Kyoto University

Connecting bottom-up future technologies transformation models FTTs to a global macroeconomic model E3ME

E3ME-FTT

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Overview

- E3ME macroeconomic model
- FTT bottom up technologies submodules
- Combining E3ME and FTTs

E3ME: Energy-Environment-Economy Model

What is E3ME?

A computer-based global model for the economy, energy and environment, covering 61 regions

The model consists of collections of econometric behavioural equations and accounting identities

Based on an accounting framework and designed for projections for business and policy analysis

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What are the key dimensions & features of E3ME?

Detailed Coverage
- 61 regions (33 European, 28 World)
- 70/44 economic sectors and 42/28 consumption categories
- 23 fuel users of 12 fuels

Comprehensive
- whole energy, environment and economy system
- two way feedback between each module
- covers many policy instruments

Highly Empirical
- 1970-2016 database
- 28 econometric equations
- relationships validated from data
- econometrics allows for short-medium and long term analysis

Consistent
- based on system of national accounting
- input-output tables
- bilateral trade

Forward Looking
- annual projections to 2050 (2100 possible)
- behavioural equations with effects from previous outcomes
- ex-ante scenario analysis (ex-post is also feasible)

Modular
- E3: Energy, Environment, Economy and material modules
- power generation, road transport, heating, iron and steels sub-module

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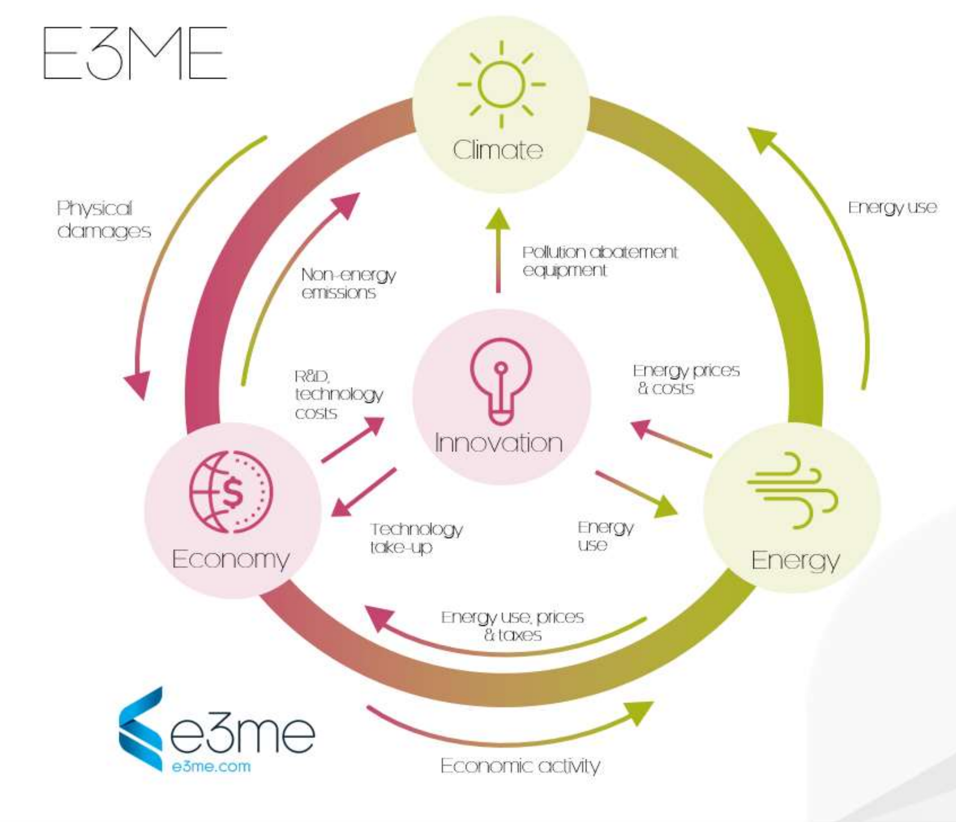
E3ME as an E3 model

- Each component of the model is shown in its own box
- The linkages between the components are shown by arrows that indicate which values are transmitted



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Comparison with CGE models

E3ME is often compared to CGE models. In many ways the modelling approaches are similar, (e.g. similar inputs and outputs), however, E3ME offers some advantages due to its theoretical differences:

- Varying competition over sectors
- Varying returns to scale
- Product supply-demand balance
- Model allows for voluntary and involuntary unemployment
- Economic parameters based on nearly 50 years of data

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What can E3ME be used for?

Energy & Climate

- Decarbonisation
- ETS/ carbon market
- carbon/energy targets
- carbon/ energy tax
- ETR
- renewables energy
- power generation mix
- green jobs
- CDM
- removal of harmful subsidies

Economics/ Labour Market

- fiscal policies: government revenues and spending
- monetary policies
- trade agreement
- labour supply and demand forecasts
- labour market policies e.g. improving female participation rate

Others

- sector specific studies e.g. aviation, water transport, engineering, chemical
- impacts of R&D and innovations
- resource efficiency

What are the typical model outputs of E3ME?

Economy

- **GDP** and its **aggregate components**
- **sectoral** output **&** GVA, prices, trade & competitiveness effects
- **sectoral** international **trade** in **bilateral** format & can be presented by trade blocs
- **consumer prices & expenditures**, & implied household **distributional** effects

Labour Market

- **sectoral employment** by gender
- **labour force** and **participation rate** by gender and age groups
- **unemployment** rate and level
- **sectoral wage** rate
- **real income** of different **socio-economic** groups
- **GINI** coefficients

Energy & Environment

- **energy demand**, by users and by fuel
- energy **prices**
- **Power, road transport, heating, iron and steel** sector detailed results
- **CO_2 emissions** by sector and by fuel
- **other** air-borne **emissions**
- **material demands** (DMC, DMI, DE, M, X, TMR), by users and by materials

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What are the strengths and limitations of E3ME?

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- close integration of economy, energy & environment, with 2-way linkages between all
- detailed sectoral disaggregation
- global coverage, also allowing for analysis at national level
- econometric approach and its empirical grounding
- econometric specification makes it suitable for short, medium and long-term assessment

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Data:
- annual model
- quality and availability of data

Econometric:
- dealing with structural change
- based on historical relationships (Lucas critique)

Complexity:
- complex linkages between different part of models
- treatment of financial markets

The role of technology

Technological progress plays an important role in the E3ME model, affecting all three E's: economy, energy and environment:

- The model's endogenous technical progress indicators (TPIs), a function of R&D and gross investment, appear in nine of E3ME's econometric equation sets including trade, the labour market and prices
- Investment and R&D in new technologies also appears in the E3ME's energy and material demand equations to capture energy/resource savings technologies as well as pollution abatement equipment
- In addition, E3ME also captures low carbon technologies in the power, road transport, heating, and iron and steel sectors through the FTT (Future Technology Transformations) sector models

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Energy modelling in E3ME

- Based on IEA data
- Key users are calculated using bottom up energy technology sub-model (the FTT- Future Technology Transformations)
  - ✓ Power
  - ✓ Road transport
  - ✓ Residential heating
  - ✓ Iron and Steel
- Remaining final users are calculated by econometric equations

