GRADUATE SCHOOL OF ECONOMICS,
FACULTY OF ECONOMICS,
Kyoto University

Policy design for diffusing hydrogen economy and its impact on Japanese economy by 2050 carbon neutrality using E3ME-FTT model

Soocheol Lee Meijo University
Xu Han Kyoto University
Aileen Lam World Bank
Pim Vercoulen *Cambridge Econometrics & University of Exeter*

Date: March 2023

Contents

GRADUATE SCHOOL OF ECONOMICS,
FACULTY OF ECONOMICS,
Kyoto University

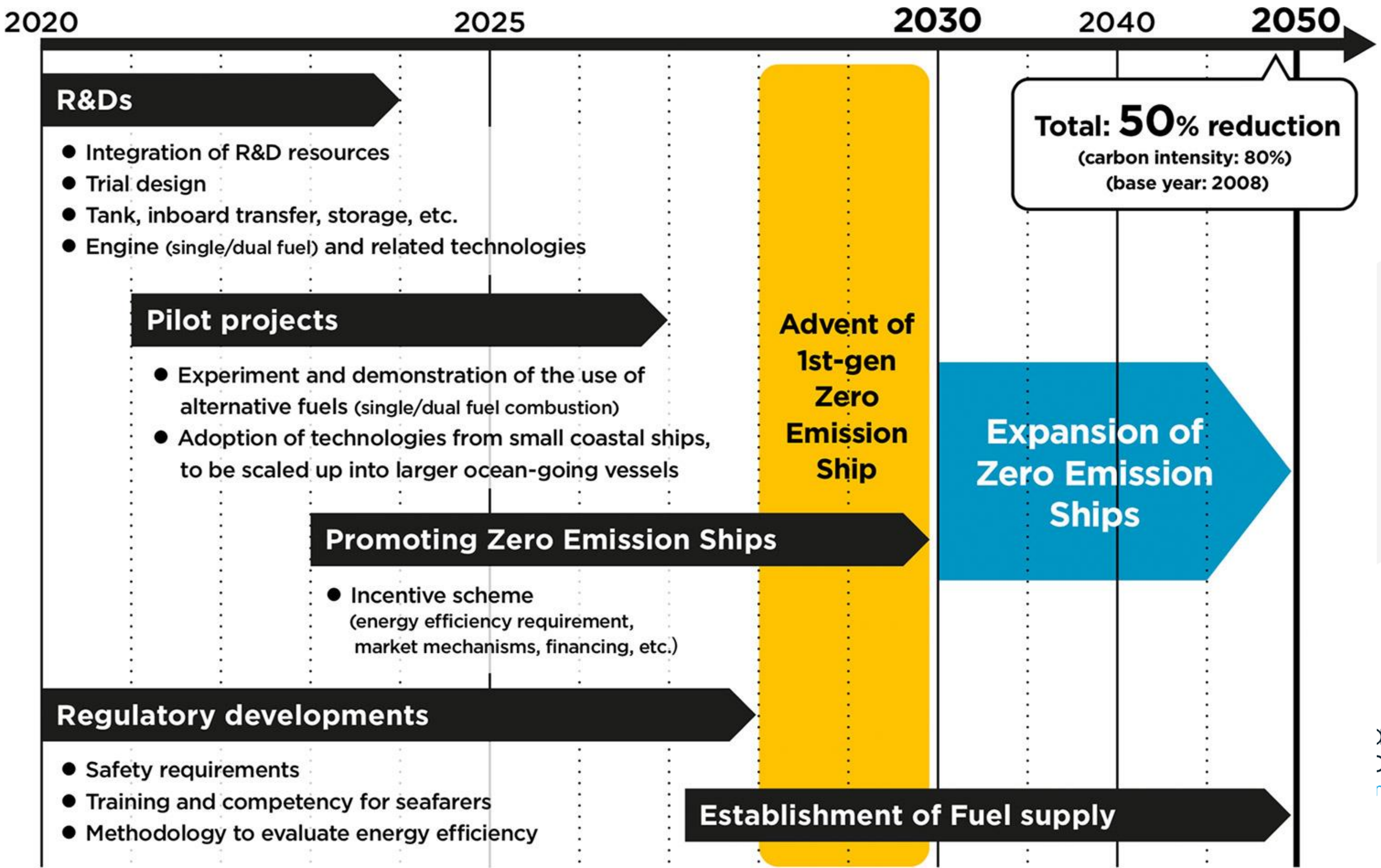
Introduction

cambridge econometrics
camecon.com

Background

- Japan has announced to achieve Net-Zero by 2050
- The Ministry of Economy, Trade, and Industry (METI) launched a Roadmap to “Beyond-Zero” Carbon
  - Scale up hydrogen supply
  - Make hydrogen affordable
  - Decarbonise downstream sectors such as power generation and hydrogen supply
  - Exploit CC(U)S
- Last year, Lee et al. published a Net-Zero scenario but that excluded the scope of the hydrogen economy

Roadmap to “Beyond-Zero” Carbon



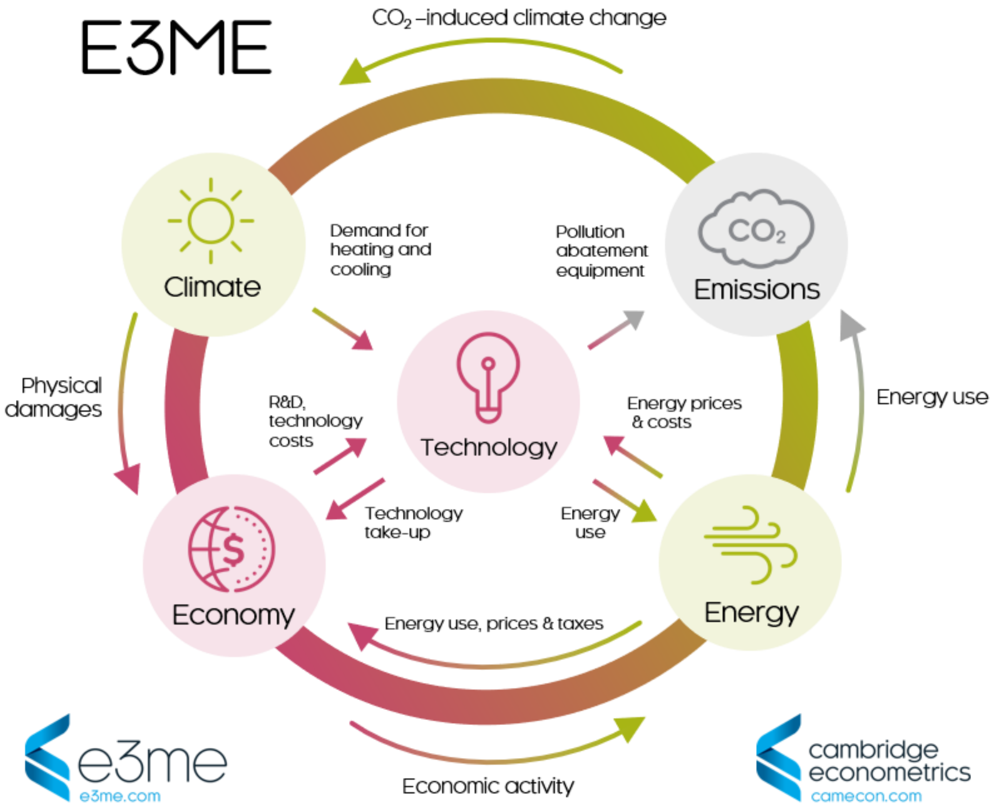
Methodology

cambridge econometrics
camecon.com

Introduction to E3ME-FTT:Steel

- **E3ME is macro-econometric model**
  - Follows the post-Keynesian school of thought
  - Demand-driven
  - Economies do not per se operate in equilibrium

