Modelling future private car energy demand using two techno-economic approaches

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Abstract

This study presents two bottom-up approaches for forecasting private car energy demand in Ireland, one a car stock simulation model and the second an energy systems optimisation approach.

The car stock model uses historic sales, activity and car scrappage rates to iteratively simulate the structure of the car fleet and vehicle activity for each year up to 2025. Vehicle fuel efficiency and emissions factors for each vintage and technology type are applied to calculate annual energy demand and associated CO_2 emissions. Scenario analysis on new-car sales technology and efficiency is used to evaluate technology orientated policy measures, such as Ireland's 10 % electric vehicle target for 2020. Different policies can then be evaluated on the basis of their expected contribution to national renewable energy and CO_2 reduction targets.

The methodology, some results and applications of this car stock model are compared with those of the Irish TIMES project, an energy optimisation framework developed for the Irish energy system. TIMES identifies the least-cost technology mix to satisfy a specified energy service demand, subject to renewable and emissions constraints. Specifically for private cars, the least-cost technology mix to satisfy annual travel demand is produced given a range of energy efficiency, renewable energy and emissions constraint scenarios. Demand elasticities, crude oil price, economic performance and technology cost are key input parameters.

Results from these two studies give insights firstly into the likely outcomes of current government measures in terms of their contribution to meeting climate targets, and secondly, into what measures are necessary and most cost effective for meeting these targets.

Introduction

The case for energy policy modelling is strong in Ireland, which faces stringent climate change targets from the EU which are likely to be strengthened by a domestic climate change bill. Arising from EU Decision 406/2009/EC, non-emissions trading sector (non-ETS) emissions, compromising services, transport, residential and small industry sectors, are required to be reduced by 20 % on 2005 levels by 2020. The 20 % reduction imposed on Ireland, as well as Denmark and Luxembourg, is the strictest of all EU member states, because the burden of emission reductions was distributed in 2008 according to each country's relative wealth, and Ireland had a relatively high GDP. Since then Ireland entered into an economic recession, where GDP has declined by 12 % in the three years 2008-2010 (Barrett et al., 2010). The cost of reducing carbon emissions is therefore now more pressing for a government that has cut spending and increased taxation. The recent economic downturn has lessened pressure on the government to reach this target due to a decrease in energy demand, with Environmental Protection Agency post-recession emissions forecasts for 2020 showing a 19 % reduction on pre-recession 2020 forecasts (EPA, 2010). However, the difference in non-ETS forecasts as a result of the recession is only 5 %, still leaving Ireland overshoot the EU target by 12.4 Mt CO_2, 24 % over. Furthermore, the Irish government has published a draft climate change bill, which extends carbon emissions targets to a 40 percent cut relative to 1990 levels by 2030 and 80 percent relative to 1990 levels by 2050.

Private car transport is a particular sector for focus for carbon reductions in Ireland, with transport representing 30 % of non-ETS emissions in 2008 and cars being the most significant mode. Little has been achieved to reduce the footprint of cars, whose energy demand has grown by 37 % between 2000 and 2008 and not decoupled from economic growth as in other sectors. This has been as a result of increasing demand for larger and more powerful cars and overall travel demand (which has grown by 38 % between 2000 and 2008) (Daly and Ó Gallachóir, 2011). In 2009, renewable energy in road and rail transport (RES-T) was 1.5 %; EU Directive 2009/28/EC sets a mandatory target of 10 % by 2020, which won't be met without the introduction of alternatively fuelled vehicles.

Transport energy demand has been the focus of recent Irish policies (DoT, 2009), the most significant being a target that 10 % of Irish road vehicles are to be electrified by 2020. The EU has also set an upper limit for the average emissions (gCO_2/km) of new passenger cars of 130g/km by 2015 (EC, 2009), and the Irish government has set out targets for biofuel blending in non-aviation and marine transport fuels (3 % biofuel blending in transport fuels in 2010) (Ireland, 2010).

