Financing Renewable Energy through Household Adoption of Green Electricity Tariffs: A Diffusion Model of an Induced Environmental Market

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Abstract: Green electricity tariffs are a means by which 'green consumers' can contribute to investment in renewable energy. In order to conceptualize factors constraining the adoption of green electricity tariffs this paper develops a model that links the willingness-to-pay (WTP) literature with the established innovation diffusion literature. This concern arises from a need to reconcile the large disparities that have been empirically observed between the proportion of households actually adopting green electricity tariffs and the proportion in WTP surveys that claim they would (Stated-Willingness-to-Adopt or SWA). Using the Bass Model as the point of departure our model depicts how increasing consumer environmental concern, driven by word-of-mouth and mass media communication channels, results in an increasing proportion of households with a SWA. The presence of response bias and the free rider problem result in 'feasible adoption' being below the SWA. Feasible adoption

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Introduction

For over a decade now the EU has sought to liberalise the electricity sector so as to ensure more efficient allocation of resources via competitive forces (Newbery 2002). A component of this process has been retail electricity liberalisation as encapsulated in Directives 2003/54/EC which explicitly mandated that all European retail consumers should have the ability to choose between competing electricity suppliers. The liberalisation of the electricity has coincided with mounting concerns about global warming which has lead to the establishment of the European Emissions Trading Scheme (EU ETS) as the principal means of meeting Europe's CO2 reduction commitment under the Kyoto Protocol (Eichner and Pethig 2009).

Energy sector liberalisation and mounting concern for the environment have precipitated the emergence of another means of achieving CO2 reductions by incentivising the deployment of renewables: green electricity tariffs. Accordingly, green electricity tariffs are product innovations whereby the electricity supply company guarantees that the quantity of electricity delivered to the end consumer is match by an equivalent amount of renewable energy generation. The tariffs thus provide additional investment incentives for the deployment of renewable energy sources (RES). A critical component in the development of these markets has been the use of willingness-to-pay (WTP) surveys to measure market potential or latent demand for green tariffs. However, a growing body of empirical and policy focused research has found that this apparent latent demand has not, on the whole, materialized into households actually adopting these tariffs (Diaz-Rainey and Ashton 2008, Salmela and Varho 2006, Wiser 2003).

The reasons originally advanced to explain these divergences relate to the free rider problem and to biases in WTP estimates (in particular upward response bias) (Diaz-Rainey and Ashton 2008, Wiser 2003, Wiser and Pickle 1997). More recently, additional explanations have been mooted in a policy literature that has identified contextual problems in individual markets or market imperfections common in many markets (Diaz-Rainey and Ashton 2008, Salmela and Varho 2006, Wiser 2003, Boardman et al. 2006, Ozaki 2009). In the latter case, an often cited market imperfection is a lack of trust in product offerings due to insufficient transparency, with non-government organizations often stepping in to try to alleviate these problems by providing accreditation and labeling schemes (Rohracher 2009).

In order to conceptualize the various factors constraining the adoption of green electricity tariffs, this paper develops a model that links the WTP literature with the established innovation diffusion literature. As already intimated, this concern arises from a need to reconcile the large disparities that have been empirically observed between the proportion of households actually adopting green electricity tariffs and the proportion in WTP surveys that claim they would (To avoid confusion we call this proportion of households Stated-Willingness-to-Adopt or SWA)[1]. Using an epidemic diffusion framework our model depicts how increasing consumer environmental concern, driven by word-of-mouth and mass media communication channels, results in an increasing proportion of households with a SWA. The presence of response bias and the free rider problem result in 'feasible adoption' being below the SWA. Feasible adoption is, in turn, differentiated from actual adoption by the extent of market imperfections, such as the supply side problems and regulatory failures often discussed in the empirical literature.

The distinctions between SWA, feasible adoption and actual adoption, should help policymakers conceptualize the difficulties experienced in green energy markets, thereby making it easier for them to assess the role that these markets can play in incentivizing additional RES investments over time. The rest of the paper develops the 'Diffusion Model of an Induced Environmental Market' in the following way. Immediately following (Section 2), is a brief introduction to the WTP and innovation diffusion literatures that provide the grounding for the model. Section 3 provides a summary of the empirical research on green energy markets that have explored the divergence between SWA and actual adoption. Section 4 discusses the merits and demerits of using WTP/SWA estimates to measure market potential in green energy markets. Section 5 presents the model itself, while Section 6 provides some concluding remarks.

[1] SWA measures the proportion of consumers that have a WTP>g, where g is the lowest available premium for green electricity, which, for the sake of simplicity, we assume to be zero. The assumption is, therefore, that for now there is a marginal green tariff g which satisfies g=0 but the model is flexible enough to accommodate for any g (see Footnote 5 for further discussion). Though clearly SWA and WTP are closely related, the dichotomy allows for the possibility that the dollar or price premium estimate of WTP may be correct but market imperfections or free rider concerns are preventing the actual adoption of the tariff (SWA) at the given WTP. Thus, our model is concerned with why WTP estimates do not materialise into equivalent proportions of green tariff adoption, once we take into account the lowest cost tariff. Accordingly we do not necessarily question the accuracy of WTP estimates. The model presented here incorporates a WTP upward bias measure; however, this could be set to zero (See also Section 5.2. and Footnote 8).

2. Theoretical Framework

2.1. The WTP literature

Mirroring government attempts to tackle environmental decay, the last three decades have witnessed the emergence of a substantial body of work that can best be described as the willingness-to-pay (WTP) literature. Recent contributions range from efforts to understand the WTP for micro-generation technologies amongst households (Scarpa and Willis 2010) to attempts to ascertain the WTP for environmental improvements in hydropower regulated rivers (Kataria 2009). Contributions have emanated principally from environmental economics and environmental management (including the consumer psychology end of marketing) though a sizable literature has evolved in health and healthcare related research where applications include exploring the WTP for mortality risk reductions (Lui and Neilson 2006, Olsen and Smith 2001). The literature has used survey methods to explore two 'non-market' concerns, namely, (1) valuing externalities and (2) measuring the 'pre-market' or 'future market' potential of induced environmental markets.

