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REFEREE: Real Value of Energy Efficiency

The state of art of the existing models and tools to support policy makers in the analysis of the real effects of the energy efficiency measures

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1 Introduction and summary

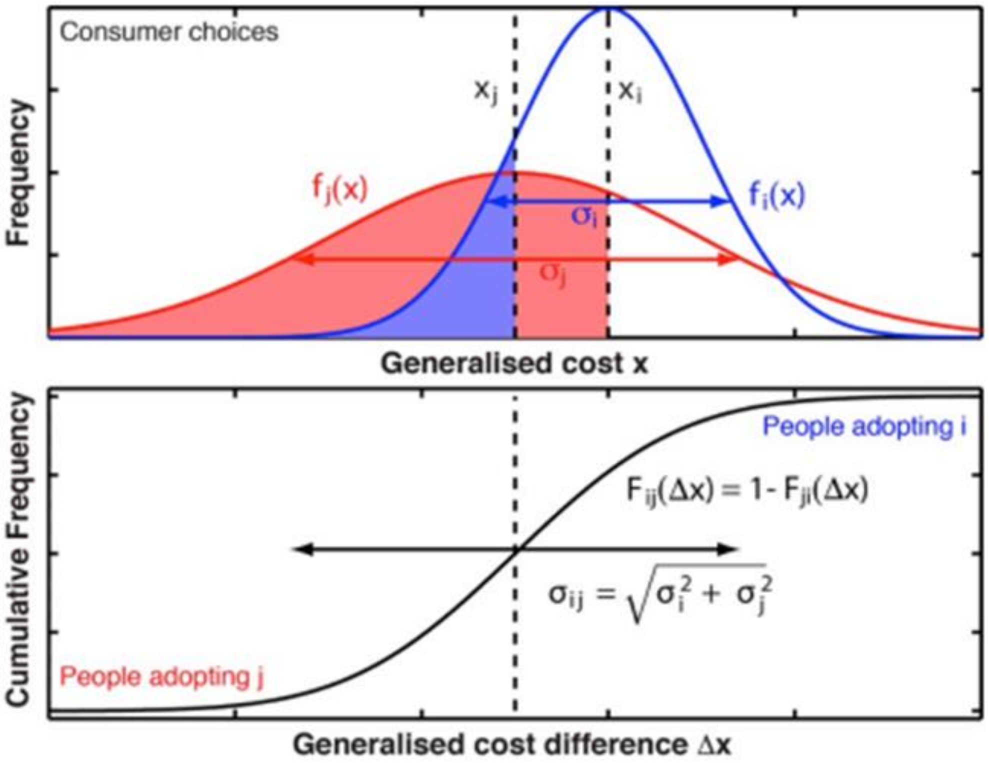
For key energy-using sectors, the REFEREE decision tool will incorporate a set of evolutionary models called Future Technology Transformations (FTT). These tools simulate technological decision making, and the investments and expenditure decisions that flow from this. The technological choices, investments, end-use prices and energy consumption are fed into the reduced-form economic model (E3ME-Lite), and ultimately to the calculation of multiple benefits.

Within each FTT model, investors are faced with several options to build new capacity (Mercure & Salas, 2012) New capacity is required to replace old capacity and to meet changing demand. The decision-making core estimates investor preferences by comparing technological levelised costs between options on a pair-wise basis; this is conceptually equivalent to a binary logit model, which is parameterised by measured technology cost distributions of several cost components. The costs include upfront investments (which can decline through learning effects), energy costs and policy costs. Distributions of these costs indicate local variabilities but also the heterogeneous character of investors, which stems from different perceptions and outlooks.

The diffusion of technology follows a set of coupled non-linear differential equations, sometimes called 'Lotka-Volterra' or 'replicator dynamics'. These equations represent the better ability of larger or well-established industries to capture the market, the investor preferences, and the rate at which one technology can replace another technology. The key characteristics of FTT include path-dependency, sub-optimal decision-making and non-marginal change in responding to external influences. The FTT framework produces the characteristic S-shaped curve often found in historic cases of technology diffusion.

