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The Diffusion of Renewable Energy Technologies (RETs)

An assessment of the determinants and challenges for policymakers

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1) Introduction

In recent years, economic policy debates have been dominated by the widespread diffusion of renewable energy technologies. There is a consensus that the spread of renewable energy technologies will be crucial towards achieving global climate objectives and enhancing the security of energy supply. These policies originated in the industrialised world, and have since slowly begun to disseminate to developing countries. Notably, this phenomenon has intensified in Africa given the shortage of a stable energy supply and an abundance of RE potential across the region.

Diffusion rates should be taken into context given the technical, institutional and economic influences which shape the trajectory of an innovation. Much of the existing literature in this field has highlighted how these factors tend to either accelerate or restrict the diffusion process. With this in mind, a limited amount of attention has been paid to the interlinkages which exist between these factors, the part which actually makes this process a complex phenomenon (Narayanan, 2001). Renewable energy technologies (RETs) are primarily influenced by the fact that they offer an environmentally friendly alternative as well as the fact that it utilises infinite inputs compared to traditional fossil fuels. RETs have been able to obtain a substantial amount of financial incentives from public agencies to accelerate its rise across energy markets. With that being said, the rate at which RETs diffuse in these markets has not been lower than expected. This raises the question as to whether policy measures in RE markets have been designed poorly, or whether the slowdown in diffusion rates is a result of other structures in the market.

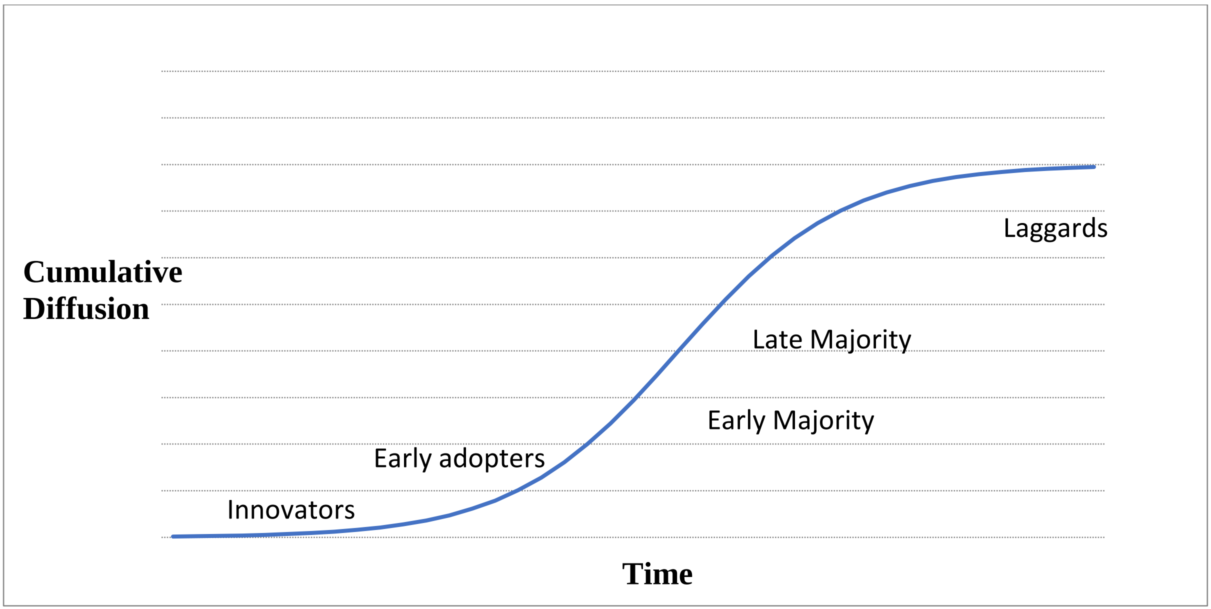
Considering the above, the objective of this paper is to assess the theory related to diffusion models with specific reference to RETs. This research fulfils its objective by unpacking the determinants of RET diffusion rates extracted from various case studies, as well as understanding the reasons behind why RETs haven't diffused as quickly as initially forecasted. The main findings of this research indicate that the rate of change in these diffusion models can be attributed to 1) learning by doing, 2) economies of scale and 3) access to a wide range of funding models in RE markets. Furthermore, a convolution of technical, economic and institutional factors explain why RETs have struggled to overcome the dominance of fossil fuel technologies in energy markets.