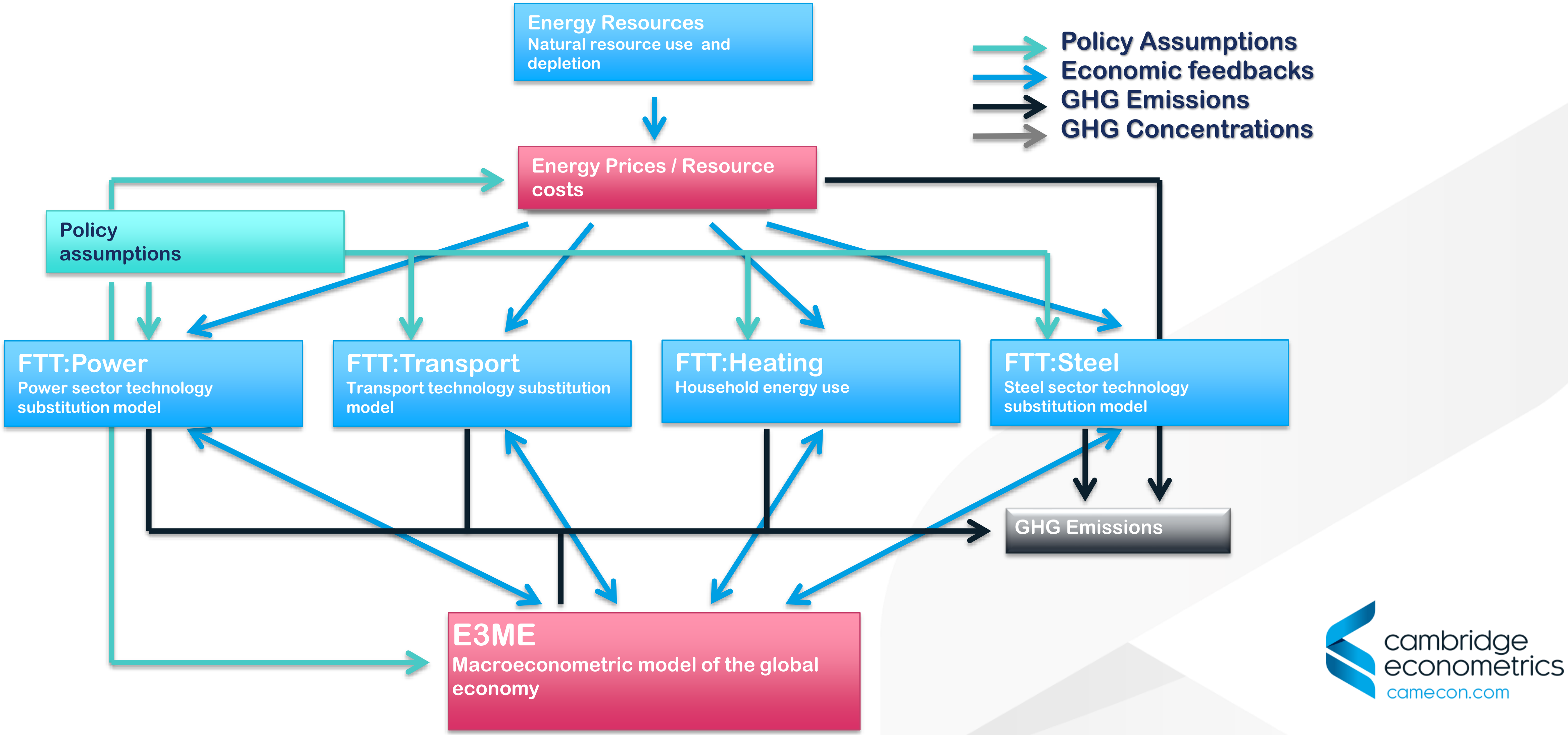
- **FTT is techno-economic diffusion model**
  - Builds on evolutionary economics
  - Heterogeneous agents
  - Does not per se follow a least-cost approach



cambridge econometrics
camecon.com

Future Technology Transformations

Introduction to E3ME-FTT



Introduction to E3ME-FTT:Steel

- **The representation of agents is important**
  - Different agents have different perceptions and hold different valuations of the future
  - Entrepreneurs are risk-seeking agents and expect higher rates of returns (but that is not guaranteed)
  - Without risk-seeking agents, new technologies will never see the light of day!
  - Because some agents take risk today, costs will be lower in the future

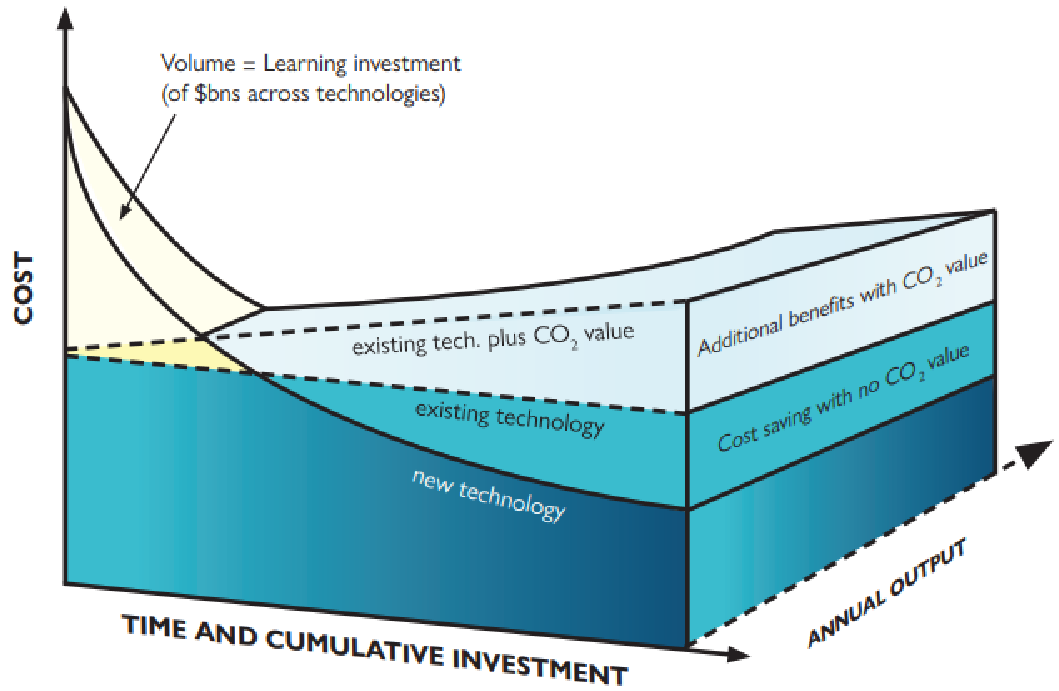


Figure 7: The stylised economics of strategic investment
Source: *Planetary Economics*, Chapter 9, Grubb, Hourcade & Neuhoff (2014).[82]