Other final users – econometrics approach

- No explicit production function
- 2-level hierarchy: aggregate energy demand equations and fuel share equations
- Demand affected by industrial output of user industry, household spending in total, relative prices, technical progress

Energy and emission classifications

FU:22 (fuel users)

1. Power Generation
2. Own use
3. Hydrogen production
4. Iron & Steel
5. Non-ferrous Metals
6. Chemicals
7. Mineral Products
8. Ore-extraction
9. Food, Drink & Tobacco
10. Tex., Cloth. & Foot.
11. Paper & Printing
12. Engineering etc
13. Other Industry
14. Construction
15. Rail Transport
16. Road Transport
17. Air Transport
18. Other Transport serv.
19. Households
20. Agriculture, forestry, etc.
21. Fishing
22. Other Final Users
23. Non-energy use

J:12 (fuels)

1. Hard coal
2. Other coal etc
3. Crude oil etc
4. Heavy fuel oil
5. Middle distillates
6. Other gas
7. Natural gas
8. Electricity
9. Heat
10. Combustible waste
11. Biofuels
12. Hydrogen

EM:14 (air emissions)

1. CO_2
2. SO_2
3. NO_X
4. CO
5. Methane
6. Black smoke
7. VOC
8. Nuclear - air
9. Lead - air
10. CFCs
11. N_2O (GHG)
12. HF_6 (GHG)
13. PFC (GHG)
14. SF_6 (GHG)

Future Technology Transformation (FTT)

Why FTT?

- Bottom-up model; econometric equations no appropriate for power generation because there is typically a small number of large plants and the econometric approach is not well suited for the development of new renewable technologies
- Current standard in energy systems modelling is by cost-optimisation/linear programming
  e.g. TIMES/MARKAL, MESSAGE, AIM, etc
- Is optimisation always what policy-makers find useful?
- Replacing the social planner by real people

What is FTT?

- Can be classified as a post-Schumpeter, evolutionary, innovation model
- Framework was designed by Jean-Francois Mercure for the power sector in 2012
- Since then, models have been developed for the road transport, residential heating, and iron and steel sectors
- Soon to be expanded by an agricultural/land-use model
- More to come in the future!

Mercure (2012). https://doi.org/10.1016/j.enpol.2012.06.025
Mercure & Lam (2015). https://doi.org/10.1088/1748-9326/10/6/064008
Knobloch & Mercure (2017). https://ec.europa.eu/energy/en/dataanalysis/energy-modelling/macroeconomic-modelling
Vercoulen, et al. (2018). http://wwwecono.meijo-u.ac.jp/discussion/dp_0008.pdf
Lindner & Mercure (2018). https://www.ceenrg.landecon.cam.ac.uk/other-files/bridge-files/bridge-ws-06-18-p07-s-lindner.pdf

What does it do?

FTT steps into the shoes of the entrepreneur

- Calculates technology-specific cost of production
- Assumes imperfect knowledge leading to sub-optimal preferences
- Preferences are fed in to the decision-making core
- Mimics S-curve (accumulated adoption over time)
- Learning-by-doing
- Spews out investment demand, average prices, and fuel consumption, which, in turn, communicates with other parts of the E3ME-FTT framework

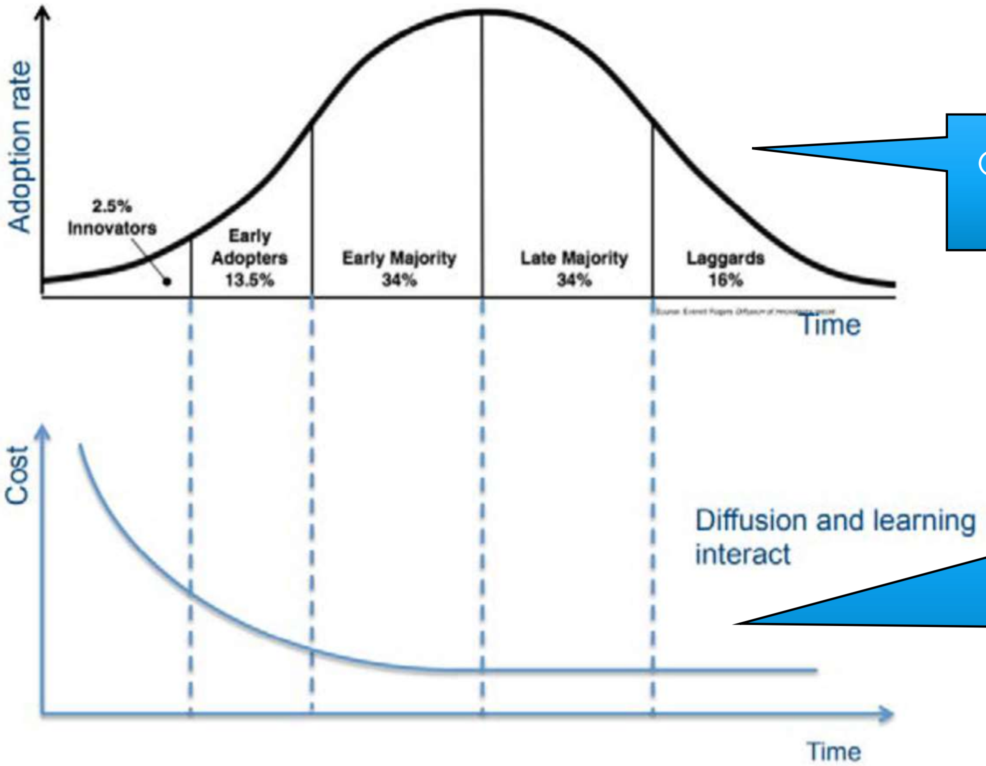
The FTT methodology

- Modelling innovation requires approximation of investor behaviour
- Investors will estimate the revenue and expenses associated to varying technologies to produce the same product within the constraints of a sector
- ...even if investors are consumers investing in a new car or boiler! The only difference being that intangible costs come into play
- Every FTT model calculates the levelized cost and uses it to estimate investor preferences
- Preferences are decided upon by a pairwise comparison of technologies based on distributions of cost
- The preference feeds into a Lotka-Volterra equation (predator-prey) to decide upon market shares while taking into sectoral constraints

Strength of FTT

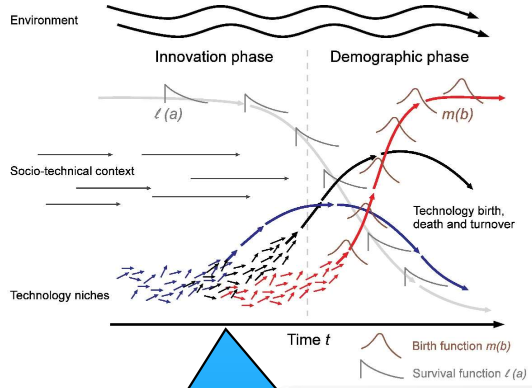
- Highly detailed
- Lucas critique does not apply (for the most part)
- Takes into account sector-secific limitations
- Allows for a myriad of sector-specific policies and therefore allows us to analyse said sectors in greater detail
- Coupling with E3ME allows us to analyse innovation in an ever-changing economic environment and impacts of innovation on economy and jobs

What is innovation?