This paper is structured as follows. Section 2 provides a detailed overview related to the composition of standard diffusion models. Sections 3 and 4 focus on the explanatory factors which accelerate the rate of technological diffusion in RE markets, as well as the restricting factors thereof. Section 5 concludes the research by discussing policy implications and recommendations to facilitate higher diffusion rates in the future.

2) A review of the technological diffusion process

The diffusion of a technology is a process where an innovation develops and is deployed within and across economies (Rao and Kishore, 2010). Diffusion can be broken down into 5 phases - awareness, interest, evaluation, trial and adoption (Rogers, 1962). The cumulative process takes on the shape of a logistic S curve (seen in figure 1), which classifies five stages based on the phases mentioned above.

Figure 1: Cumulative Diffusion Curve – Rate of Adoption vs Time



Source: Rogers, 1962

Technology diffusion models were developed using life science theory related to the growth of biological cells. Cells faces nutrient and location constraints which limit how much they can grow, in a similar way to the constraints a technology experiences considering how far and quickly it can disseminate. The standard technology diffusion model assumes that the growth of an innovation is contingent on the number of individuals which adopt it, with the rate of change (which is known as the internal influence diffusion equation) expressed as

$$\frac{\partial N}{\partial t} = bN(t)\left(N^{u} - N(t)\right) \qquad (1)$$

where N(t) and N^u denotes the cumulative adoption at a given time *t* and the ultimate potential respectively, and *b* denotes the coefficient of diffusion.

Equation (1) is a logistic function similar to that of figure 1, and assumes that the diffusion process is determined by previous adopters. If the impacts on diffusion are determined exogenously, the external influence diffusion equation is given by

$$\frac{\partial N}{\partial t} = \left[a\left(N^u - N(t)\right)\right] \tag{2}$$

where *a* now represents the exogenously determined coefficient of diffusion

Bass (1969) revolutionised the way researchers view technology diffusion models by combining elements from both of these equations. The Bass model introduces three parameters, denoted as *p* (the coefficient of innovation, which is *a* in equation 2), *q* (the coefficient for imitation) and *m* (the total potential). The mixed influence Bass model can therefore be expressed as follows, where $\frac{q}{m}$ represents the endogenously determined diffusion rate (which is *b* in equation 1)

$$\frac{\partial N}{\partial t} = [p + \frac{q}{m}(N(t)][m - N(t)] \tag{3}$$

According to Mahajan and Peterson (1985), diffusion models can be characterised into the following

1) ***Fundamental diffusion models,*** which consider diffusion to be a binary process. The parameters in the Bass model are assumed to be static over time.
2) ***Flexible diffusion models***, which impose similar constraints to the Fundamental model case, however with some flexibility to the turning point of the model (where the rate of diffusion is at its maximum)
3) ***Dynamic diffusion models***, where the total potential and rate of diffusion evolves over time
4) ***Multistage diffusion models,*** where the binary constraint in the Fundamental model is relaxed
5) Diffusion models with forces which recognise diffusion is not only a function of time, but also technology specific parameters.

These models highlight the importance of empirical research in understanding the diffusion process. Mahajan and Petersen (1985) discuss how these models can be applied when making decisions on the timing of launching a new product in to the market, or to facilitate an understanding on the volatility in an innovation's economic performance from a pricing or marketing perspective. While these models have used extensively in the analysis of consumer goods, its application in the RET context has been limited. Furthermore, it should come as no surprise that this underutilisation is magnified in developing countries, which explains why renewables have been slow to take off despite the abundance in RE resource availability in these regions. Summarising the applications of diffusion models, they 1) deepen our understanding on how effortlessly a technology trickles down in markets, 2) decompose a product's price structure as a diffusion variable, and 3) enable us to forecast market demand or returns.

3) Applying the diffusion model process to RETs

The previous section unpacked how diffusion models are formulated, as well as introducing its applications in the analysis of product and market development. Recent literature has attempted to use these models to explain why the development of renewable technologies has not been as rapid as we would've hoped. Rao and Kishore (2010) discuss four core issues which RETs experience.

Firstly, RETs are characterised by a relatively low load factor, particularly in wind and small scale hydro plants. This phenomenon essentially highlights the inefficiencies in the generation process of renewable energy plants compared to their fossil-fuel based counterparts. Secondly, developing RE storage systems can be a complex (and costly) process considering the fact that RE sources aren't available throughout a given day. Thirdly, RE plants typically have a smaller production capacity compared to fossil production plants, meaning that the major corporations which are best suited to develop these technologies are inclined to leave it to the rest of the market. Finally, the high initial capital outlays which RETs are characterised by makes them difficult to afford, particularly in the case of developing economies where power utilities face extreme financial constraints.