Theoretical framework

- Uncertainty is key in FTT and there are many sources of uncertainty. The heterogeneity of agents is just one of them
- Technologies compete with each other for market shares on the basis of expected costs differentials, which can be influenced by
- FTT uses a replicator function to determine market share changes based on the Lotka-Volterra (LV) equation (or predator-prey)
- The LV equation contains parameters for “births” and deaths”, like in demographic and ecological modelling
- For a full description of the theoretical and mathematical framework I refer to:
  - Mercure, J. F. (2012). “FTT: Power: A global model of the power sector with induced technological change and natural resource depletion”. *Energy Policy*, 48, 799-811.
  - Mercure, J. F. (2015). “An age structured demographic theory of technological change”. *Journal of Evolutionary Economics*, 25(4), 787-820.

See Mercure (2015), DOI: 10.1007/s00191-015-0413-9

Future Technology Transformations

Levelised cost

Net present value of expenses	$NPV_{expenses} = \sum_{0}^{\tau} \frac{IC(t)/CF(t) + OM(t) + FC(t) + CO2T(t) + \cdots}{(1+r)^t}$
Net present value of benefits	$NPV_{benefits} = \sum_0^\tau \frac{P(t)*Production(t)}{(1+r)^t} = P * \sum_0^\tau \frac{1}{(1+r)^t}$
Break-even point	$\frac{NPV_{expenses}}{NPV_{benefits}} = 1$
Levelised cost – mean (LC)	$LC = P = \frac{\sum_0^\tau \frac{IC(t)/CF + OM(t) + FC(t) + CO2T(t) + \cdots}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}}$
Levelised cost – st.dev (LC)	$LC^{sd} = \frac{\sum_0^\tau \frac{\sqrt{\left(sdIC/CF\right)^2 + sdOM^2 + sdFC^2 + \cdots}}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}}$

See Mercure (2015), DOI: 10.1007/s00191-015-0413-9

Investor preferences

Difference of the average LC	$\Delta C_{ij} = LC_i - LC_j$
Gumbel distribution of LC	$f_i(C) = e^{-e^{-(C-LC_i)/LC_i^{sd}}}$
Standard deviation	$F_{ij}^{SD} = \sqrt{2 \cdot {LC_i^{sd}}^2 \cdot {LC_j^{sd}}^2}$
Preferences as convoluted Gumbel distributions (yields a logistic distribution)	$\mathrm{F}_{ij} = \int_{-\infty}^{+\infty} (f_i * f_j) d\Delta C = \frac{1}{1 + e^{\Delta C_{ij}/{F_{ij}^{SD}}^2}}$
Preferences for the alternative	$F_{ji} = 1 - F_{ji}$