The need to quantify the cost towards reaching these targets has been highlighted in public debate (O' Halloran, 2011); these particular regulations and targets have given a need for effective policy modelling, particularly in the area of transport. This paper studies the methodologies and results of two particular models which have been created for this end. Energy systems modelling can have an instrumental role in setting climate and energy targets, the formulation and planning of specific policies, and the ex-ante evaluation of policies for efficiency and cost effectiveness. Energy models can also be used for visioning the future by describing the technological and structural changes needed in order to reach a visionary target, for example through backcasting (Hickman and Banister, 2005). Strachan et al. (2009) describes a MARKAL-Macro energy-economic model which was used to inform the development of the UK's 2050 carbon dioxide reduction target of 60 %. Also described in this paper are the roles other energy models have played in formulating policy. Mundaca et al. (2010) reviews and classifies bottom-up energy-economy models using the residential sector as an example, and concludes that while such models have gained wide acceptance for informing policy instruments, there is limited literature on their development, use and evaluation.

Two energy-economy models of Irish private cars have been developed; a car stock-based bottom-up demographic forecasting model which compares the results of differing technological scenarios, and a whole energy systems model, of which private cars are a part, which cost-optimises the technology mix up to 2050 given different climate constraints. The purpose of this paper is twofold: Firstly, the two modelling paradigms are compared through an analysis of the respective methodologies, equations, inputs, assumptions and desired outcomes. The possibility for integrating the two essentially complementary models is discussed. Secondly, the results of both models are used to give insights into Ireland's future with respect to climate targets and specific technology-orientated measures.

Comparison of two modelling frameworks

This section introduces energy modelling and two specific models which have been developed for Ireland. Kannan and Strachan (2009) compares several types of residential energy stock models with the UK MARKAL energy systems model in how they model UK's ambitious climate change targets. Many different types of energy model exist: Jebaraj and Iniyan (2006) give a review. A broad classification system groups energy models into "top-down" and "bottom-up" models. At one end of the spectrum, top-down models are generally interested in the whole energy system and its interaction with the economy. The specific characteristics and interactions of the energy system are aggregated into a number of variables and equations, and the energy system is modelled as being embedded in the larger economy. Technologies are aggregated and implicitly modelled through average efficiencies. Elasticities of substitutions determine the mixture of inputs required to produce a unit of sectoral output (Loulou et al., 2005).

On the opposite end of this spectrum, bottom-up models focus on technological detail, where interactions with the larger economy are minimal. Sectors are modelled focussing on the characteristics of technologies providing an energy service demand. Energy using technologies are explicitly defined by technical and economic characteristics including lifecycle cost, inputs, outputs and unit costs. The production function in bottom-up models is generally implicitly constructed using the output of the technologies which are chosen in a scenario.

Stock modelling is typically bottom-up. In this paper we describe a detailed simulation model of the Irish car stock, incorporating technology and vintage variables. While macro variables drive travel demand and car sales, there is no interaction with power generation or other sectors, and no competition with other sectors, and exogenous emissions factors are used. Exogenously determined scenarios are constructed to evaluate the impacts of different mixes of technologies. Behaviour (modal shifting, demand reduction) is not addressed in either model.

TIMES (The Integrated MARKAL-EFOM System) is an economic model generator which estimates energy dynamics over a long time period. The Irish-TIMES model has been created to represent the entire energy system; the user inputs the energy service demand of each sector (residential heating, freight tonne-kms, for example), provides the capacities and costs of available technologies, and TIMES selects technologies to serve the service demand such that the system is least cost under a range of climate constraints. Private cars are one component of the Irish TIMES model; we later provide preliminary results on how three climate target scenarios effect personal travel technology selection in TIMES.

TIMES can be used to study one sector in detail. For example, Gül et al. (2009) uses MARKAL to examine the global prospectives for alternative transport fuels. TIMES as a modelling tool is a type of hybrid model, combining the technological richness of a bottom-up model while still representing the macro-economy.

Table 1 gives a broad analytical comparison of the two modelling frameworks by comparing the purposes, inputs, modelling methodology and level of disaggregation in each method. The next sections describe in more detail both models and results.

Table 1. Broad analytical comparison of the two modelling frameworks.