Characteristic S-curves!

Cost of a technology / product decreases as it gets adopted more due to learning-by-doing, i.e. incremental innovation



Usually multiple new technologies arise around the same time, and usually one of them becomes the dominant design

Mercure (2015). https://doi.org/10.1007/s00191-015-0413-9
Grübler, et al. (1999). https://doi.org/10.1016/S0301-4215(98)00067-6

Mathematical framework - Levelized cost calculation

$$NPV_{expenses} = \sum_{0}^{\tau} \frac{IC(t) + OM(t) + FC(t) + CO2T(t) + \cdots}{(1+r)^t}$$

$$NPV_{income} = \sum_0^\tau \frac{P(t) * Production(t)}{(1+r)^t} = P * \sum_0^\tau \frac{1}{(1+r)^t}$$

$$Break - even: \frac{NPV_{expenses}}{NPV_{income}} = \frac{\sum_0^\tau \frac{IC(t) + OM(t) + FC(t) + CO2T(t) + \cdots}{(1+r)^t}}{P * \sum_0^\tau \frac{1}{(1+r)^t}} = 1$$

$$LC(t) = P = \frac{\sum_0^\tau \frac{IC(t)+OM(t)+FC(t)+CO2T(t)+\cdots}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}} + \gamma$$

$$\text{sdLC} = \frac{\sum_0^\tau \frac{\sqrt{(sdIC)^2 + sdOM^2 + sdFC^2 + \cdots}}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}}$$

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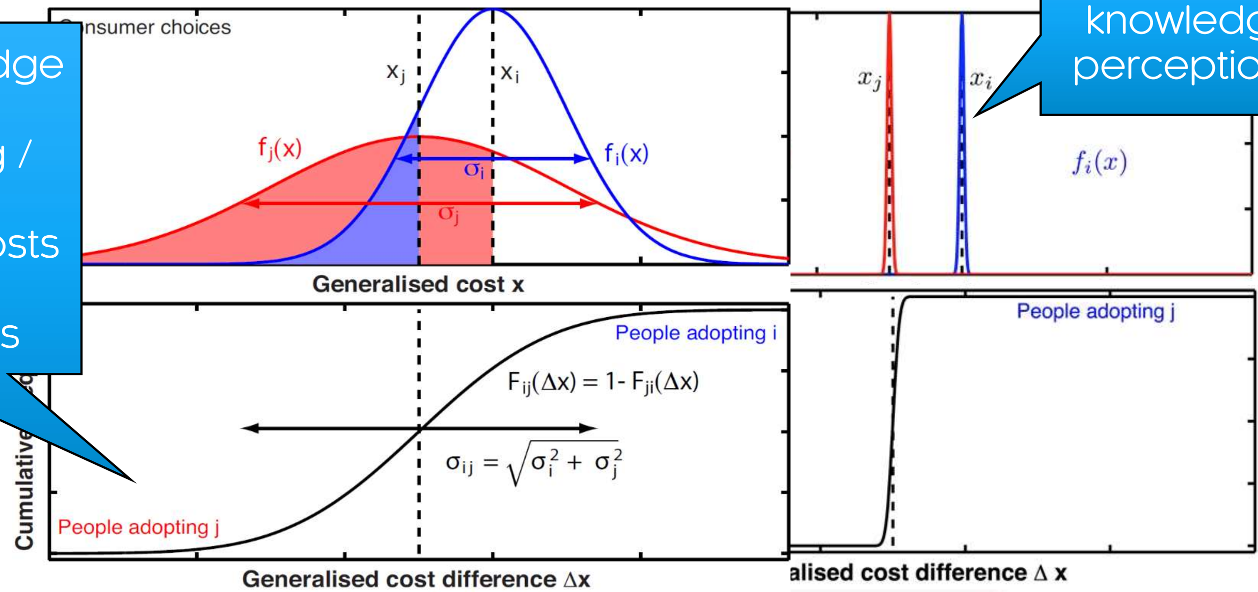
Mathematical framework - Investor preferences

$$F_{i\to j} = \mathrm{erf}\left(\frac{LC_j - LC_i}{sdF_{ij}}\right) = \mathrm{erf}\left(\frac{x_j - x_i}{\sigma_{ij}}\right)$$

$$F_{j\to i} = 1 - F_{j\to i}$$

$$sdF_{ij} = \sqrt{sdLC_i^{\,2} + sdLC_j^{\,2}} = \sqrt{\sigma_i^{\,2} + \sigma_j^{\,2}} = \sigma_{ij}$$

Imperfect knowledge / imperfect decision-making / different perceptions of costs …i.e. different investing agents



(Nearly) perfect knowledge / clear perception of costs

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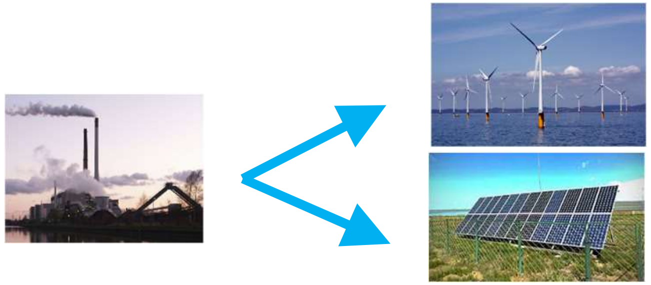
Mathematical framework - Market share changes



t → $t + \Delta t$

Power sector

t → $t + \Delta t$

Transport sector

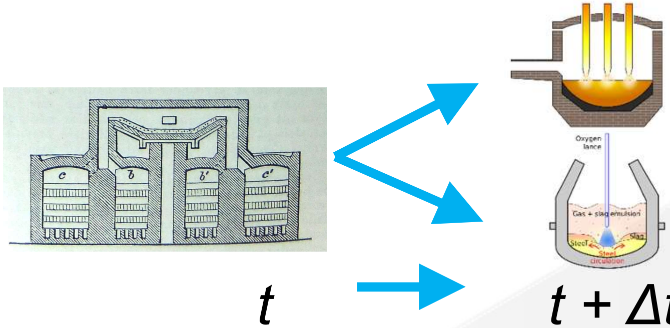
$$\Delta S_{j \to i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \cdot \Delta t$$

$$\Delta S_{i \to j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \cdot \Delta t$$

$$\sum_j \Delta S_{j \to i} = \Delta S_i = \sum_j S_i S_j \cdot \left(F_{ij} A_{ij} - F_{ji} A_{ji}\right) \cdot \Delta t$$