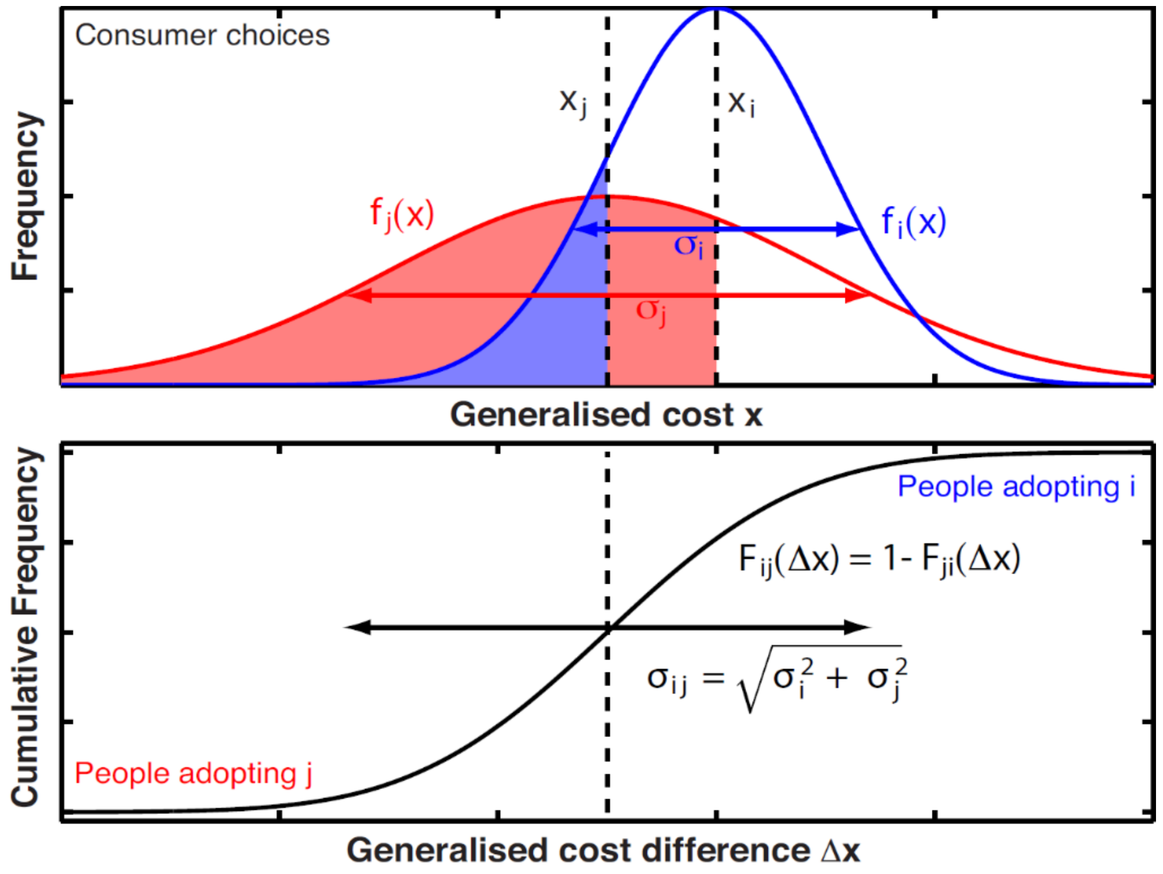
Future Technology Transformations

cambridge econometrics
camecon.com

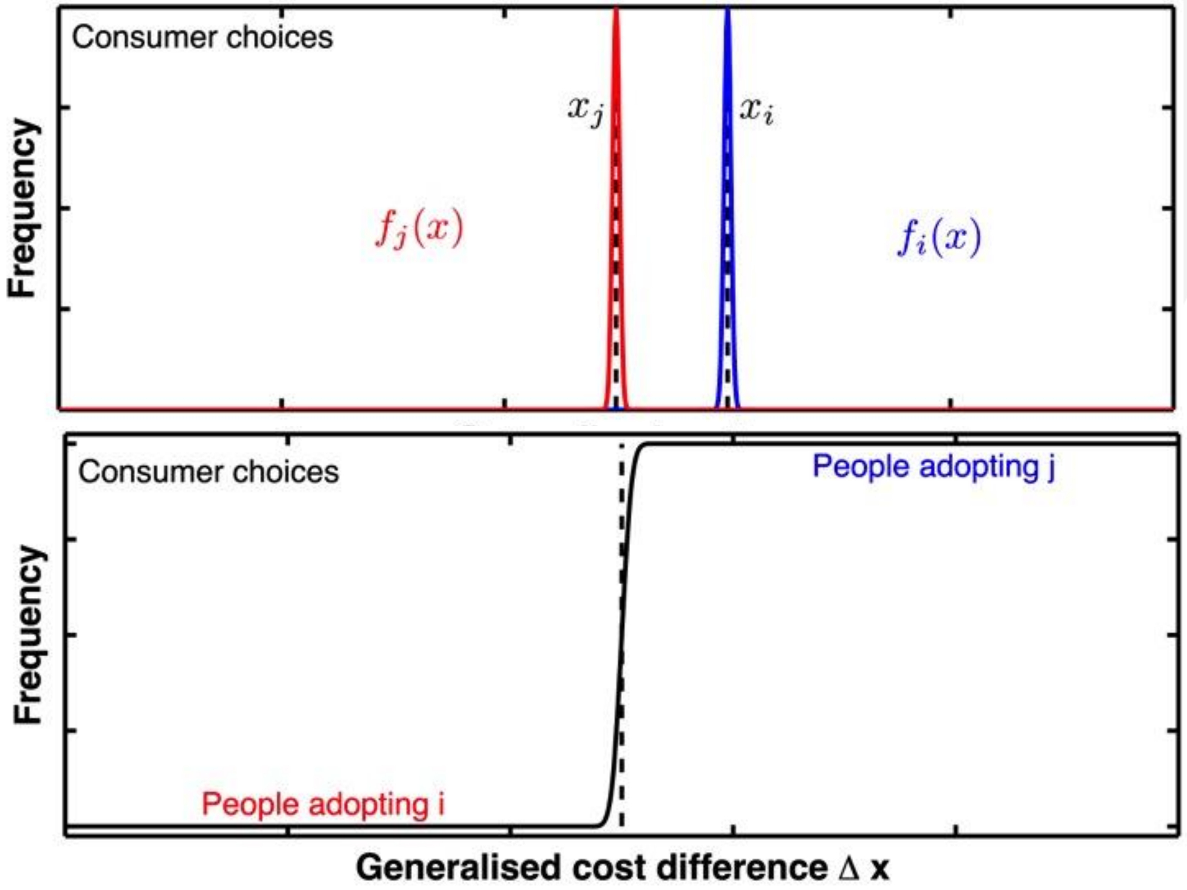
See Mercure (2015), DOI: 10.1007/s00191-015-0413-9

Investor preferences

Imperfect information / knowledge / foresight



Perfect information / knowledge / foresight



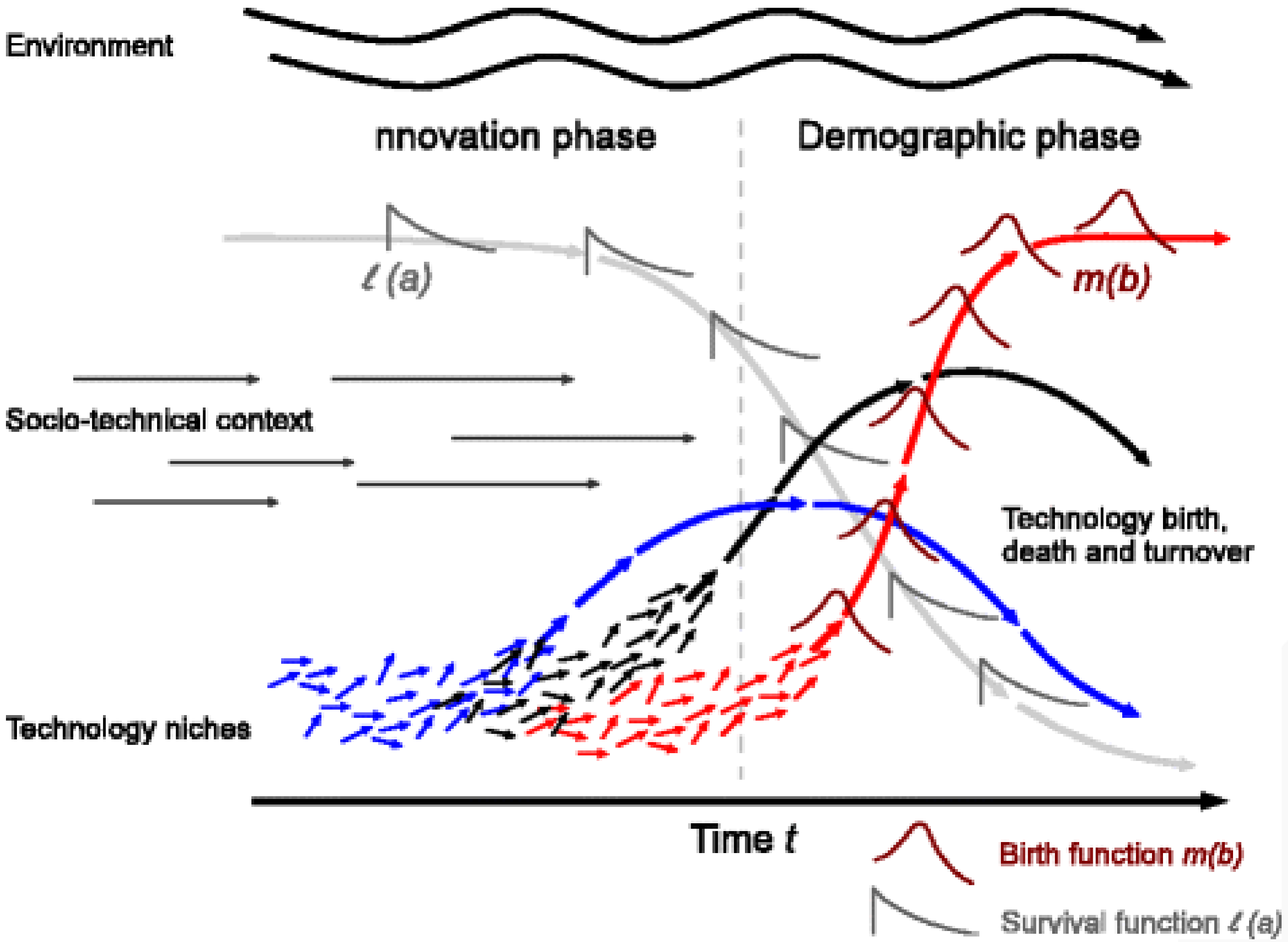
See Mercure (2015), DOI: 10.1007/s00191-015-0413-9