The latter is the least cited application and relates to markets that do not yet exist or are nascent but which policymakers believe offer potential to internalize externalities and/or reap the benefits of green consumerism. In the former case the valuations obtained are used for a variety of purposes. They can be used to determine the reparation costs polluters will need to pay for their transgressions or they are used in cost-benefit analyses so that, for example, governments can decide how much support to give to 'non-polluting' renewable technologies such as wind energy. Since financial and policy decisions rest on the use of WTP estimates, it is critical that these valuations are valid and reliable (Carson et al. 2001, Diamond and Hausman 1994).

A lively debate concerning the validity and reliability of WTP estimates has surrounded the development of the literature. The debate is involved and has dragged on for well over a decade (Carson *et al.* 2001, Portney 1994, Spash 2008). On the one hand, critics argue that WTP estimates are limited by, *inter alia*, the presence of upward response bias and 'embedding effects' that raise issues of reliability and validity (Diamond and Hausman 1994). On the other hand, advocates argue that careful study design and implementation and the use of a contingent valuation (CV) approach can overcome these problems (Carson et al. 2001). CV has become the preferred survey-based method of carrying out WTP surveys. Such has been the importance of non-market valuation on issues like pollution control that US's National Oceanic and Atmospheric Administration commissioned a panel headed by eminent economists to explore the controversies surrounding contingent valuation (Arrow et al. 1993). The panel concluded that CV surveys can provide estimates reliable enough to be of some use when considering non-market valuation. However, on the issue of validity, they cautioned that:

> *"The Panel is persuaded that hypothetical markets tend to overstate willingness to pay for private as well as public goods.... No automatic or mechanical calibration of responses seems to be possible. The judicial process must in each case come to a conclusion about the degree to which respondents have been induced to consider alternative uses of funds and take the proposed payment vehicle seriously.*" (Arrow et al. 1993, p.44)

The existing empirical evidence on green energy markets points to a large and persistent divergence between actual adoption rates and the proportion of consumers with a positive WTP (SWA). Thus, the nature of the subject would understandably seem to lead to upward response bias, whether such bias can be corrected for by current advances in CV methodology is no doubt open to ongoing debate (Spash 2008). Either way the 'Diffusion Model of an Induced Environmental Market' presented here can be adapted for alternative views in this debate and as such is principally concerned with the other reasons, such as the free rider problem, market imperfection and supply constraints that may lead to differences between WTP and actual adoption of green electricity tariffs.

2.2. Innovation diffusion literature

Diffusion research has developed over the past few decades as a specialist but well established field of research in marketing and economics (Geroski 2000, Lissoni and Metcalfe 1994, Rogers 1995). In the marketing tradition, epidemic models are emphasized, while in economics diffusion tradition, probit or hurdle rate models have become increasingly popular (Geroski 2000, Lissoni and Metcalfe 1994). The reason for these different approaches is that epidemic models recognise the important role information channels play in the process of diffusion where individuals are the unit of analysis. By way of contrast economists have found that probit/hurdle-rate models are better suited to ascertain the various determinants, including the profitability of the innovation, at the firm level (Davies 1979, Kemp 1997, Lissoni and Metcalfe 1994).[2]

Rogers (1995) observes that the rapid expansion of diffusion research in marketing in the 1970s is largely attributable to applicability of the Bass (1969) model of innovation diffusion to new product development. This model is an epidemic model of diffusion that emphasizes communication channels as the key factor in the 'S' shaped diffusion process. In the model, diffusion is the result of two types of communication processes; namely, the mass media and interpersonal word-of-mouth communication channels. The mass media communication channels play a large role in persuading earlier adopters (innovators) to adopt, while word-of-mouth begins to dominate adoption decision of those that follow (imitators). Since the concern in this paper is with developing a model of an induced environmental market for consumers the Bass model will be used as the point of departure in linking the diffusion and WTP literatures.

3. Empirical context: Green energy markets

The emergence of modern environmentalism has been accompanied by a desire to reap commercial benefits from individuals' growing concern for the environment. This has resulted in a dramatic growth in green consumerism. Ottman (1993, cited in Zarnikau 2003), provided valuable insights into the demographic characteristics of green consumers; namely, that they are educated, affluent and under 55 years of age. The desire to further harvest green consumerism has seen a dramatic growth in the contributions to the WTP literature to assess market potential of, *inter alia*, green energy markets.

The willingness of consumers to pay for green energy has been examined in numerous countries including Finland, USA, Canada, Germany and the UK. WTP

[2] Several recent studies, including Chatterjee and Eliashberg (1990), Horsky (1990), and Song and Chintagunta (2003), model the diffusion at the individual level within the porbit tradition by linking consumer utility factors to aggregate diffusion patterns. The purpose of our model is very different. Our aim is to present a model that reconciles the WTP and diffusion literatures and suggests ways to incorporate certain factors such as upward response bias, free rider effects and supply chain problems so as to explain the discrepancy between SWA and actual adoption. Accordingly, our focus is on how different communication channels impact these factors, meaning that a traditional epidemic approach that abstracts from issues of heterogeneity in consumer preferences ensures that analytical focus is not obscured and that the model does not become unduly complex.

surveys have implied that there is considerable consumer demand for innovative green energy products (SWA). These surveys have therefore played a major role in justifying the development of markets for green electricity tariffs (Farhar and Houston 1996, Fouquet 1998). Research on green energy markets has focused on two broad issues. First, the research has been concerned with measuring consumers' willingness to pay a premium for green energy both in an absolute sense (WTP) and as a proportion of the population (SWA). Second, the more policy focused literature has sought to explain the large differences between SWA and actual take-up of green electricity tariffs. As will be apparent in the following discussion, the former has tended to find high SWA for green energy (Section 3.1.), while the latter has observed a large divergence between SWA and actual adoption of green electricity tariffs (Section 3.2.) with a number of reasons being mooted for this large divergence (Section 3.3.).