$$A_{ij} = \frac{\kappa}{BT_i \cdot LT_j}$$

Lotka-Volterra replicator function



t → $t + \Delta t$

Steel sector

t → $t + \Delta t$

Residential heating sector

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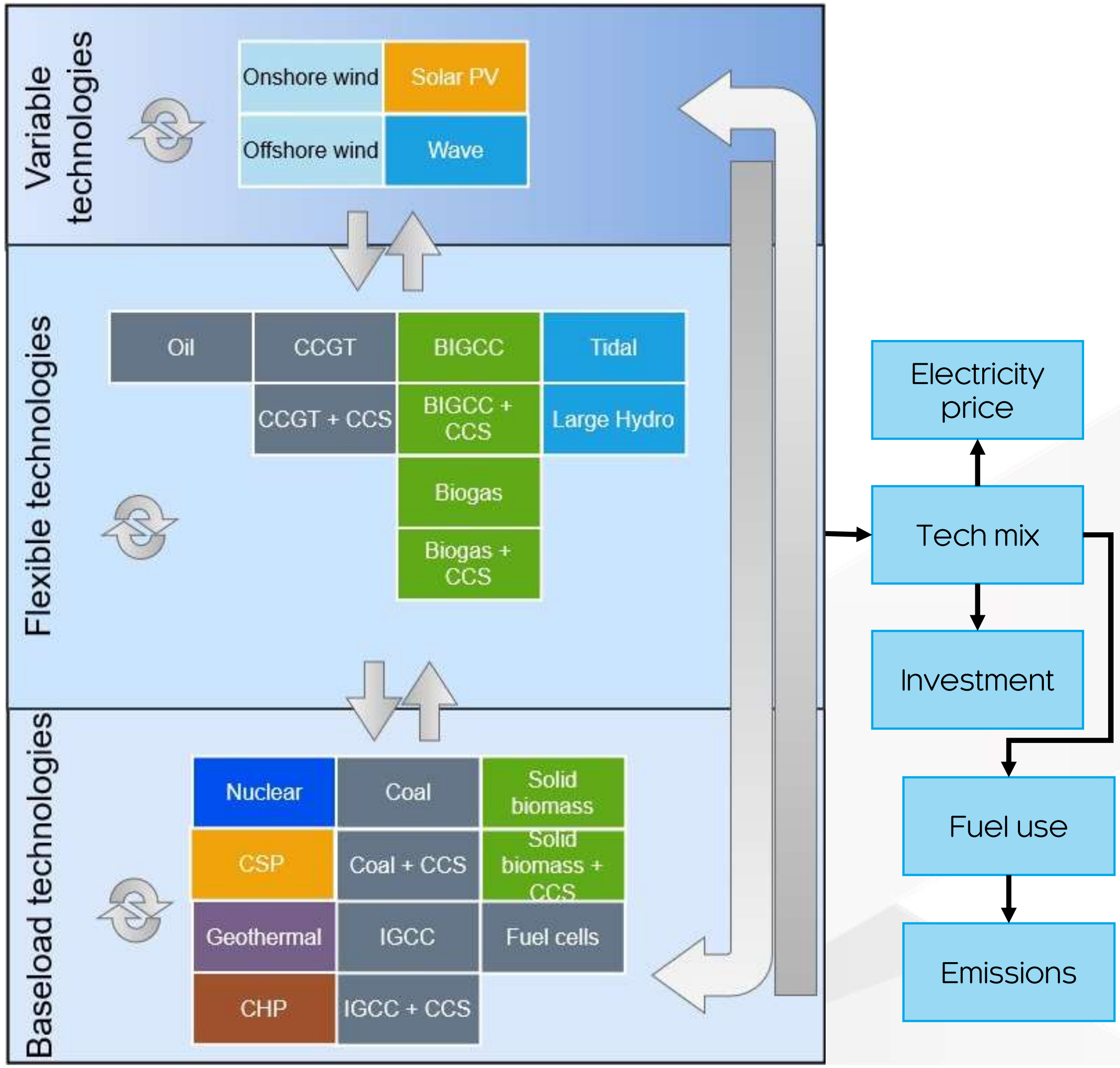
Domain of FTT:Power



Policies in FTT:Power

- Feed-in-tariffs
- Subsidies on capital investment
- Regulations
- Plant lifetimes
- Planned capacity additions
- Electricity demand-side policies

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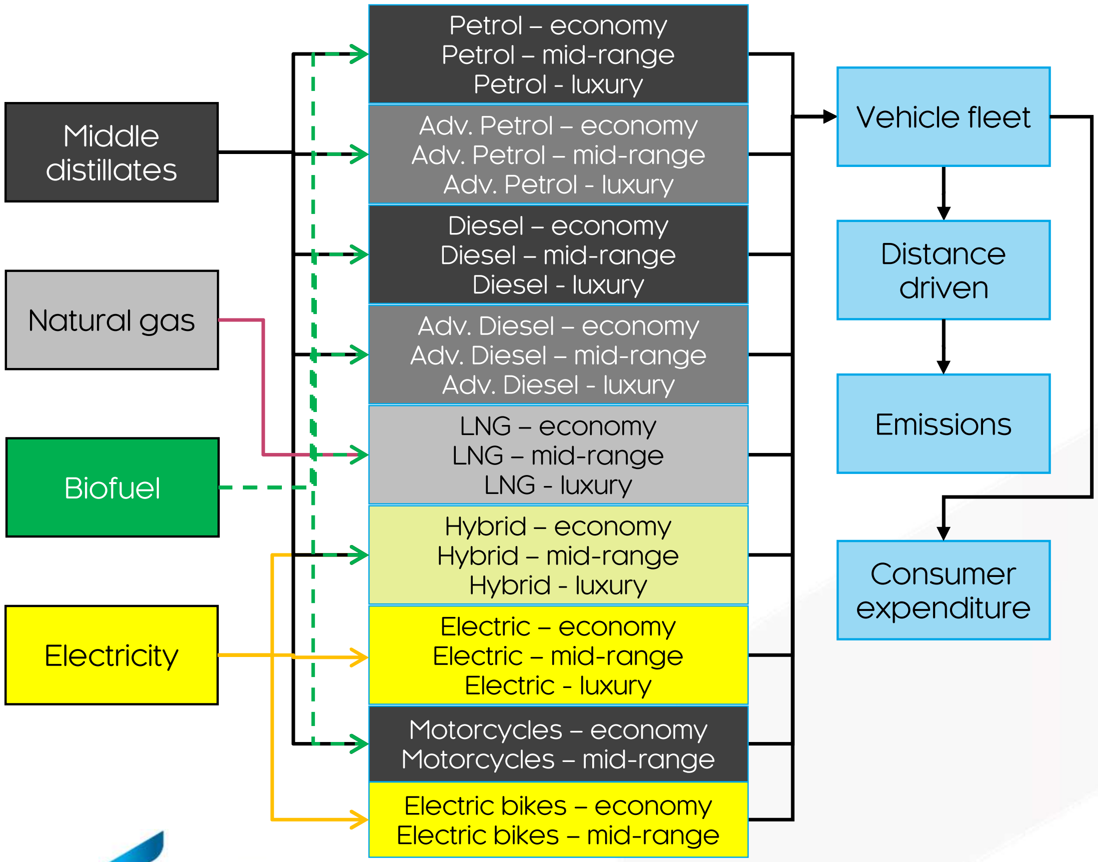
Domain of FTT:Transport



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Policies in FTT:Transport

- Vehicle tax
- Road tax
- Fuel tax
- Carbon tax
- Biofuel mandate
- Regulations
- Planned vehicle additions