Market share dynamics

Market share substitution between incumbent technology j and alternative i	$$\Delta S_{j\to i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \cdot \Delta t$$
Market share substitution between incumbent technology i and alternative j	$$\Delta S_{i\to j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \cdot \Delta t$$
Replicator function (core of the model)	$$\sum_j \Delta S_{j\to i} = \Delta S_i = \sum_j S_i S_j \cdot \left(F_{ij}A_{ij} - F_{ji}A_{ji}\right) \cdot \Delta t$$
Substitution frequency matrix (combines "births" and "deaths")	$$A_{ij} = \frac{\kappa}{BT_i \cdot LT_j}$$

See Mercure (2015), DOI: 10.1007/s00191-015-0413-9

Market share dynamics

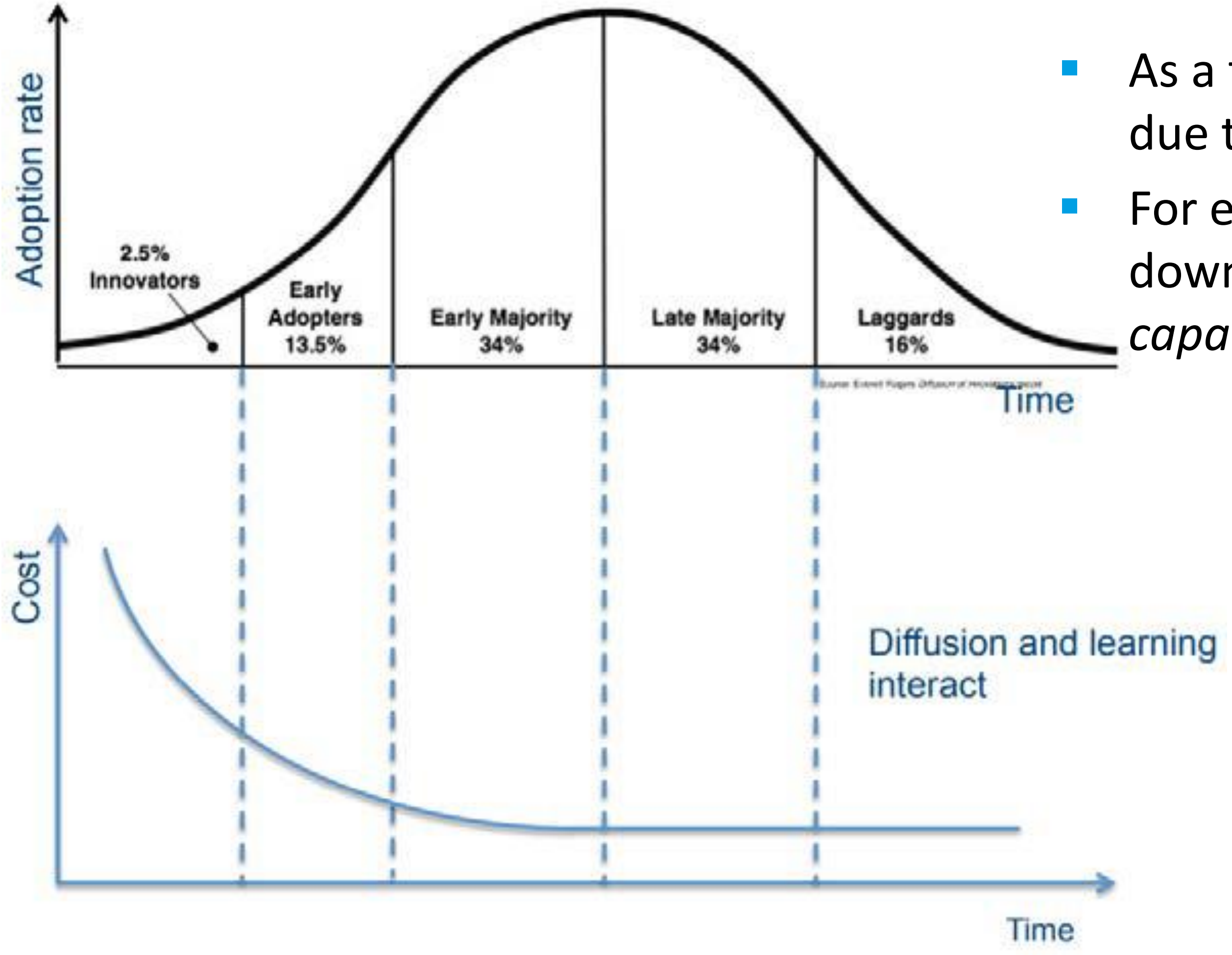


- Technology diffusion takes place in a certain context
- Technology diffusion may change the context
- Not all efforts are successful

Source: Mercure (2015), DOI: 10.1007/s00191-015-0413-9 (adapted from Geels (2002), DOI: 10.1016/S0048-7333(02)00062-8

Learning-by-doing

Future Technology Transformations



- As a technology diffuses into a system its costs go down due to learning-by-doing effects
- For every technology ***i*** at time ***t***, the investment costs ***I*** go down at a rate ***b****, for every doubling of global cumulative capacity* ***C***.

$$\Delta I_{i,t} = -b_i \frac{\Delta C_{i,t}}{C_{i,t}} I_{i,t}$$

$$I_{i,t+1} = I_{i,t} + \Delta I_{i,t}$$

$$I_{i,t+1} = I_{i,t}(1 - b_i)^{\frac{\Delta C_{i,t}}{C_{i,t}}}$$

cambridge econometrics
camecon.com

See Mercure (2012), DOI: 10.1016/j.enpol.2012.06.025

Calibration

Future Technology Transformations

- The method outlined here requires a lot of data and a lack of data can lead to strange behaviour because FTT is path dependent model
- However, bad or missing data is unavoidable and to remedy that calibration is needed
- Calibration occurs by adding values to the levelised cost estimates