Figure 1 is a schematic representation of the distribution of consumer preferences to invest in two alternative technologies (as shown in the top panel), which determines cumulative take-up for those technologies (as shown in the bottom panel). FTT takes account of expected variation in both agent preferences and technology costs in calculating rates of technology take-up. The relative preference of agents for technology *j* over technology *i* is denoted with the matrix $F_{ij}(x)$, a fraction between 0 and 1. This leads to shares of technologies being transferred between technology categories as agents gradually replace the stock.

Figure 1 Schematic representation of pair-wise comparison of technological options by heterogenous agents with varying preferences in FTT.



2 The Individual FTT models

The FTT model framework has been applied to a number of areas across the energy system to model how various sectors will decarbonise. In the course of the REFEREE project, four models have been updated or created;

- Household heating (FTT-Heat) - *updated*
- Passenger road transport (FTT-Transport) - *updated*
- Road freight transport (FTT-Freight) – *newly created*

- Industrial heating processes (FTT-Industrial Heat) – *newly created*

2.1 FTT-Heat

Aim/Purpose

FTT:Heat (Knobloch et al, 2018; 2021) simulates households' choices for heating technologies. The model is driven by useful energy demand for residential heating, which is comes externally. A household's useful energy demand for heating is assumed to be independent of the used heating technology, but determined by characteristics such as climatic conditions, building characteristics, household size, household income, and individual preferences for room and water temperatures.

Final energy demand follows from useful energy demand delivered by heating technology and the respective conversion losses. Consumers invest in capacity, but FTT:Heat does not capture behavioural aspects that may change how the heating technologies are used. To a degree, behaviour is captured by the total residential useful energy demand. Usage of heating technologies is, however, affected by climate zones, which serves as an indicator for capacity factors.

Based on the technology mix, consumer expenditure on heating equipment and fuel expenditure are fed into E3ME-Lite.

Possible policies that can be assessed in FTT:Heat include upfront subsidies, energy tax/subsidies, phase-outs and government procurement programs.

Technology classifications

FTT:Heat covers 13 heating technologies that compete to deliver the useful energy demand for heat.

FTT Heat Technologies
1 Oil
2 Oil condensing
3 Gas
4 Gas condensing
5 Wood stove

6 Wood condensing
7 Coal
8 District heating
9 Electric
10 Heatpump ground
11 Heatpump Air Water
12 Heatpump Air Air
13 Solar thermal

Data sources

Historical Final energy demand is sourced from:

- Main heating demand by fuel: ODYSSEE database (Enerdata, 2017)
- Data on heat generation by heat pumps over time is taken from the European Heat Pump Association (European heat pump association (EHPA), 2016), supplemented by the (EurObserv'ER, 2017) database.
- For solar thermal heating, time-series from the annual reports of the (IEA, 2017).

Technology cost assumptions are collated from a combination of sources:

- Mapping and Analyses of the Current and Future (2020 - 2030) Heating/cooling Fuel Deployment (Fossil/renewables) (Fleiter, Steinbach, & Ragwitz, 2016)
- Technology data for energy plants - Danish Energy Agency (2013, 2016),
- Solar Heating, Cooling Programme (IEA, 2012)
- (European heat pump association (EHPA), 2016)

Learning rates are collected from:

- A review of experience curve analyses for energy demand technologies (Weiss, Junginger, Patel, & Blok, 2010)
- *Modelling the Diffusion of Innovative Heating Systems in Germany - Decision Criteria, Influence of Policy Instruments and Vintage Path Dependencies* (Henkel, 2012)

