown industry in arresting policy intervention in large market-driven countries such as the US and the UK. The policy advice drawn from this analysis is that counteracting the negative feedback phenomenon from the FF industry should be considered when setting the green energy policy.

More work is required to complement the findings of this dissertation. Potential areas of interest include the role of long-term petrol contracts and subsidies that keep countries locked into carbon.

The European transition from an agricultural to an industrial economy was gradual (Broadberry, Fremdling, & Solar, 2008). Although the technology was developed in the UK, it was adapted to local characteristics as it diffused throughout Europe. A similar transition can be expected for renewable energy. Every country has different natural endowments and absorption/learning capacities which much be accounted for in the transition. The institutional setting will also have an impact on transition. Nielsen (2017) discusses the need for examining transitions over a more extended period of time. Therefore, analysing data that only goes back a few decades cannot help identify structural and institutional changes precisely because these changes take place over decades. When it comes to specific technologies, although the data for the use of that particular technology only goes back a few decades therefore, to understand the development of the socio-technical regime around that technology as well as the decision-making that went into the development of that regime, might require looking at data even older than the technology.

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