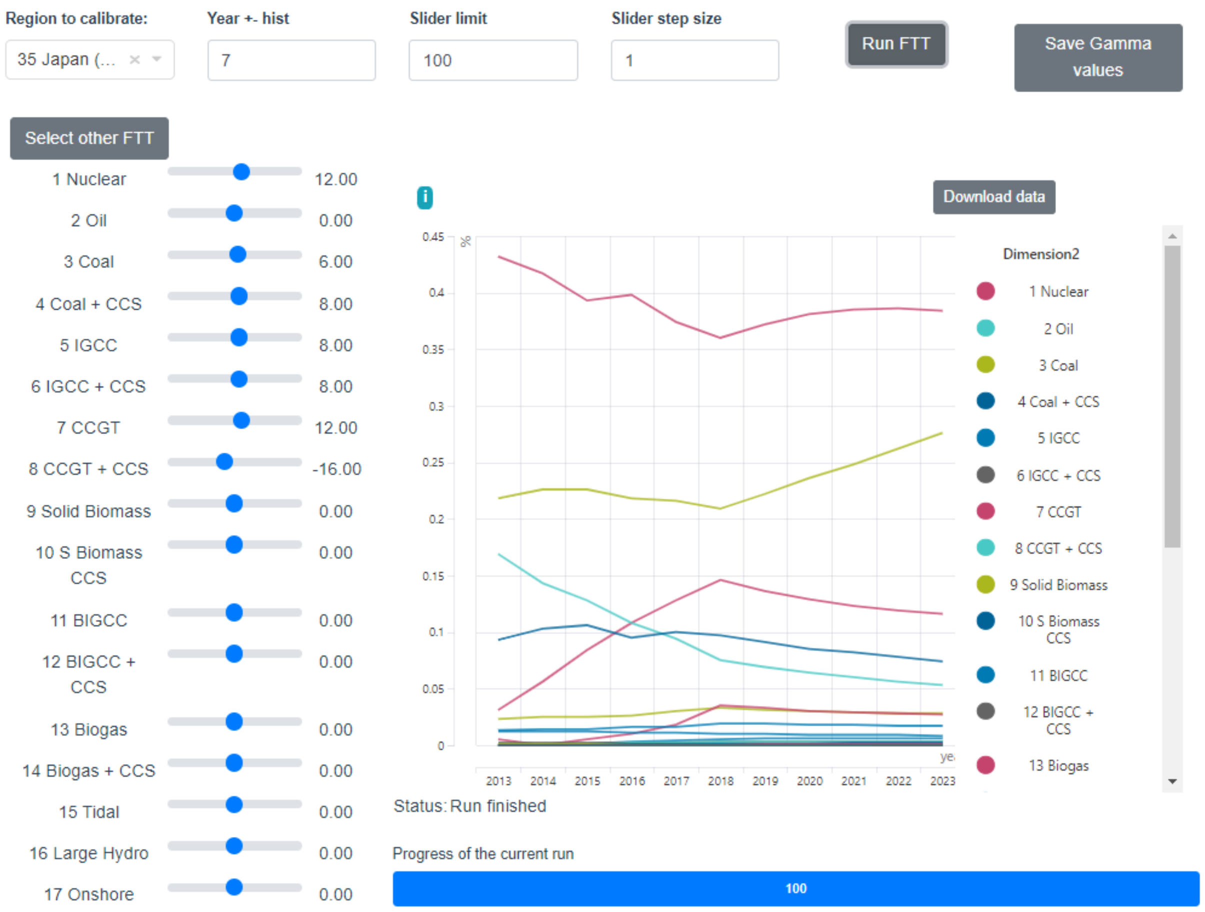
$$LC^{\gamma} = LC + \gamma$$

- The calibrated levelised cost feed into the preference matrix which changes the decision-making core
- We calibrate “by eye” and calibration is assumed to be finished when the market share increments of the last few historical years are aligned to the market share increments of the first few simulated years