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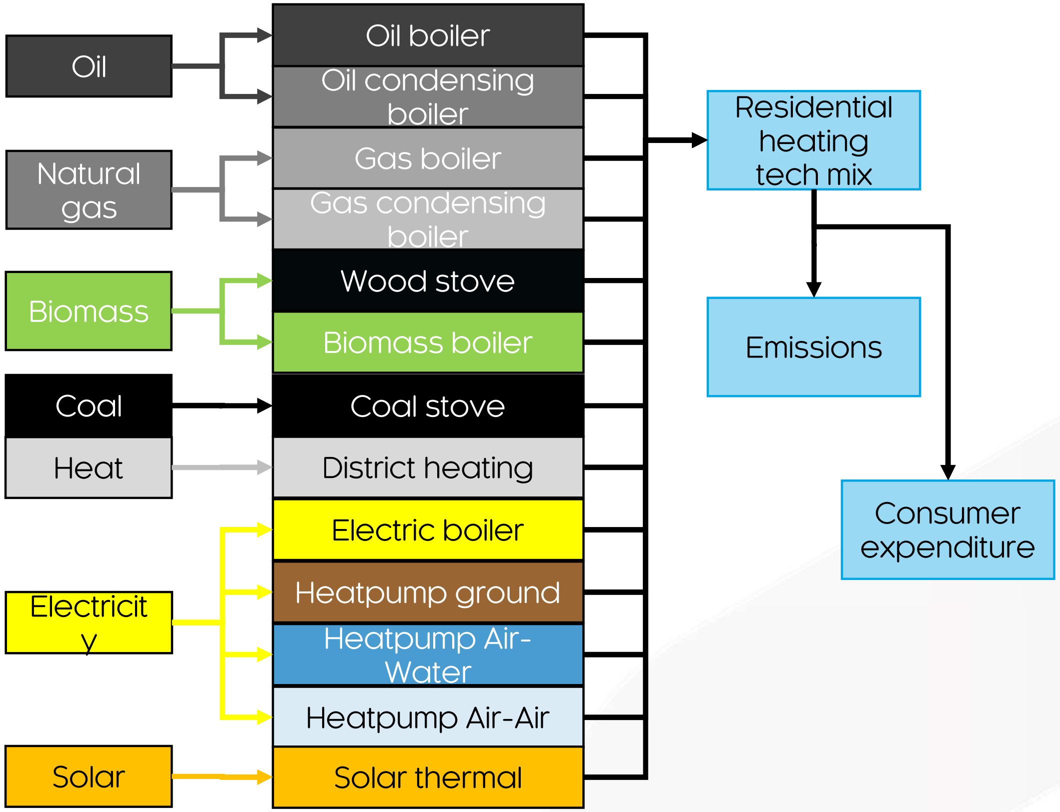
Domain of FTT:Heat



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Policies in FTT:Heat

- Subsidies/taxes on capital investment
- Energy tax
- Carbon tax
- Regulations
- Kick-start mandate
- Heat demand management (e.g. building requirements to improve insulation)

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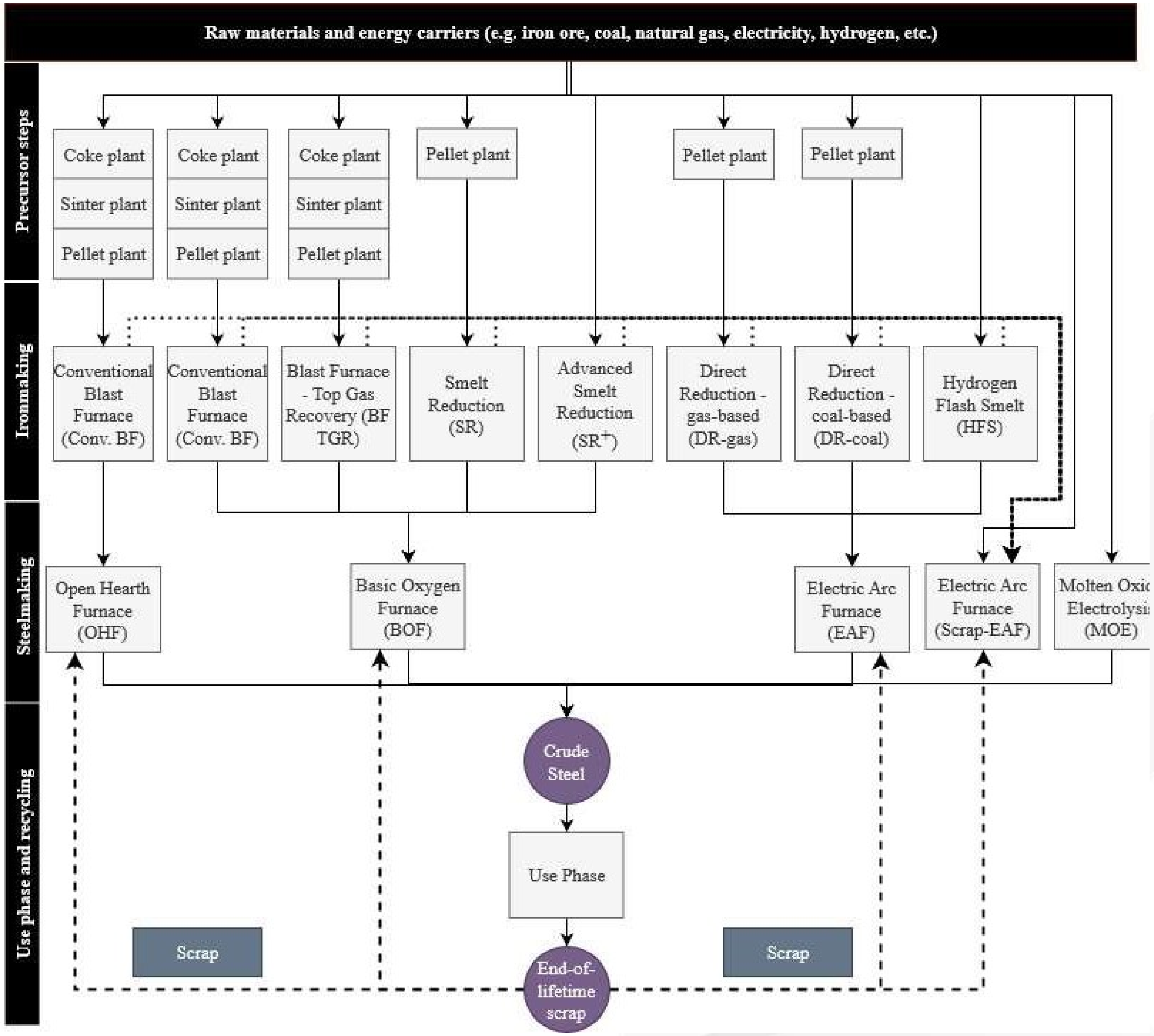
Domain of FTT:Steel



Policies in FTT:Steel

- Subsidies on capital investment
- Regulations
- Planned capacity additions
- Material tax/subsidy
- Energy efficiency investments
- R&D investments
- Capacity utilisation regulation
- Steel sector subsidies