2.2 FTT-Transport

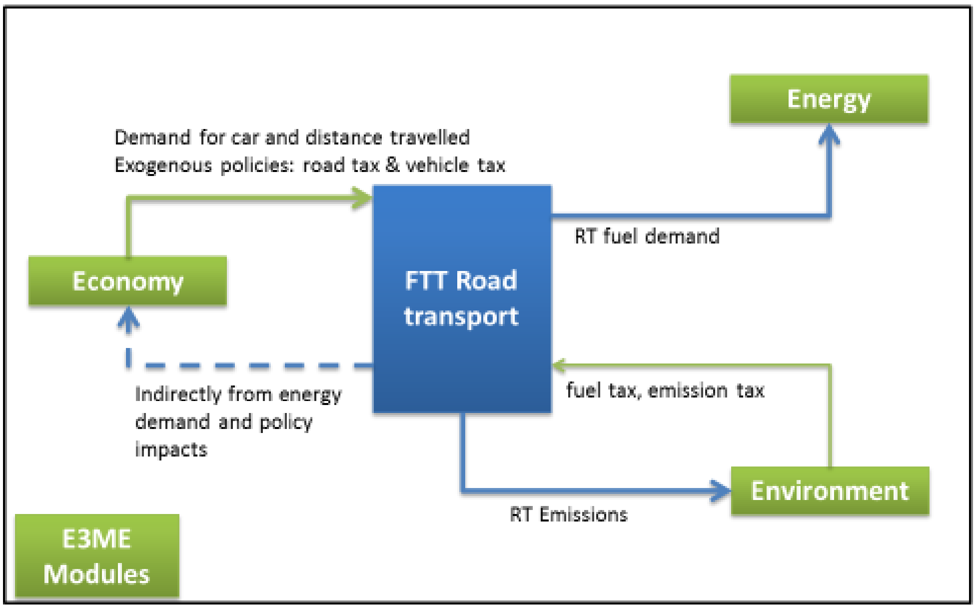
Aim/Purpose

With road transport contributing a large share of global emissions and fuel use, it is imperative to have a reliable description of consumer decisions on vehicle purchases and use (Mercure, Lam, Billington, & Pollitt, 2018)The standard approach of optimisation disregards consumer preference and therefore sits far from the observed reality. Many consumers buy the most expensive car they can, rather than the cheapest.

Decision making in regard of these preferences, along with sub-optimal behaviour, is captured in FTT:Transport (Mercure & Lam, 2015) Using the levelised cost of transport, all vehicle types are compared on a pair-wise basis. To account for regional consumer preferences, an adjustment factor has been introduced, which captures intangible costs.

Based on the vehicle fleet composition and use, consumer expenditures on vehicle purchases and transport-related fuel expenditure are fed back to E3ME-Lite, as shown in Figure 2.

Figure 2: Feedback from FTT:Transport to E3ME modules



FTT:Transport allows for simulation of a wide range of real-world policies, including road taxes, vehicle taxes, (carbon-related) fuel tax/subsidies, fuel standards, subsidies on upfront purchase prices, phase-outs and government procurement programs.

Technology classifications

FTT:Transport covers 25 different vehicle types consisting of 9 different power trains and 3 different engine sizes (Economy (Econ), Medium (Mid) and Luxury (Lux) plus separate categories for passenger cars and motorbikes .

FTT Transport technologies
1 Petrol Econ
2 Petrol Mid
3 Petrol Lux
4 Adv Petrol Econ
5 Adv Petrol Mid
6 Adv Petrol Lux
7 Diesel Econ
8 Diesel Mid
9 Diesel Lux
10 Adv Diesel Econ
11 Adv Diesel Mid
12 Adv Diesel Lux
13 LPG Econ
14 LPG Mid
15 LPG Lux

16 Hybrid Econ
17 Hybrid Mid
18 Hybrid Lux
19 Electric Econ
20 Electric Mid
21 Electric Lux
22 motorcycles Econ
23 motorcycles Lux
24 Adv motorcycles Econ
25 Adv motorcycles Lux

Data sources

FTT transport database is collated from:

- Registration data
    - National statistics
    - Marklines
- Historical fleet size and distance travelled
    - Eurostat
- Vehicle price data were matched model by model to sales numbers for 18 representative regions, used as for other regions based on economic and regional similarities, following data availability

2.3 FTT-Freight

Aim/Purpose

The road freight sector is a significant contributor to global emissions and a crucial part of global supply chains. FTT-Freight captures decision-making in the road freight sector, accounting for sub-optimal preferences of investors with incomplete information. Similar to FTT-Transport, the levelised cost of each freight type is calculated and compared on a pair-wise basis to all alternatives.

It is possible to simulate a number of different policies - such as biofuel mandates, road taxes, vehicle taxes, fuel taxes or subsidies, and subsidies on the purchase of vehicles – to encourage or discourage uptake of different technologies.