[INSERT FIGURE 1 ABOUT HERE]

3.1. Stated-Willingness-to-Adopt (SWA) green energy

US surveys of WTP for green energy have found that between 40% to 70% of respondents are willing to pay a premium for green energy (Farhar 1996, Fouquet 1998). High SWA rates are also apparent in the European research. Figure 1 shows a broadly equivalent situation in Europe with most countries reporting a SWA of between 30 and 60%. The average EU-15 SWA was 38% in 2002 (EU Commission 2002). Worryingly, two of the pioneers of green tariffs, the Netherlands and Sweden, have seen large declines in SWA between 2002 and 2009, hinting at consumer dissatisfaction based on product experience.

[INSERT FIGURE 2 ABOUT HERE]

Over the years there have been various attempts to measure WTP for green energy in the UK context. This allows for an understanding of how SWA has evolved over time. These estimates are plotted and compared to electricity prices in Figure 2.

As the first UK green tariffs were introduced in 1997 (Boardman 2006) it is apparent that differences over time in SWA may be linked to familiarity with the concept of green tariffs. The jump in SWA between 1996 and 1997 may also be explained by the Kyoto Protocol of 1997 and the international attention it received. The protocol marked the beginning of a period of increased media and public interest in climate change that has continued for well over a decade. Though survey design is likely to account for some of the differences in terms of reported SWA, there does appear to be a clear upward trend until 2005.[3] The link between ecological concern and WTP has been confirmed in the empirical literature on green energy (Diaz-Rainey and Ashton 2010; Rowlands et al. 2003). Ecological concern is defined as

> *"general environmental attitude and [individual's] perception of the necessity for societal change commensurate with the concept of sustainable development"* (Scott 1999 cited in Rowlands et al. 2003, p.39)

The notion that consumers' valuation of green tariffs is dynamic is consistent with finance theory where asset prices repeatedly adapt to news flow and tend to trend based on fundamentals. In this case the fundamental driving valuation is ecological concern; however, this may be offset by rising energy prices and/or lowered incomes. The former, rising energy prices, may explain the fall in SWA from 2006 onwards since UK retail energy prices rose dramatically between 2006 and 2008. Indeed, in Akcura (2008, p.25) 60% of respondents that claimed not to be willing to pay for green energy gave the reason that energy prices had gone up too much already in the past few years.

3.2. Adoption estimates

Despite this high level of customer intent, the actual take-up of green electricity tariffs is relatively low in most countries where the choice exists. In the US average rates estimated to be at or below 2% (Wiser 2003, Wiser and Pickle 1997, Zarnikau 2003, Bird et al. 2002), though some of the best performing regional programs have

[3] Survey design differences plus missing years and the need to control for factors such as income mean that a formal empirical analysis of the patterns and determinants of SWA depicted in Figure 2 was not undertaken. It is possible to derive unbiased standard errors in a regression framework by using bootstrap simulations, however with so few observations the coefficients would be vulnerable to volatility jumps. These data limitations highlight the need for panel data or representative repeated cross sectional surveys (such as the European Social Survey) on these matters.

achieved penetration rates of between 5% and 17% (Bird et al. 2007, p.6). In Europe only modest levels of green electricity tariff adoption by consumers have been observed, with the Netherlands providing a notable exception. Markard and Truffer (2006) find that up to 2001 only the Netherlands had reached a level of retail customer adoption that exceeded 1.5%.

UK estimates for the take-up of green tariffs have seen a rising trend but are still far below the UK SWA estimates discussed earlier. For instance, Bird *et al*. (2002, p.531) indicated approximately 0.2% of households in 2001 had taken up a green electricity tariff, Graham (2006, p.2) estimated that this had grown to just under 1% of households by 2006, while Diaz-Rainey and Ashton (2008) estimated that adoption reached 1.5% by 2007. The low penetration levels achieved in the UK contrast markedly to those in the Netherlands. For instance, within the Netherlands, take-up of green electricity tariffs in 2001 was approximately 11%, a figure that rose to 26% in 2003 (Markard and Truffer 2006). The increased take-up of green electricity tariffs in the Netherlands was attributed to (1) tax exemptions that made green electricity of broadly equivalent cost when compared to conventional tariffs and (2) heavy advertising by utilities (Bird et al. 2002). Post 2003 the tax breaks that so incentivized green energy tariff adoption in the Netherlands were removed as they had resulted in energy retailers importing renewable energy rather than incentivizing increased domestic generation (Van Rooijen and Van Wees 2006). Further, reports that more green energy was being accredited than produced led to a loss of consumer confidence in the market and it is this that is likely to explain the dramatic fall in SWA between 2002 and 2009 in the Netherlands (See Figure 1).