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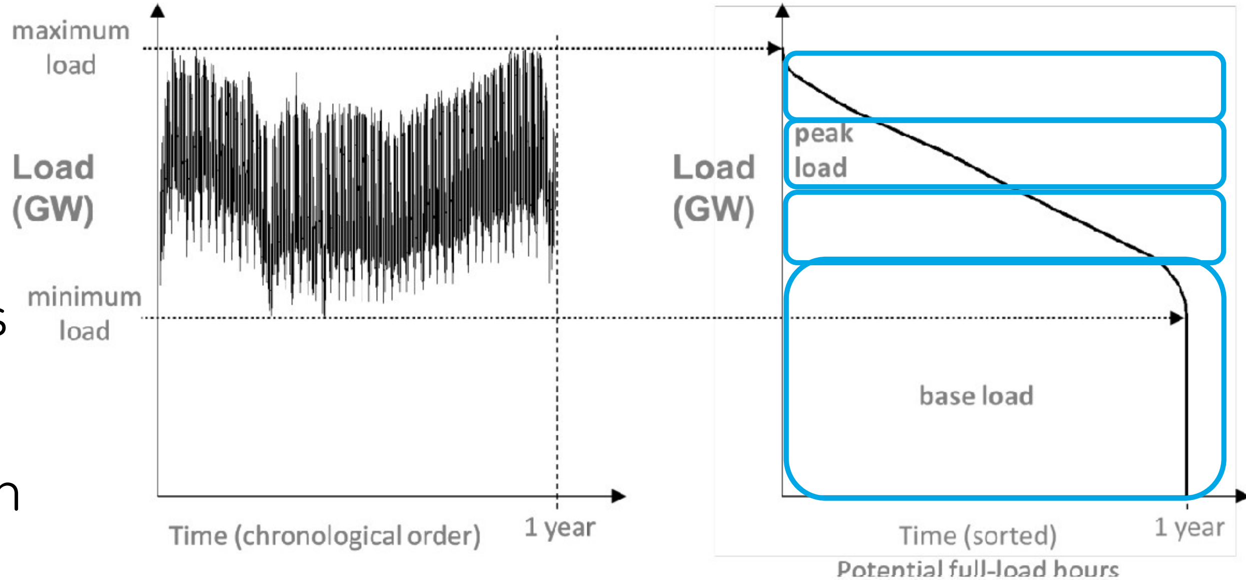
New feature: dispatch model for the power sector

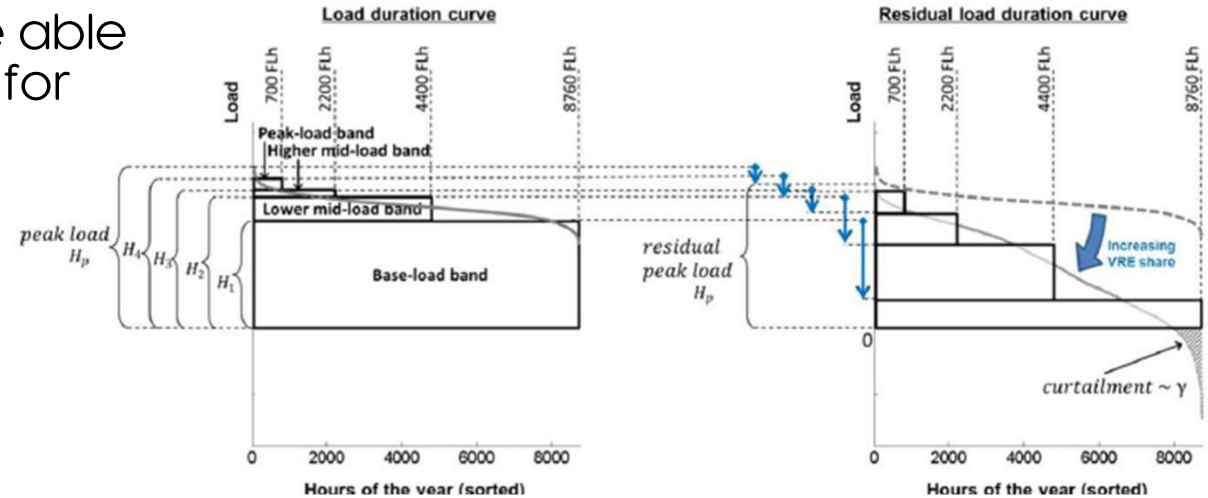
- FTT:Power solves annually and therefore lacks detail on seasonal variation in electricity demand and electricity supply of variable renewable energy sources
- FTT steps into the shoes of the entrepreneur/investor, while dispatch models step into the shoes of the dispatcher
- The role of the investor is to maximise profit (within constraints and without perfect foresight); the role of the dispatcher is to minimise the risk of power outages
- In the age of renewables, ways to storage electricity across seasons becomes increasingly important
  - ✓ when will investors / dispatchers prefer seasonal storage over curtailment or increasing the intermittent stock? Nobody knows this answer
  - ✓ without storage, full deployment of variable renewable energy sources is impossible
  - ✓ an older version of FTT:Power might underperform because the system lacks flexibility to allow for higher share from intermittent renewables
- Using statistics, the seasonal variability of electricity demand can be mimicked without the need of modelling it explicitly. This is because capacity planning occurs in larger timeframes than seasonal variability

Dispatcher meets investor

- By ordering the hourly demand in a year, we get load-duration curves
- We can divide this in different load bands and assign technologies to each based on their characteristics
- Variable renewables can be subtracted from the load-duration curves to get residual load-duration curves
- Using this framework we could be able to estimate investor preferences for increasing intermittent capacity, storage capacity, or curtailment