See Mercure (2012), DOI: 10.1016/j.enpol.2012.06.025

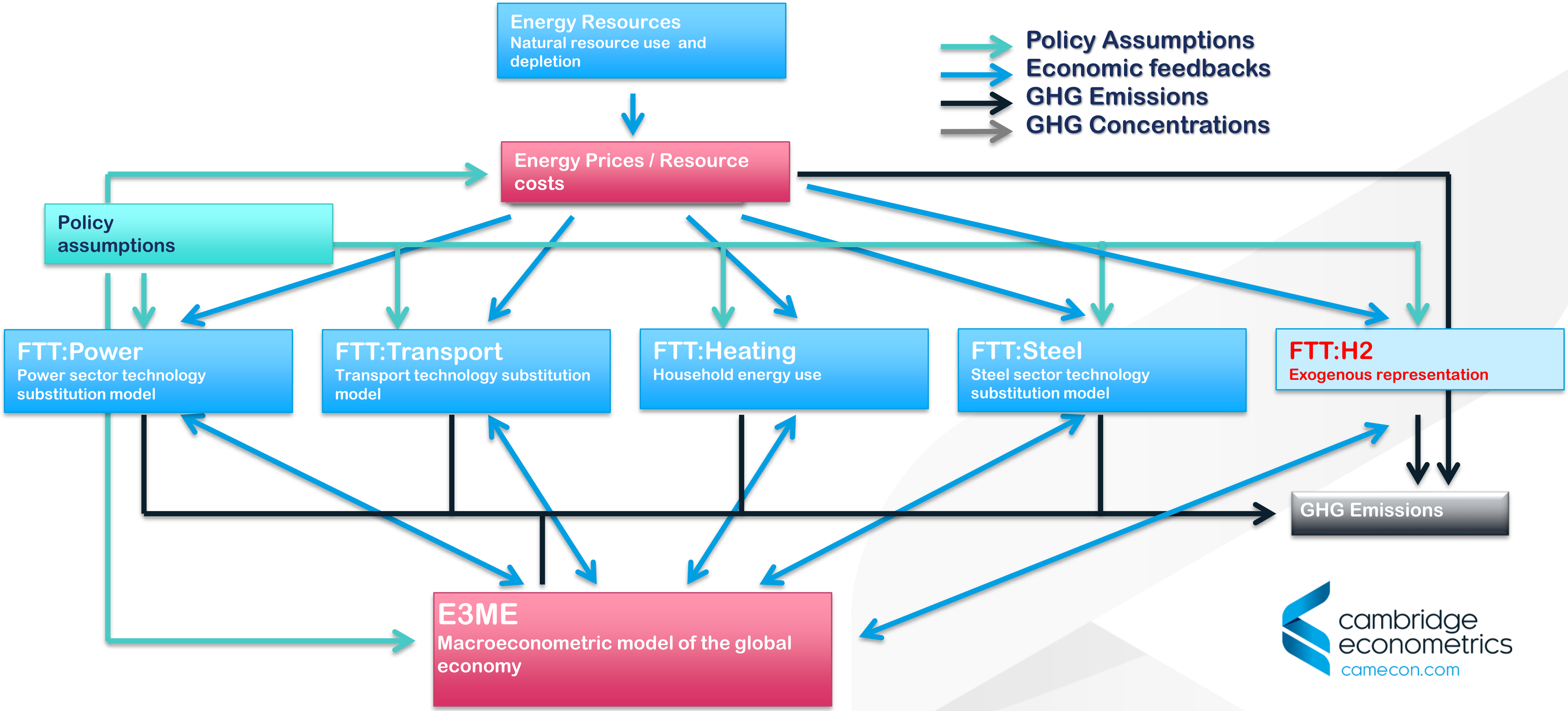
Calibration

Future Technology Transformations



econometrics
camecon.com

Introduction to FTT



cambridge econometrics
camecon.com

Technological representation in FTT

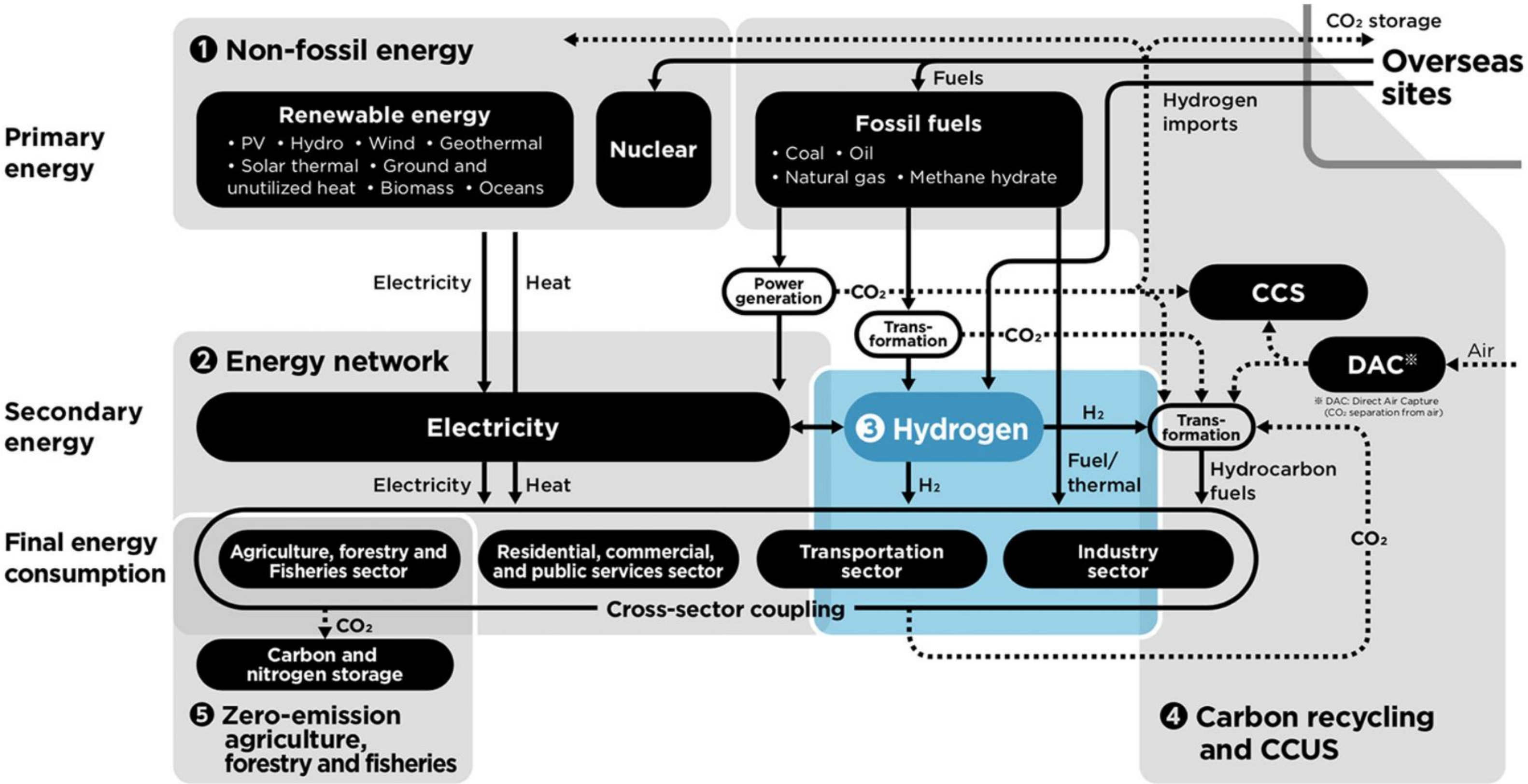
	FTT-Power	FTT-Transport	FTT-Heat	FTT-Steel	H2 supply
Technologies	24	25	13	26	Exogenous representation of Hydrogen supply (includes exogenous hydrogen prices)
Inputs from E3ME	Electricity demand	Fleet/ car demand	Heat demand	Steel demand	Hydrogen demand
Output to E3ME	• Fuel demand and emissions • Electricity price • Electricity investment • Detailed PG employment	• Fuel demand and emissions • Average car price	• Fuel demand and emissions • Costs of boilers	• Fuel demand and emissions • Steel investment • Steel price • Detailed steel employment	• Fuel demand and emissions • Investments
Policies	• Tax (carbon, fuel, vehicle, boiler) • Subsidy • Regulations (phase out, limits) • Turnover time • Discount rate • Feeds in tariff • Demonstration technology • Demand side policies e.g. building energy efficiency				

cambridge econometrics
camecon.com

Representation of the hydrogen economy

cambridge econometrics
camecon.com

Hydrogen economy



(Figure 1) Extract from Environment Innovation Strategy materials

Resource: METI (Japan's Roadmap to "Beyond-Zero" Carbon)