3.3. Explaining the divergence between SWA and actual adoption

A range of explanations for this large divergence between stated and actual behavior has been forwarded. The most often cited reasons have been the free rider problem and upward bias in WTP surveys (Diaz-Rainey and Ashton 2008, Wiser 2003, Wiser and Pickle 1997). A broader range of explanations have been mooted in recent years as researchers have examined the peculiarities of individual markets, including:

- **Lack of knowledge as to green power availability:** Mentioned in the context of Finland, UK and the US markets (Salmela and Vahro 2006, Wiser 2003, Ipsos MORI 2008)
- **Hesitancy in switching electricity supplier and high search costs:** Again in the context of Finland, UK and the US (Diaz-Rainey and Ashton 2008, Salmela and Vahro 2006, Wiser 2003, Osaki 2009)
- **Distrust of energy product suppliers and their motives for introducing green energy tariffs:** Evident in Finland, the UK and the US (Diaz-Rainey and Ashton 2008, Salmela and Vahro 2006, Wiser 2003, Boardman 2006)
- **Consumer confusion due to a complex regulatory structure and the absence of effective green energy guidelines for green power retailers:** Mentioned in the UK literature on numerous occasions and relates to the complex interaction between green tariffs and the supply side incentive system for renewables, the Renewable Obligation (Diaz-Rainey and Ashton 2008, Boardman 2006, Graham 2006)
- **A lack of renewables supply:** This has been mentioned in the UK context and has lead energy utilities to innovate in terms of their product offering. This has meant that green tariff offerings have been developed that make some form of environmental commitment but that do not derive their energy from renewables, thus adding to customer confusion (Diaz-Rainey and Ashton 2008)
- **Failure to meet customer expectations:** In the UK, public opinion clearly associates green tariff with electricity from renewables, yet many product offerings do not meet this expectation, this has not only caused confusion but it has also put consumers off taking up existing offerings (Diaz-Rainey and Ashton 2008, Osaki 2009, Ipsos MORI 2008).

4. Market potential and pre-market valuation

When exploring the potential of green energy tariffs and the characteristics of potential green energy consumers in Ontario, Rowlands et al. (2003, p.39) noted that

> *"Ideally, we would have investigated actual consumer behavior. However, given the only recent introduction of green electricity, few opportunities exist to study this phenomenon".*

Even in countries where green tariffs have existed for some time, the low levels of adoption that are evident in most countries mean that studies of actual adopters would need to have extremely large samples or would need to overcome confidentiality issues and the reluctance of utility companies to release details of their green consumers. These challenges are not insurmountable since two recent studies have explored actual adopters in the US (Kotchen and Moore 2007) and the Netherlands (Arkesteijn and Oerlemans 2007).

In both studies, customer contact information was obtained from utility companies. In Kotchen and Moore (2007) customer information was obtained from two green power programs in Michigan, a state where competition has not been introduced at the retail level (Bird et al. 2007). Hence, the companies involved could not have been concerned that the results of the study would facilitate a competitor. In the Netherlands, there has been retail competition since 2001; however, most customers that have switched to a green tariff have done so with their incumbent utility supplier (Bird et al. 2002, Markard and Truffer 2006).

More fundamentally, however, where adoption is low, as is the case in most countries that have liberalized their retail electricity markets, exploring actual adopters has the problem that it reveals nothing about market potential. The alternative to investigating actual adopters is to use a WTP/SWA approach. This approach also has limitations; not least the potential for upward response bias and the free rider problem discussed earlier. As will become apparent in the depiction of the Diffusion Model of an Induced Environmental Market (Section 5), exploring both actual adopters and WTA prove to be complementary to understanding the adopter environment and, hence, being able to make more accurate assessments of the role that green tariffs can play in funding new RES generating capacity.

5. The Model

In this section the 'Diffusion Model of an Induced Environmental Market' is developed in an attempt to link the WTP and innovation diffusion literatures introduced in Section 2. The aim of the model is to provide a framework with which to conceptualize the large differences between actual take-up of green tariffs and the SWA reported in surveys (Section 3). Our model is based on Bass (1969) and extends this model in two ways[4]. First, it accounts for the upward response bias and the free rider problem discussed in Section 3.3. Second it accounts for various other 'market imperfections' such as supply side problems or customer confusion (also discussed in section 3.3) by introducing a variable which represents those imperfections.

5.1 Assumptions of the model and Stated-Willingness-to-Adopt

The model starts from the assertion that WTP/SWA estimates offer some information as to the potential of green energy markets (see Section 4). Further, consistent with empirical findings, it is asserted that the increasing individual concern for the environment ('environmental or ecological concern') leads to a gradual increase in the number of individuals reporting a positive WTP (i.e. resulting in a rising SWA) (See Section 3.1.). Environmental or ecological concern can itself be seen as a function of numerous social and psychological factors driven by the spread of information about the environment and climate change. Other assumptions implicit in the model are that energy prices are constant (See discussion in Section 3.1.) and that tariffs exist for those that are only willing to pay a very small premium over conventional tariffs.[5]

Further, the model, following Bass (1969), assumes that adoption is influenced by two types of communication channels that disperse information related to ecological concern; mass media, we call this type of influence m, and interpersonal word-of-mouth communication, we call this type of influence w. We assume that both m and w are aggregate influences so that for example it is not information on the news today that affects m but rather a total effect of what has been on the news over a period of time. We define the probability of an initial

[4] For a review of literature extending the Bass (1969) model of diffusion see Mahajan, Muller and Bass (1990) and Georski (2000).