These challenges represent a significant stumbling block towards the development of RETs, which explains why recent policy efforts have been shifted towards how these barriers can be alleviated. This section explains the factors which drive the deployment of RETs with reference to case studies in European countries.

3.1) Learning Curves, Experience Curves and Economies of Scale

Learning and experience curves have proven to be a strong explanatory factor in the analysis of RET diffusion rates. The learning curve approach highlights the gains associated with a specific technology are a product of research and development, experimentation and implementation (Wright, 1936; Henderson, 1968). These curves decompose the productivity gains exhibited in a technology which arise from learning by doing.

Ibenholt (2002) investigated the application of wind energy in Germany, Denmark and the UK by using learning curves to estimate the relationship between costs and production. Through analysing the slope of these learning curves, this paper showed that the differences in wind based technologies across countries is primarily attributable to aerodynamics and policy attitudes.

An industry (or firm) which exhibits economies of scale can expect these impacts to shape the trajectory of their diffusion rates. Economic theory tells us that long run cost curves experience increasing returns to scale at low production levels, and these returns dissipate when production levels increase. Isoard and Soria (2001) investigated the impacts which learning and returns to scale have on decreasing the cost of capital in renewable markets, and both of these factors had a considerable impact on the deployment of wind and solar PV technologies. Furthermore, this research justifies the case for policy measures to exploit scalability in order to accelerate the spread of RETs.

The use of experience curves, a broader extension of the learning curves discussed above, also explains the behaviour relating to the deployment of RETs. Neij (1997) used experience curves to develop an index which estimates the relative cost reduction associated with specific RETs in Sweden as production rises. This paper founds that despite the experience curves for smaller scale solar PV modules and wind turbines being progressive in nature (which signals the ability for an innovation to reduce costs), the diffusion of these technologies was largely contingent on the difference in efficiency rates relative to alternative technologies (such as fossil fuel infrastructure). Overall, this paper advocated for policy instruments to be used in order to drive the diffusion process further.

This raises the question as to how policy efforts can exploit these learning and scalability factors to influence the rate of diffusion within their economies. Jacobsen and Johnson (2000) highlighted how public schemes can facilitate the establishment of large firms or a convolution of smaller ones, known as “prime movers” to spearhead the diffusion process. Prime movers can use their sheer presence to pool capital and skills which are required to improve the product development and market analysis components of an innovation, which are widely regarded as the two focal channels needed to accelerate diffusion rates.

3.2) The viability of specific RETs when comparing alternative technologies

A study conducted by Del Rio and Unruh (2007) investigated the diffusion of solar and wind systems in Spain by applying evolutionary economic theories, and concluded that economic and institutional aspects were central towards influencing diffusion rates. Through building an evolutionary framework which accounts for institutional and economic factors, the paper found that solar technologies diffused at a higher rate relative to wind technologies despite the relatively equal total production potential between the two. Crucially, these findings explain that the dominance of solar PV generated energy in Spain within the renewables context can be attributed to 1) a higher lock in effect and 2) a higher availability of funding models compared to other renewable technologies.

4) The barriers to the diffusion of RETs

There are a considerable amount of barriers which restrict the dispersion to RETs in energy markets. Seminal papers such as Zhao *et al* (2016), Kemp *et al* (1998), Tsoutsos and Stamboulis (2005), and a recent paper by Seetharman *et al* (2019) identify barriers which inhibit the success of RET diffusion, however a limited proportion of the literature has pooled these barriers together to examine the implications these barriers have on RE markets collectively. To this end, this section provides a detailed discussion of these factors which should be of particular interest to policymakers looking to accelerate the development of RE in their economies.

4.1) Technological factors

A critical barrier which limits the deployment of RETs arises when these technologies are incompatible with incumbent systems. Due to the complexity in the designs of these technologies, they are required to be embedded to complimentary systems such as centralised transmission grids or energy storage units. As these complimentary components were initially designed for fossil fuel energy generation, it should be of no surprise that they're often outdated (this phenomenon can be seen when examining parts of the transmission grid in South Africa, which was designed in the late 80's and early 90's). These issues are exacerbated by the fact that complimentary systems are often in short supply (particularly in remote areas where there are no transmission lines) or extremely costly to employ. Since the introduction of RETs, integrating them into the existing grid networks has been identified as one of the biggest challenges faced in China (Zhao et al, 2016)

Research and development (R&D) efforts in RE markets have not received the attention they've needed to accelerate the transition towards an environmentally friendly future. Given the perceived investment and operational risks associated with these technologies, both the public and private sectors have sometimes been reluctant to fund these R&D efforts (Cho *et al*, 2013). The complexities highlighted in the previous paragraph raise concerns on the reliability and performance of RET system when factoring in how storage solutions are required to compensate the grid when an RE source is unavailable during a given day. With that being said, this issue has been mitigated to some degree in recent years given the emergence of hybrid powered renewable energy systems which employ a combination of energy sources to offset production when a specific energy source is unavailable.