Model overview

Taking total demand for freight transport by country, the model simulates changing technology shares to ensure this demand is met. The respective share of each technology is dictated by existing capacity and pair-wise comparisons of levelised costs. From this, fuel usage can be calculated.

The initial purchase price of different vehicles can be lowered through learning-by-doing, and different technologies possess different learning rates. Additionally, different policy schemes can be simulated to feed into the levelised costs and further influence pair-wise decisions.

At each time step, levelised costs are re-evaluated and applied to define preferences, followed by simulation of market-share dynamics using replicator dynamics equations.

Based on the share of each fuel user in the fleet, fuel demand is fed back into E3ME-Lite, allowing estimation of emissions from freight transport.

Technology classifications

FTT Freight includes 20 different classifications, covering 8 fuel types.

FTT Freight technologies
1 Petrol Small
2 Petrol Large
3 Petrol adv small
4 Petrol adv large

5 Diesel Small

6 Diesel Large

7 Diesel adv small

8 Diesel adv large

9 CNG/LPG Small

10 CNG/LPG Large

11 Hybrid Small

12 Hybrid Large

13 Electricity Small

14 Electricity Large

15 Bioethanol Small

16 Bioethanol Large

17 Biodiesel Small

18 Biodiesel Large

19 Hydrogen small

20 Hydrogen large

Data sources

The FTT-Freight database is collated from:

- Demand and historical market shares
    - Eurostat, OECD, Marklines and supplemented by national statistics
- Sales history and fleet size
    - Eurostat, Marklines and OICA, again supplemented by national statistics

- Cost data was taken from vehicle manufacturers
- Load factors
    - Eurostat and national statistics

2.4 FTT-Industrial Heat

Aim/Purpose

Industrial processes are known to contribute significantly to global emissions, and decarbonisation of industry is a monumental task, with many processes requiring innovation in order to be electrified.

FTT: Industrial Heat simulates investors' choices for industrial heating technologies. There are 5 sub-models which correspond to different sectors or groupings of sectors:

1. Chemicals,
2. Food, beverages, and tobacco
3. Non-ferrous metals, machinery equipment, and transport equipment
4. Non-metallic minerals
5. Other industrial sectors (this includes paper, textiles and leather, wood and wood products, as well as sectors not explicitly defined in the JRC-IDEES dataset).

Industrial Heat looks at two types of heating technologies: direct (such as furnaces, calciners, etc.) and indirect (such as water or steam boilers). These technologies are then disaggregated by their fuel use type. Heat pumps are a unique category which run on electricity; however, they can only compete with indirect heating technologies. Similarly, direct and indirect heating technologies cannot compete in general, due to them not practically being able to replace one another.

Many industrial processes cannot currently be replaced, which is why market share caps are an important component of FTT: IH; these caps ensure any technologies which cannot be replaced are not substituted based on investor choices. However, the model will allow the electrification of industrial heat processes to occur to its current maximum potential if the right policies are enacted in the model.

The model allows fuel use by different industries to be fed back to E3ME-Lite and will allow us to estimate changes in emissions for industrial heat processes.

Technology classifications

FTT Industrial heat includes 13 different classifications, covering 6 fuel types across both direct and indirect heating methods. The classification is kept common across the different industry sectors modelled.

FTT: IH technologies
1 Indirect Heating Coal
2 Indirect Heating Oil
3 Indirect Heating Gas
4 Indirect Heating Biomass
5 Indirect Heating Electric
6 Indirect Heating Steam Distributed
7 Heat Pumps (Electricity)
8 Direct Heating Coal
9 Direct Heating Oil
10 Direct Heating Gas
11 Direct Heating Biomass
12 Direct Heating Electric
13 Direct Heating Steam Distributed

Data sources

The FTT: Industrial Heat database is collated from:

- The JRC-IDEES-2015 database from the Joint Research Centre of the European Commission (Mantzos, et al., 2018).

- The Danish Energy Agency Technology Data Catalogue for Industrial Process Heat (Danish Energy Agency, 2021).
- CO2 reduction potential for the European industry via direct electrification of heat supply (Madeddu, et al., 2020)

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