[5] As noted earlier (Footnote 1), the tariff on offer with the lowest available premium will determine to what extent SWA could be satisfied. This will in turn be context specific. The model is, however, flexible enough to allow for this. Thus a WTP>20% could be modeled versus actual adoption if the cheapest green tariff was 20% more expensive than the cheapest conventional tariff. The assumption is that for now there is a marginal green tariff that can satisfy WTP>0. This is not as strong an assumption as it may first seem. Diaz-Rainey and Ashton (2008) show that UK consumers would, on average, have to pay a premium of 2.1% for a green tariff, yet less than 1.5% of the population had adopted these tariffs despite the fact that survey evidence pointed to 42% of the population being willing to pay a premium of between 5% and 10%.

purchase been made at time t given that no purchase has been made up to t as $p(t) = m + \frac{w}{N}Y(t)$ so that this probability is equal to a constant $p(0) = m$ at time $t = 0$ (this is the probability of a purchase at time $t = 0$ when there is no word-of-mouth effect and all purchases are due to the influence of the mass media)[6] plus an additional term $\frac{w}{N}Y(t)$ which captures adoption due to the influence of word-of-mouth as the number of previous buyers increases[7]. In the term $\frac{w}{N}Y(t)$, $Y(t)$ is the number of buyers up to time t and N is the population of potential buyers.

At this stage we define the population of potential buyers as $N = N_0 v_0$, where N_0 is the country population and v_0 represents the fraction of consumers who are potential adopters. It will be the case that not all consumers can be adopters due to a number of factors which include low income (therefore they cannot afford the premium) and low or no endowed environmental motivation (their natural concern for the environment is so low they will never voluntarily adopt or state they will pay a premium price for green energy). As a result only some consumers will be prepared to state a willingness to pay for green energy represented by a percentage price premium (WTP_i). Whether $WTP_i > 0$ or $WTP_i = 0$ will determine if a consumer will be included in the fraction of the population which can be adopters of green energy. We assume that v_0 represents the fraction of citizens who have stated-willingness-to-adopt (SWA or in other words who's $WTP_i > 0$).

Let $f(t)$ be the likelihood of a purchase at time t with $F(t) = \int_0^t f(x)dx$ and $F(0) = 0$ so that the likelihood of a purchase at time t given that no purchase has been made yet is

[6] Note that since this is an induced market, adoption is not possible until government provides the legal and regulatory framework for the creation of the market. In energy markets this has meant liberalization of retail energy provision and de-regulation of tariffs. For simplicity in notation and exposition, we consider that for our model time $t=0$ is when the legal and regulatory framework is provided so as to induce the market.

[7] Alternatively we can say that w is a parameter which is influenced by both mass media and word-of-mouth so that the mass media influences initial purchases as well as later purchases. This is consistent with assuming that the coefficient of imitation in Bass (1969) is influenced by both mass media and word-of-mouth communication channels.

$$p(t) = \frac{f(t)}{1 - F(t)} = m + \frac{w}{N} Y(t) = m + wF(t) \tag{1}$$

with $Y(t) = NF(t) = N\int_0^t f(x)dx$ being the total number of buyers up to time t and $Nf(t)$ being the number of purchases at time t. This number of purchases at time t is given by

$$Nf(t) = N[1 - F(t)]p(t) = \left[m + w\frac{\int_0^t S(x)dx}{N} \right]\left[N - \int_0^t S(x)dx \right] \tag{2}$$

which can be written as

$$Nf(t) = mN + (w - m)Y(t) - \frac{w}{N}[Y(t)]^2 \tag{3}$$

From the total number of purchases we can solve for the likelihood of a purchase at time t as

$$f(t) = m + (w - m)\frac{Y(t)}{N} - \frac{w}{N^2}[Y(t)]^2 = m + (w - m)F(t) - w[F(t)]^2 \tag{4}$$

which together with $\frac{dF(t)}{dt} = f(t)$ yields the differential equation for $F(t)$

$$\frac{dF(t)}{dt} = m + (w - m)F(t) - w[F(t)]^2 \tag{5}$$

Together with the initial condition $F(0) = 0$ the differential equation, as in Bass (1969), has a solution

$$F(t) = \frac{1 - e^{-(m+w)t}}{\frac{w}{m}e^{-(m+w)t} + 1} \tag{6}$$

From this we get

$$f(t)=\frac{(m+w)^2}{m}\frac{e^{-(m+w)t}}{\left[\frac{w}{m}e^{-(m+w)t}+1\right]^2} \tag{7}$$

As a result the number of buyers up to time t is

$$SWA(t)=Y(t)=NF(t)=N\frac{1-e^{-(m+w)t}}{\frac{w}{m}e^{-(m+w)t}+1} \tag{8}$$

From equation 8 the initial premise of the model is that SWA is a perfect predictor of adoption and that adoption is, in turn, driven by the dispersal of heightened ecological concerns through mass media and word-of-mouth communication channels. This process results in a typical S-shaped diffusion trajectory.

5.2 Achievable adoption

However, as discussed in Section 3, SWA is always much higher than actual adoption, with the difference often attributed to upward response bias in the WTP surveys and the free rider problem. Accordingly, with the aim to capture the upward response bias effect, we introduce the variable u which we subtract from WTP_i, the stated percentage price premium individuals are willing to pay.[8] As a result the actual price premium that the consumer is willing to pay is WTP_i-u. So the actual fraction of consumers who are potential adopters (those for whom $WTP_i-u>0$), which we call v, will be smaller than v_0, which makes our population of potential buyers[9] equal to $\hat{N}=N_0v<N$. Also, to account for the free rider problem we introduce an additional effect on the population which we call the incentive to free ride. We capture this effect by introducing the variable $0<r\leq 1$. We assume that, because of

[8] The model assumes that a single reliable WTP CV methodology is used. The model is flexible enough, however, to accommodate to differing opinion about the validity of WTP estimates as represented by different values of u (upward response bias), including, as noted in Footnote 1 setting u =0. u is introduced as a percentage and is assumed to be constant over time (since energy prices are assume to be constant).