4.2) Regulatory Factors

The stance of public policies has understandably had a major effect on the trajectory of technology diffusion rates. Despite the fact that governments may be committed to certain environmental targets, they often do not communicate the importance of these new technologies to the market effectively. A lack of communication from public bodies has exacerbated the uncertainty of the renewable energy market's future. Coupled with bureaucratic complexities such as lengthy delays in approving project plans, weak coordination between government agencies, and higher costs associated with lobbying officials to pilot these projects, it should be of no surprise that regulatory factors have limited the deployment of RETs considerably. Tsoutsos and Stamboulis (2005) also found that governments can be reluctant to be risk averse in financing energy projects if a change in behaviour is in direct contravention with their personal interests.

4.3) Economic Factors – Demand and Supply Side

Economic factors which impact the demand of RETs, such as consumer preferences, risk aversion and willingness to pay provide further rationale behind stagnant diffusion rates (Kemp *et al*, 1998). The asymmetric nature of information as well as a lack of a track record results in consumers often being unsure on how to value a new technology when it enters the market. Consumers sometimes lack the knowledge on the future trajectory of lower costs and a lower probability of externalities associated with RETs. This issue is particularly prevalent in developing economies, where the cost of obtaining information is high.

Tsoutsos and Stamboulis (2005) relate the willingness to pay concept to RETs by examining how consumers are unwilling to pay a higher price for RETs given that the benefits of a lower carbon footprint from renewable energy can't always be observed directly and consumers perceive generation from RETs to be less stable compared to fossil fuel technologies. From an investment perspective, fossil fuel technologies have a higher probability of being funded because they exhibit both higher returns to scale as well as a lengthier learning curve (Negro *et al*, 2012)

The points highlighted above raise questions surrounding the reasons behind somewhat of a reluctance towards investing in RETs. Ward's (1967) widely applied theory known as the sailing ship effect is a phenomenon which arises when a new technology is introduced into a market and results in the acceleration of the growth in an existing technology in the process (which could be fossil fuel technologies in this paper's case). Naturally, one would expect the sailing ship effect to discourage any further investment in the new technology if the incumbent technology develops automatically. Therefore, these issues together with high initial investment requirements and a lack of funding models (such as sale and leaseback options, crowdfunded models or climate bonds) explain much of the investment issues associated with these technologies, particularly in developing economies.

5) Conclusion

Diffusion models have proven to a be a useful aid when analysing the development of technologies. Despite the complexities associated with the diffusion process, the Bass model discussed in section 2 of this paper has allowed researchers to estimate parameters describe the magnitude as to how successfully these RETs disseminate across markets. Overall, this paper explained how learning by doing, economies of scale and the availability of funding models have shaped the deployment of these technologies by referring specifically to solar PV and wind case studies in Denmark, Sweden, the Netherlands and Spain. Seminal research in this field has broken down the drivers of RET diffusion rates into three subsets; namely institutional, economic and technical factors.

The widespread adoption of RETs has proven to remain elusive, however this does not imply that these technologies are inferior to their fossil fuel counterparts. The barriers which RETs experience highlight the importance of policy efforts to create an environment which facilitates the sustainable diffusion of RETs. These policy efforts should be targeted on both the supply side (through increased subsidies, introducing a wider range of funding models, and the unbundling of energy tariffs), as well as the demand side (by addressing the consumer asymmetric information problem in RE markets, and discovering ways to reduce the cost of RETs continuously).

Given the potential of renewable energy and the limited knowledge we have on the drivers of RETs in developing economies, this advances the case for diffusion models to be applied in developing economy analyses in the future. To add to this, previous literature has paid little attention to the reasons why countries emulate each other's renewable energy policies, which could explain the similarities or differences in diffusion rates between them (Baldwin et al, 2019). Conclusively, incorporating these two factors in the future can be a valuable contribution to research in this field. Furthermore, using the methodology mapped out in section 2 and applying it to dynamic empirical simulations (similar to Kumar and Agarwala (2016)) can also deepen our understanding on the magnitude of investment risks as well as diffusion rates in RET models.

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