	Stock Model	TIMES
Baseline inputs	Base year stock, scrappage profiles, mileage and aged efficiency by technology and vintage; GNP forecast and sales and activity elasticities	Available technologies, capacities and associated costs; future passenger kms.
	Technology cost not included	Capital, OM, fuel costs defined for each tech
Scenario inputs	Sales by technology types; new car efficiencies; fuel mix	System-wide climate constraints
Purpose	Evaluates specific technology measures	Informs cost effective technology measures given climate targets
	Forecasting pkms	Least cost technology mix for each scenario; Marginal cost of CO2
Targets	Implications of policies for targets may be inferred	Targets imposed on model
Model	Car stock demographic model	Linear optimisation
	Forecasts passenger kms	Pkms determined exogenously
Level of disaggregation	High: 17 vintaged technology types. Each technology type has an associated efficiency, mileage and scrappage pattern.	7 technologies, no vintaging. Mileage or scrappage not disaggregated. Distance travelled divided by "long" and "short" distance.

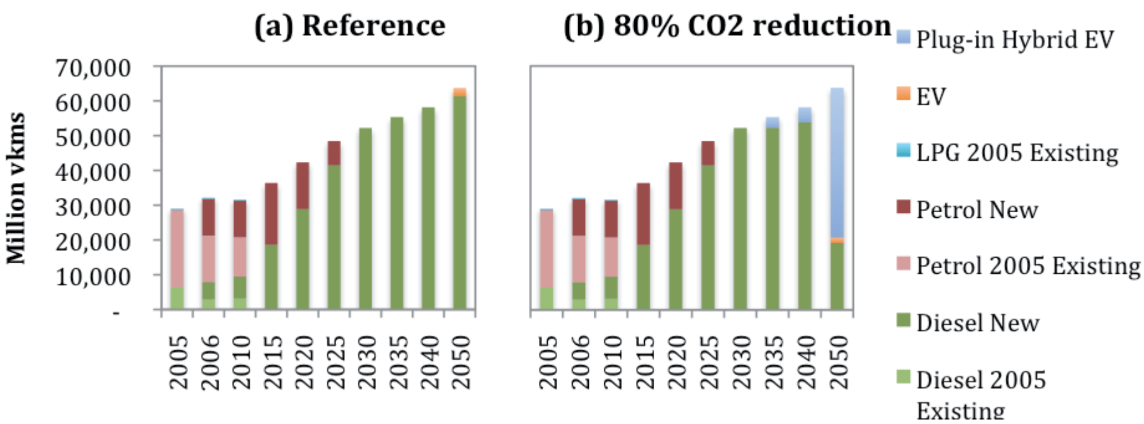

Figure 1: TIMES private car activity by technology, reference and CO_2 reduction scenarios.

PRIVATE CARS IN IRISH TIMES MODEL

Car transport in Irish TIMES is driven by a passenger kilometer (pkm) energy service demand (ESD). Pkms are forecast econometrically using GNP macro forecasts, as vehicle kilometers in the stock model. Pkms are divided into long journeys and short journeys, as technology types can fill long and short journeys at different rates, due to limited range of, for example, battery electric cars. Calibrated to 2005 data, "current" technologies in the system are used and expire at a rate of 10 % per year, and are replaced by new technologies to fill the ESD. Using the available technologies to the model – petrol, diesel, LPG, E85 ethanol, biodiesel, battery electric, CNG, hydrogen, biogas – and each technology's respective investment, operations and fuel costs and annual capacity (kilometers driven), the technology mix is optimised over a given time frame to minimise the total system cost. Scenarios are run to simulate policy targets by constraining climate variables: Renewable energy as a percentage of final energy consumption, greenhouse gas emissions, and energy security.

Figure 1(a) shows results from the reference scenario in TIMES through passenger kilometers satisfied by different technologies. The model introduces new petrol and diesel cars, but after a time petrol is phased out in favour of diesel entirely. Figure 1(b) shows the same results for a constrained scenario, where the entire energy system is optimised to meet an 80 % emissions reduction target on 1990 levels by 2050; diesel cars are replaced by plug-in hybrid cars in the years leading up to the target year.