[9] Horsky (1990) uses a similar modeling approach to account for the fact that there may be part of the population which will never adopt an innovation. According to Horsky (1990, pp. 348-349) "[t]here are numerous reasons as to why a fraction […] of the population will never buy. For example, air conditioners may not be necessary in northern states and apartment dwellers may have space constraints which preclude buying a freezer." Our population is scaled down for very different reasons than those discussed in Horsky.

the incentive to free ride, the probability of an initial purchase been made at time t given that no purchase has been made up to that time is $p'(t) = m + \frac{rw}{N} Y(t)$. Effectively what this says is that due to the incentive to free ride only the fraction r of potential adopters that would adopt the innovation due to the word of mouth effect will adopt the innovation[10]. The rest $1-r$ will not adopt due to the incentive to free ride (so to be precise, the incentive to free ride is captured by $1-r$)[11]. We assume that the upward response bias effect is constant over time while our assumptions imply that the free rider problem effect reduces over time, as the number of adopters increases, and ultimately disappears as network and reciprocity effects gradually dilute individuals' concerns about free riding by others. Substituting $p'(t)$ into equation (2) above and subsequent equations (3) and (4) we get the differential for $F(t)$ such that

$$\frac{dF(t)}{dt} = m + (rw - m)F(t) - rw[F(t)]^2 \qquad (9)$$

which together with the initial condition $F(0) = 0$ has a solution

$$F(t) = \frac{1 - e^{-(m+rw)t}}{\frac{rw}{m} e^{-(m+rw)t} + 1} \qquad (10)$$

With

$$f(t) = \frac{(m + rw)^2}{m} \frac{e^{-(m+rw)t}}{\left[\frac{rw}{m} e^{-(m+rw)t} + 1\right]^2} \qquad (11)$$

[10] Delay of purchase is also discussed in Horskey (1990). According to Horskey, delay may happen because of unawareness of the existence of the innovation, uncertainty about its characteristics and hope that its price will go down. These factors, in Horskey (1990), affect the probability $p(t) = m + \frac{w}{N} Y(t)$ of adoption at time t ($P(t) = \alpha + \beta Q(t)$). Unlike our model, Horskey does not model how the probability of adoption differs from the original Bass (1969) model due to those factors.

[11] We chose to apply the free rider effect on word of mouth communication because the earliest adopters ('innovators'), given their personality traits (Rogers 1995), are more likely to have a clear preference for the innovation and thus are less likely to be concerned by the free riding of non-adopters.

As a result the number of buyers up to time t now becomes

$$K(t) = Y(t) = \hat{N}F(t) = \hat{N}\,\frac{1-e^{-(m+rw)t}}{\frac{rw}{m}e^{-(m+rw)t}+1} \qquad (12)$$

Comparing $K(t)$ with $SWA(t)$ we find that $K(t) < SWA(t)$ as $\hat{N} < N$ and as the free rider effect lowers the probability of adoption at time t and thus pushes diffusion down.

5.3 Actual adoption

Besides the upward response bias and the free rider problem, various 'market imperfections' have been identified as impediments to the adoption green electricity tariffs. These include consumer confusion, lack of supply or lack of consumer trust (See Section 3.3.). At this point we further extend our model to take account of one such market imperfection, namely supply side problems. By doing this we can incorporate differences in the market environments in different countries. We therefore assume that of the population of potential buyers only one constant fraction can have their demand satisfied[12] so that if the population potential is $\hat{N}$ then the actual population of buyers for the product is $\overline{N} = d\hat{N}$, where $d \in (0,1)$.[13] Substituting $\hat{N}$ with $\overline{N}$ and following the same calculations as above yields the same differential equation for $F(t)$ as in (9) which together with the initial condition $F(0) = 0$ has the same solution as in (10). As a result the number of buyers up to time t becomes

[12] Alternatively we could use Jain et al. (1991) and introduce a number of Waiting Applicants $D(t)$ who would like to consume the product but their demand cannot be met due to lack of supply. In this case $N(t) - D(t)$ would be the actual population of potential buyers. The merit of using our approach is that our differential equation characterizing the diffusion process has an explicit solution which is not the case in Jain et al. (1991). Other extensions of the Bass model to account for supply constraints were presented by Ho et al. (2002) and Kumar and Swaminathan (2003). Both studies focus on determining firms' optimal choice of sales plans, product launch time (or roll-out delay), and capacity with the aim to maximize profits over the product's lifetime. Our simple approach to supply constraints allows us to keep the model focused on explaining the observed discrepancies between stated willingness to adopt and actual adoption. Further, as observed in section 3.3. supply constrains are only one of many potential 'market imperfections' that the empirical literature has observed as constraining the adoption of green electricity tariffs. Our simple modeling approach allows us to account for this broad range of constraints.

[13] To account for different 'market imperfections', d can also reflect for example poor regulation or consumer confusion or mistrust.

$$A(t)=Y(t)=\overline{N}F(t)=d\hat{N}\,\frac{1-e^{-(m+rw)t}}{\frac{rw}{m}e^{-(m+rw)t}+1} \tag{13}$$

Comparing $A(t)$ with $K(t)$ and $SWA(t)$ we find that $A(t)<K(t)<SWA(t)$ as $\overline{N}<\hat{N}<N$ and as the free rider effect lowers the probability of adoption at time t.

The framework provided above links stated-willingness-to-adopt ($SWA(t)$), the concept of 'achievable adoption' ($K(t)$) and actual adoption ($A(t)$) with the aim to conceptualize the various factors (u, r and market imperfections as captured by d) that can explain differences between actual take-up and SWA. We can see how incorporating the different factors leads to different levels of adoption of the product and how actual adoption can be related to achievable adoption and SWA.