Ueckerdt, et al. (2017). https://doi.org/10.1016/j.eneco.2016.05.012





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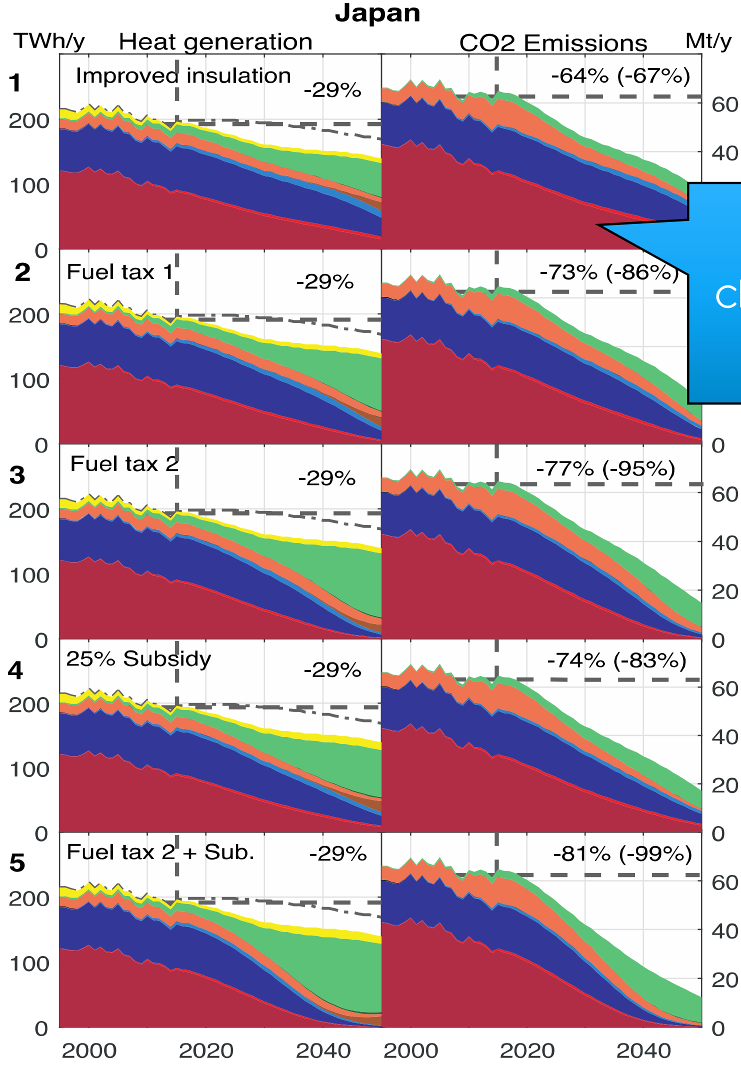
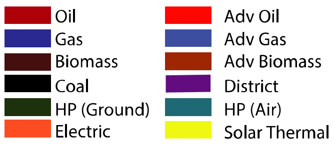
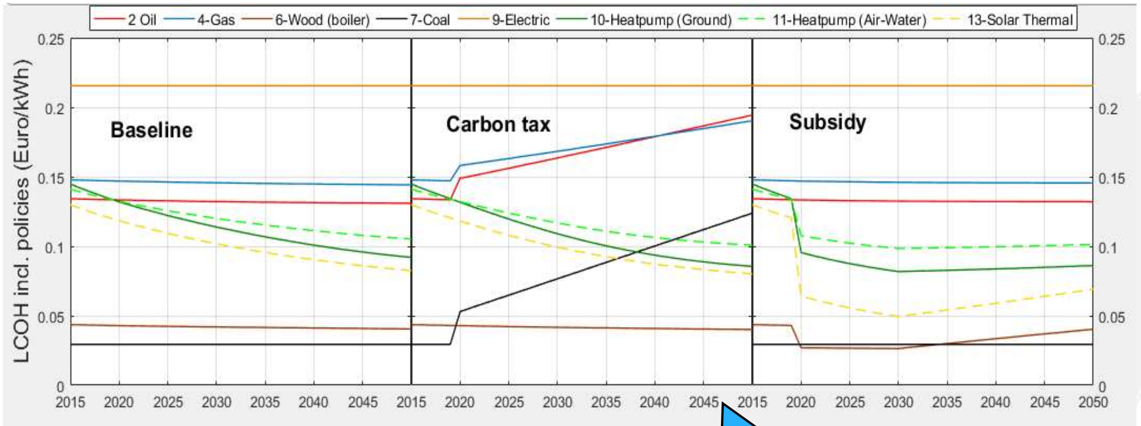
Effect of policies on the levelized cost

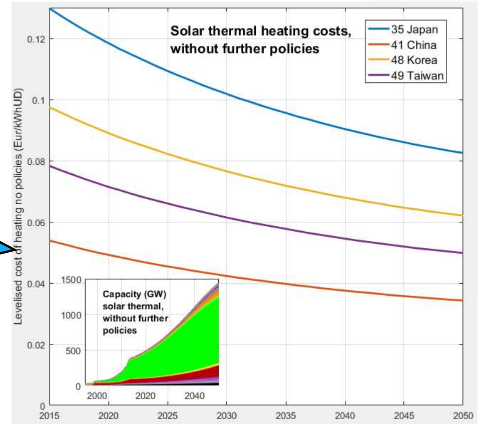




Effect of changing costs on diffusion



Effect of policies on costs



Effect of learning-by-doing on costs

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Knobloch, et al. (2017). http://wwwecono.meijo-u.ac.jp/discussion/dp_0009.pdf

Limitations of FTT

In general	
▪ how (un)certain are investors? ▪ did we get the sectoral constraints correct? ▪ did we get the regional diversity correctly?	
Power sector ▪when model goes beyond limitations, weird results appear ▪ no treatment of infrastructure or trade	**Road transport sector** ▪ no hydrogen fuel cells cars ▪ constant gamma values ▪ no relation to infrastructure
Residential heating sector ▪ no treatment of infrastructure ▪ no treatment of hydrogen-based heating	**Steel industry** ▪high technological detail but no historical record of utilisation ▪Limited data on costs

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Upcoming developments – 1

FTT:Agri

- An FTT variant where different land-uses are in competition
  - directed by demand for specific food commodities and demand for biofuels
  - constrained by land available, bio-physical parameters, and affected by climate change

FTT:H2

- A hydrogen supply model that decides upon hydrogen production technologies
  - many demand-side potential uses of hydrogen exist (energy storage, fuel substitute, etc.), which depends upon developments at the supply-side of hydrogen (can it cope? can it compete?)

FTT:Waste

- Academia Sinica Taiwan is trying to develop an FTT model for waste treatment
  - Could be interesting for research related to circular economies

Upcoming developments – 2

FTT:Chemicals

- The chemicals are almost exclusively produced using fossil-based chemistry
  - the chemical sector can therefore not be excluded from fossil carbon-free scenarios
  - many theoretical pathways to produce bulk chemicals (e.g. ammonia, methanol, simple organic compounds, etc.) from bio-based fuel stocks are being investigated