CAR STOCK MODEL

This techno-economic forecasting methodology is an energy simulation model whose power largely lies in describing the future structure of energy demand given exogenously determined vehicle sales scenarios. For example, future aspirational targets are assumed met, such as a cap on new-car tailpipe emissions, without describing the economic developments needed in order to reach that target (Mundaca et al., 2010). In the stock model, cars are disaggregated into technological categories: firstly by fuel type (petrol, diesel, hybrid electric, battery electric etc) and further by engine type (0-900cc, 15-20 kWh battery etc), and finally by vintage. Historic data for the number of cars registered in each subcategory in Ireland

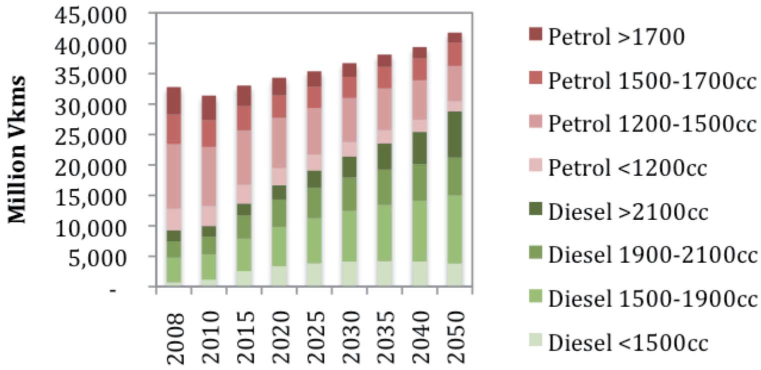

Figure 2: CSM Reference scenario car activity by technology.

was made available, analysis of odometer readings from the National Car Test gave disaggregated mileages, and official car test results provided new-car specific energy consumption and emissions (Howley et al., 2009). Daly and Ó Gallachóir (2011) describes the data sources and bottom-up energy calculation methodology for modelling historic Irish private car energy demand used in this model.

The historic energy model is then simulated into the future. A detailed description of the methodology and scenario results are found in Daly and Ó Gallachóir (2010). In this simulation model, the demographic features of each technology type – sales according to national GNP growth and car retirement rates – are used to iteratively simulate the stock in each category for each year *T* in the forecasting time horizon using the equation

$$Stock_v^T = Sales_v^T + \sum_v \left(Stock_v^{T-1} \times Scr_c(T\text{-}v) \right) \quad (1)$$

where *v* is the vehicle vintage year and $Scr_c(T\text{-}v)$ is the scrappage factor of cars of technology category *c* at age *T-v*. Irish drivers tend to import second-hand cars from the UK, and this rate is incorporated into the scrappage factor, which is in fact greater than 1 for younger cars. Total sales are forecasted econometrically using elasticities and GNP forecasts. Secondly, total stock mileage is calculated independently to the composition of the stock, and is determined using GNP and fuel price forecasts and elasticities, and incorporated a rebound effect for increased efficiency. The patterns of annual mileage by vintage and technology category are replicated. Finally, the baseline distribution of new car sales over technology types are forecasted using regression using income as the explanatory variable, and new-car efficiency by car type continues historical trends.

The model uses scenarios to predict the impact of different vehicle technology sales scenarios on the on-road fleet efficiency, taking into account the stock and distance driven of vehicles across vintages and technologies. This is a very useful tool for demonstrating the relative consequences of different technology targets, for example, targets for electric vehicles versus for biofuel vehicles, or the impact of incentives for more fuel efficient vehicles. Figure 2 shows the baseline vehicle activity by technology. As an example of the use of this model for evaluating technology targets, Figure 3 shows private car energy demand to 2020 under a range of EV scenarios, assuming that the Irish government's 10 % EV target for 2020 is met: *EV_low* assumes that lower efficiency and range EVs will displace smaller petrol cars; *EV_average* models EVs as displacing the stock average, and *EV_bestcase* models a situation where EVs displace larger and less efficient diesel vehicles which travel greater distances than average.

Limitations of the methodology include the static variables used: it is probable that scrappage and import rates change with the second hand car market and the state of the economy, as well as the driving patterns according to vintage and technology type.