[INSERT FIGURE 3 ABOUT HERE]

A graphical representation of the model is depicted in Figure 3 using the examples of the green energy markets in the Netherlands and the UK (See Section 3). This depiction further assumes that the UK and the Netherlands have identical 'diffusion' trajectories for $K(t)$ and $SWA(t)$. This implies that both countries are culturally identical since u would have to be the same in both countries. This means that citizens of one country are no more likely to over-report their propensity to adopt green tariffs than those of the other country or indeed that citizens of both report equivalent SWA at any point in time.

It is apparent that both countries at time $t+n$ have not achieved their shared penetration ceiling (K_{t+n}); however, the UK underperformed relative to the Netherlands ($A_{t+n}^{NL} > A_{t+n}^{UK}$). The differences between K_{t+n} and A_{t+n}^{NL}, and between K_{t+n} and A_{t+n}^{UK} arise as a result of the type of market imperfection in the adopter environment, such as supply constraints, discussed earlier. If we take d as a composite effect of the market imperfections it is evident that market imperfections and supply constraints are more pronounced in the UK than the Netherlands. From Figure 3 it is clear UK market imperfections are large (a small d) and they have held back the development of the market. Interestingly, one of the assumptions that underlies the Bass (1969) model is that supply constraints do not limit diffusion (Rogers 1995, p.83). As discussed in Section 2.3, supply constraints have been seen as an impediment to the development of the green energy markets in the UK. Supply constrains became an issue also in the Netherlands, but only after a high level of tariff penetration was achieved.

6. Conclusions and Policy Implications

By linking the WTP literature with the established innovation diffusion literature this paper has provided a conceptual framework with which to understand the large disparities that have been observed between actual adoption of green electricity tariffs and stated-willingness-to-adopt (SWA). Further, and most important of all, the empirical context and the model highlight that $SWA(t)$ and, therefore, achievable adoption ($K(t)$) is not constant and is likely to change over time as ecological concern rises. This is consistent with the notion in finance that asset values constantly change and tend to trend based on fundamentals. Thus valuations are constantly changing in response to news flow. If this news flow is driving up valuations it implies an ever higher penetration ceiling. Indeed, the notion that penetration ceilings are not constant is recognized in the innovation diffusion literature (Griliches 1980, Kemp and Volpi 2008). This may highlight to policymakers that the potential of such markets may take time to reap and that the low penetration rates of today may reflect a conventional trajectory of a diffusion process.

Further, we acknowledge that empirically testing our model would be of even greater policy benefit. However, the model was itself inspired by the $SWA(t)$ versus $A(t)$ gap implied by the patchwork of data that currently exists on green energy markets (see Section 3.3.). As such the model was intentionally conceptual and a response to data problems. This still leaves the two questions; (1) whether the model could be empirically identified should the data limitation be overcome? and (2) how easily would it be to overcome these data limitations?

The answer to the first question would seem to be, yes not least since there are many approaches to testing the Bass model. In our model, $K(t)$ is the critical variable that will tell policymakers what role green tariffs can play in incentivising renewables deployment. $K(t)$ may, however, appear to be an abstraction not readily measurable yet it could be estimated if the other key variables are known or can be estimated with a reasonably high degree of confidence. $SWA(t)$, $A(t)$, r (see Wiser 2003) and perhaps more arguably u can be measured through panel surveys or high quality representative repeated cross-sectional surveys (such as the European Social Survey). Estimates of d could be composed via contextual analyses for the supply side constraints and surveys for the demand side (by eliciting consumer perceived barriers to adoption, see for instance Arkesteijn and Oerlemans 2007 and Ozaki 2009). Thus, in principle it would seem that empirical testing of the model is feasible[14]. This stakes us to the second question. Clearly no such dataset currently exists. The paucity of the data in this area was highlighted in Section 3 (see Figures 1, Figure 2 and Footnote 3 in particular). As noted above the dataset to test the model would have to be a panel survey or, more realistically, a highly representative repeat cross-sectional survey. Further, an international survey instrument would allow for especially rich analyses since international comparison based on cultural and policy differences could be made in a robust manner. For Europe, in this respect, there are three options (European Social Survey, World Values Survey, European Values Study) none of which currently run a module on energy or the environment. Yet this need not always be the case with, for instance, European Social Survey having open calls for new modules, thus providing an example of one opportunity where consortia of researchers can make applications to begin to tackle the numerous data gaps in this area (see also Diaz-Rainey and Ashton 2010).

Turning once more to the implications of the model, it is important to note that a critical assumption in the model is that energy prices are constant. This does not hold in practice. It is clear from the evidence presented in Section 3.1. that the relative price of energy is important and that, as in the UK, significant rises in energy prices are likely to be associated with a drop in SWA. This indicates that green tariffs may have counter-cyclicality to generators investment incentives. When energy prices are high, generators will be incentivized to invest in RES while consumers will be put off contributing to RES investment via green tariffs. The opposite is true; a low price environment will imply poor incentives for generators to invest which is offset

[14] More conventional approaches of testing the Bass model that relied on the endogenous communication variables would be too stylized in the current context, rendering the results unreliable from a policy perspective. This is because, in the current context, assumptions about m and w would have dubious validity without a long history of prior applications in comparable contexts. To the best of our knowledge there are no prior, empirically verified, estimates of m and w in the context of green electricity.

somewhat by greater SWA/take-up of green tariffs. It is, however, unlikely that this greater SWA will replace all, or indeed to a large extent, the lost generating incentive thereby implying that more support may be needed for RES from supply side support mechanisms (e.g. higher FITs/subsidies). This interaction between demand (green electricity tariffs) and supply side (FIT, GCM) incentive systems in differing price environments would appear to offer an interesting avenue for further research. Further, it is likely that a volatile price environment will cause commitment problems for green energy markets. Consumers may be reluctant to switch to green tariffs in low price environments if they fear a high likelihood of price hikes in the near future, as this would force them to switch and incur switching cost (real or informational).