Combining E3ME with FTTs

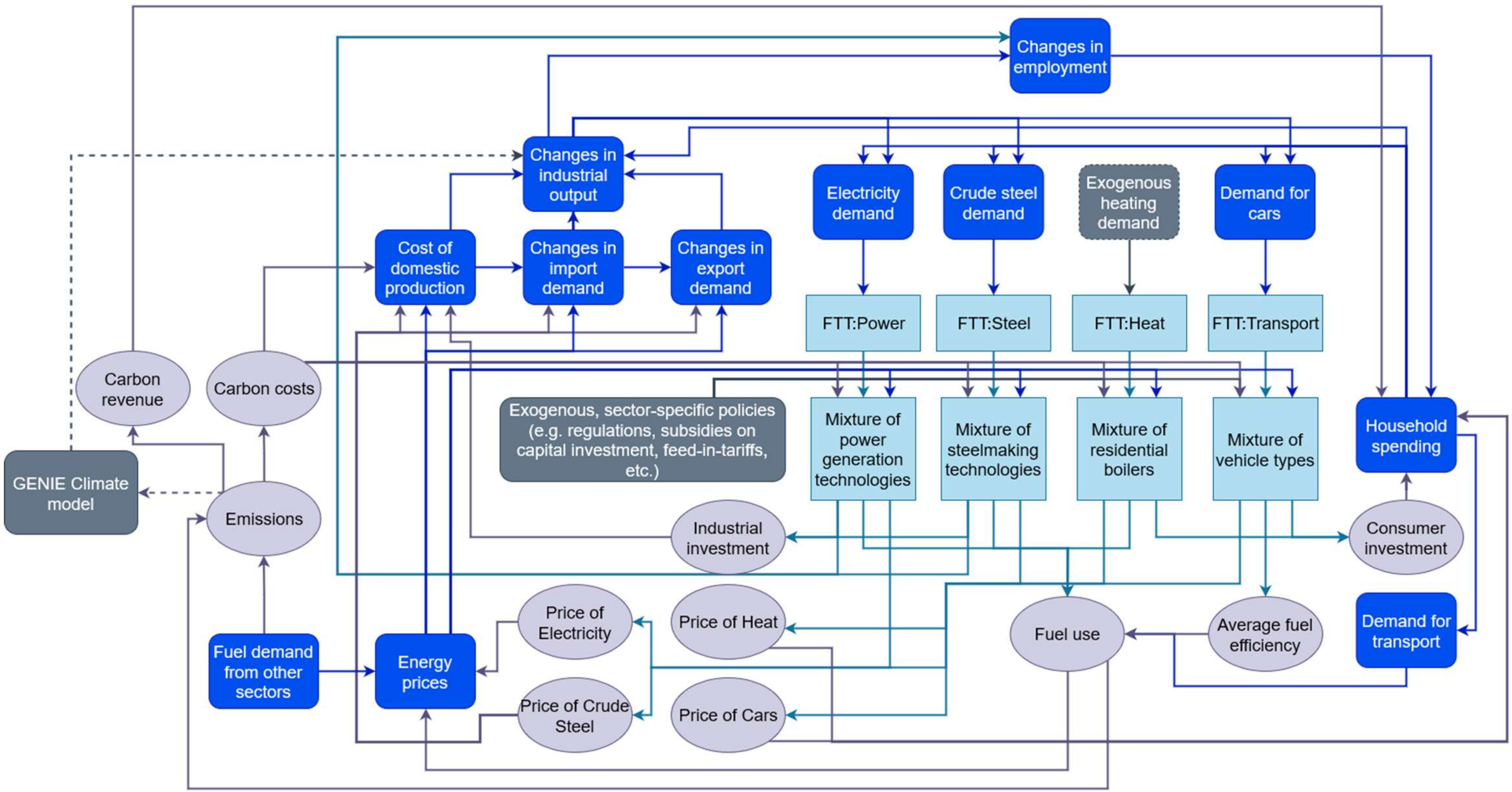
E3ME and FTTs

- E3ME and FTTs complement each other
- Both models are simulation models meaning
  - ✓ based on decision making rather than social planning (optimisation)
  - ✓ imperfect decision making due to lack of information and other barriers
  - ✓ decision makings can be affected by policies
  - ✓ learning by doing, costs come down over time and technologies are path dependent

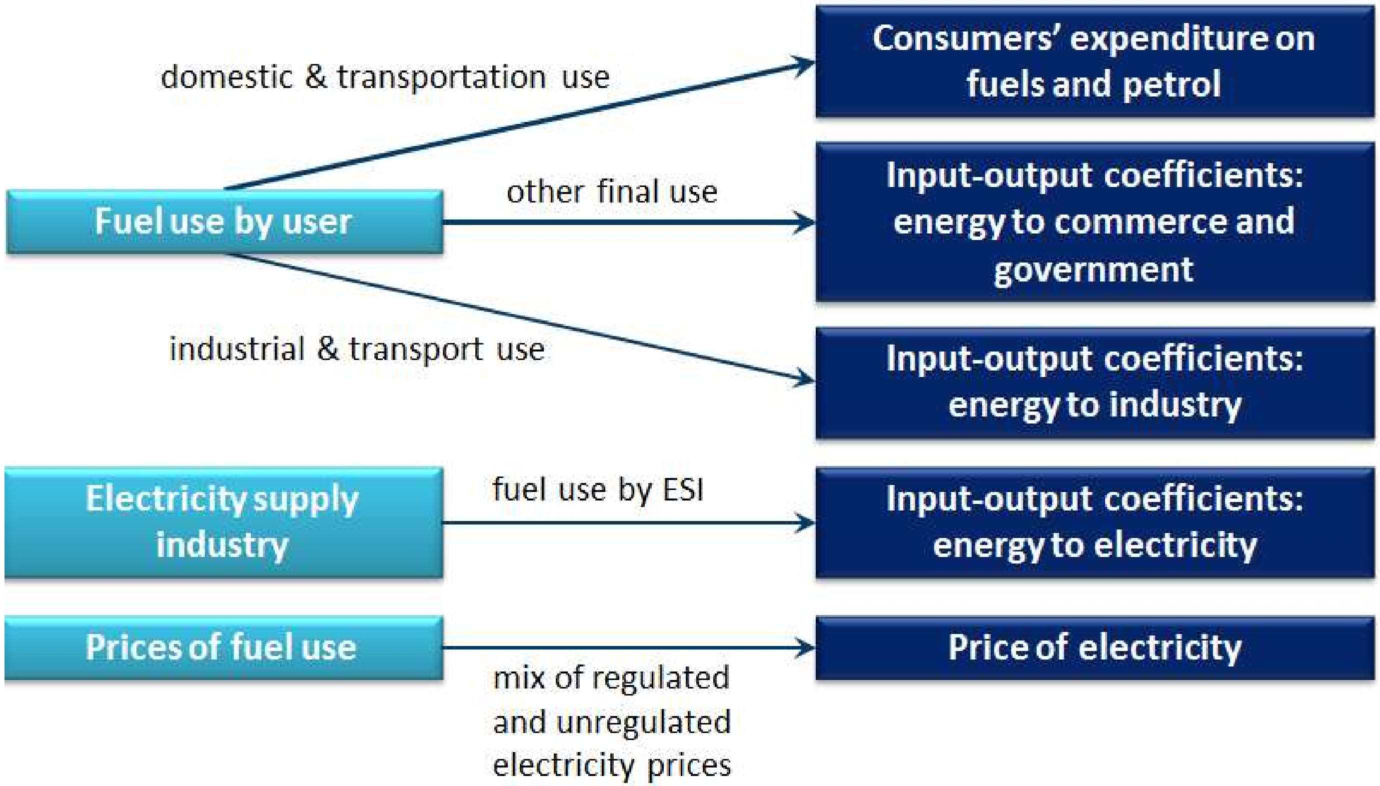
Natural Resource Constraints

- This database provides natural resources cost-supply curves for each region
- It also includes a review of non-renewable fossil and nuclear fuels.
- This means E3ME-FTT can provide:
    - endogenous fossil fuel prices (rebounds in demand)
    - endogenous capacity factors and investment costs according to maximum potentials for renewables and nuclear
    - impacts on oil exporting regions (different extraction costs)

How do FTT and E3ME complement each other?



Feedback from the Energy Sub-model



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Rebound effects

- A macroeconomic model is required to estimate indirect and induced rebound effects
  - ✓ the economic benefits of greater efficiency lead to higher rates of economic activity, meaning more energy consumption
  - ✓ some models (both energy and economic) will also include fossil fuel price feedback effects, with lower initial demand leading to lower prices and rebounds in consumption
- Estimates for the scale of rebound effects vary considerably – it is clear that they depend on sector, location, time period and several other factors


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