Discussion

We have included results from both modelling approaches in order to highlight firstly the purposes of the respective models, and secondly to highlight some consequences for passenger transport in Ireland. The stock modelling approach gives a detailed picture of the evolution of the car fleet under different sales scenarios; Figure 3 shows a range of results assuming that the 10 % EV target is met. The "average" case, assuming that EVs displace the average vehicle (in terms of efficiency and distance driven) gives a saving of 6.5 % relative to the base case, compared with a 2.5 % and 8.7 % saving from the "low" and "best case" scenarios, respectively. While this is not a study of the EV target per se, it's interesting to note that EVs are not introduced into TIMES's cost-optimal technology mixes for CO_2 constraints, in Figure 2. These models can clearly play an important role in the design of efficient energy policy.

The differences in the stock modelling and energy systems approaches are quite complementary and allow scope for integration, work which is ongoing. Because of vintaging and disaggregating mileage by technology, the stock model produces the stock average on-road efficiency (SEC) very accurately; however, technology selection is imposed on the model. The power of the stock simulation model is in calculation and description: it can give good insight into the future dynamics of the fleet with regard to the drivers of energy consumption; it is a *descriptive* model. In contrast, the TIMES approach is *prescriptive*: it selects technology to best achieve certain goals.

However, it's clear from comparing Figures 1 and 2 that the respective models' baseline assumptions must be brought in line before any meaningful comparison can be made between results – the annual fleet activity produced by the models var-

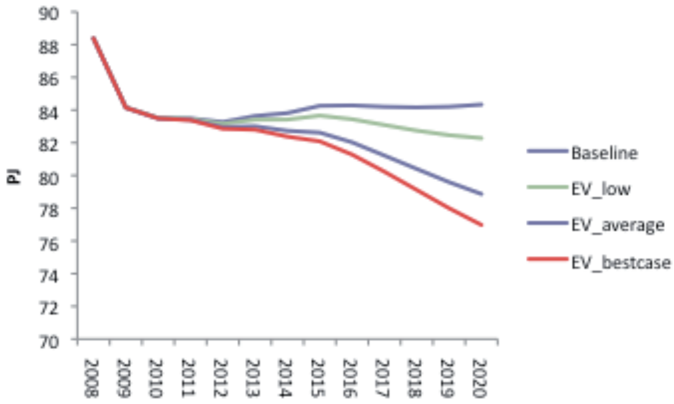

Figure 3: Car stock model energy demand under several EV penetration scenarios.

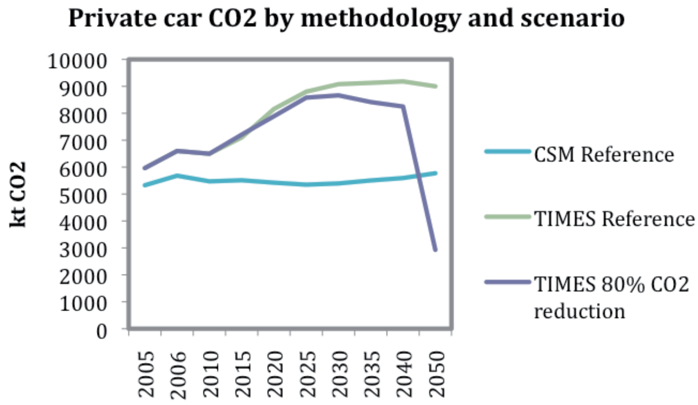

Figure 4: Energy demand under several EV scenarios.

ies by up to 60 %, the difference of which is driven by the economic underpinning of each model. Figure 4 shows fleet CO_2 emissions from the CSM and TIMES scenarios, again differing widely. The CSM baseline incorporates a dramatic increase in new-car efficiency between 2008-2010, part of which can be attributed to a change in the vehicle taxation system (Howley, 2009).

Both models are "techno-focussed": neither accounts for driver behaviour and so softer travel measures – ride sharing, public transport initiatives, for example – are not considered, and therefore are in danger of being overlooked in policy decision making should purely technology models be considered. Furthermore, technology costs and availability are uncertain over such a long 40-year time span.

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