Notwithstanding the above need for more research, it is clear that a high and or volatile energy price environment may be inconsistent with policies to support voluntary consumer contributions towards renewables investment through green energy tariffs. If a self-selecting group of consumers are to contribute voluntarily to the funding of renewables investments through green tariffs it appears that low and stable energy prices may be a precondition.

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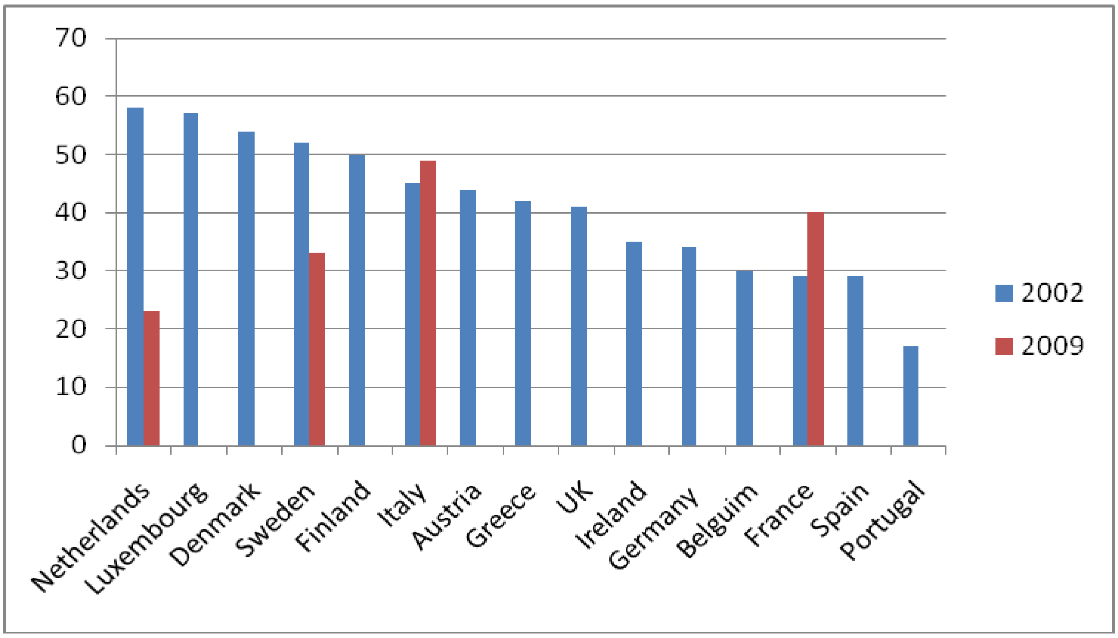
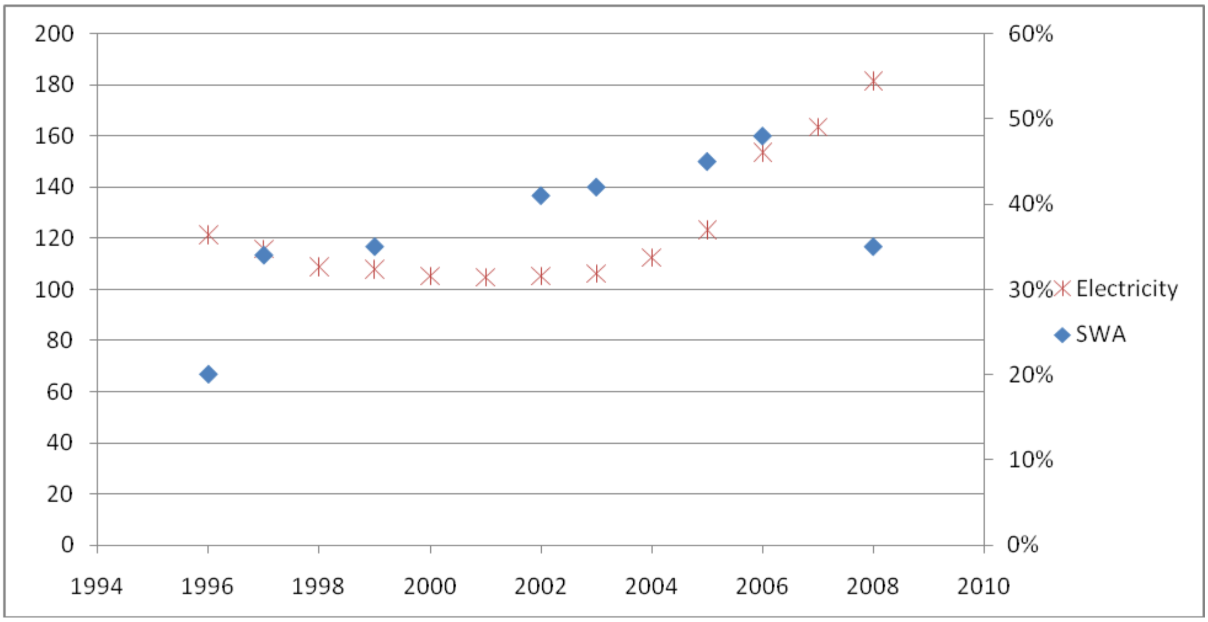
Figure 1: European Stated-Willingness-to-Adopt *



***Compiled from EU Commission (2002) and Kriström (2009) and based on a WTP >0**

Figure 2: UK electricity prices and SWA between 1996 and 2008*



*Right hand axis: SWA compiled from Fouquet (1998), Batley (et al. 2001), EU Commission (2002; 2006a; 2006b), Diaz-Rainey and Ashton (2008), Ackura (2008). Left-hand axis: Annual June electricity prices from the UK retail price index (BERR 2009).

Figure 3: Diffusion model of induced environmental market