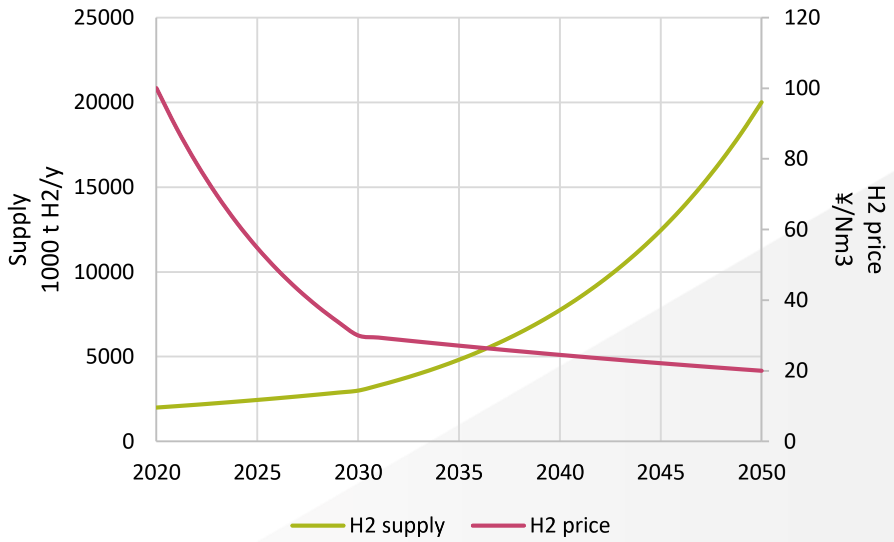
cambridge econometrics
camecon.com

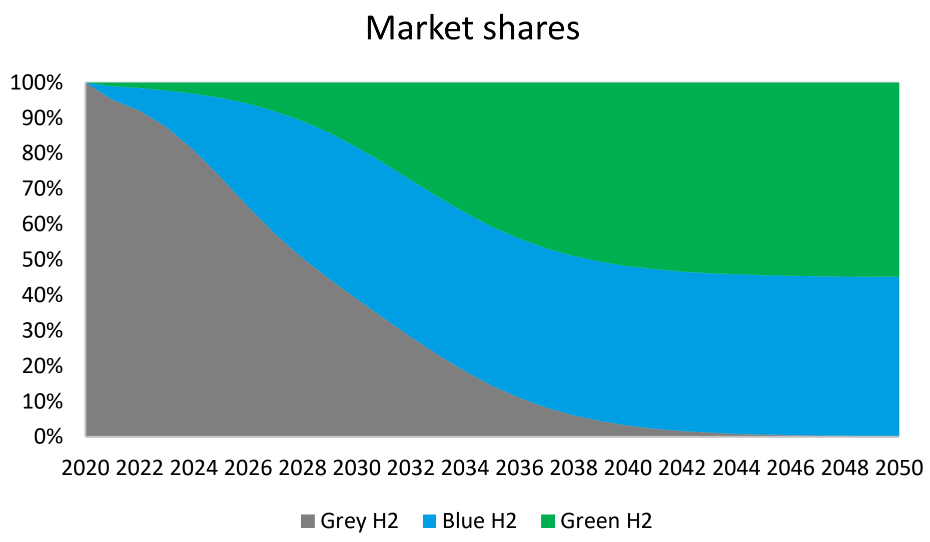
Representation of hydrogen supply

- Hydrogen demand is simulated by E3ME-FTT
  - Only no representation in the residential heating sector
  - Non-FTT sectors use relevant FTT sectors as proxy for hydrogen demand
- However, E3ME-FTT does not explicitly represent the hydrogen supply sector
- Therefore we resort to an exogenous representation of hydrogen supply

- **METI provides**:
  - Domestic hydrogen supply targets
  - Domestic hydrogen price targets
  - If demand exceeds supply projection, we assume hydrogen imports at 150% of the price

- Exogenous development of technologies



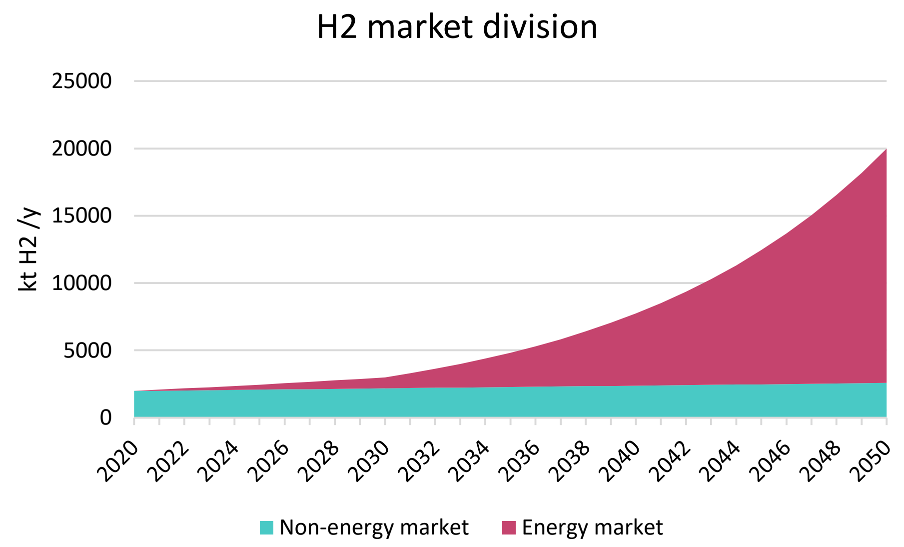


Disentangling hydrogen markets

- Captive, on-site market vs merchant markets
  - Captive: hydrogen production occurs at the site of demand (e.g. oil refineries)
  - Merchant: dedicated to supply niche markets (e.g. research institutions)
  - Merchant market << captive market
  - Statistics are scarce for the captive market due to the lack of transactions
  - Source: Pacific Northwest National Laboratory (https://h2tools.org/)

- Feedstock market vs energy market
  - Most of the current hydrogen use is feedstock (oil refineries, chemical industry)
  - Virtually no energy market as of yet

- In this study, we only consider hydrogen energy markets



Hydrogen demand in the non-energy market is set to grow with economic activity of the chemical and oil refining sectors

Scenario design

cambridge econometrics
camecon.com

Reference scenario

- Calibrated to IEEJ2021
  - GDP
  - Population
  - Employment
  - Energy use
  - Emissions

- Fixed power generation configuration

- Continued diffusion in private road transport, freight road transport, and iron & steel industry

Net-Zero policy scenario

	Sectors	Comment
Carbon tax (from 2021 onward)	All sectors	Carbon tax gradually increasing from \$50/tCO_2 in 2021 to reach around \$400/tCO_2 in 2040 (2010 prices). Fixed rate in constant term after 2040.
Coal phase out regulation	Power	Government power mix plan of 2030, 2050.
Nuclear assumptions	Power	Government power mix plan of 2030, 2050.
Renewable subsidies and Feed-in-Tariffs	Power	Government power mix plan of 2030, 2050.
Kick start for BECCS and Hydrogen	Power	Government power mix plan of 2030, 2050. A program to support BECCS and hydrogen plants by setting up a small size demonstration plant in the first few years.
Ban on petrol & diesel engines by regulation	Road transport	Ban sales from 2035 onward
Biofuel mandate	Freight and air transport	Increase share of biofuels in fuel mix (up to 50% by 2050)
ZEV subsidies in private vehicles	**Private Road transport**	**Subsidies given to *EVs and FCEVs* (passenger vehicles) in the first few years (to be refined)**
ZEV subsidies in HDV	**Freight Road transport**	**Subsidies given to EVs and FCEVs (trucks) in the first few years (to be refined)**
FCEV mandates in HDV	**Freight Road transport**	**Mandate to kick-start FCEV HDV into the system (to be defined)**
Energy efficiency investment	Buildings and industry	Similar level of investment under the IEA Sustainable Development Scenario
Coal, gas and oil boiler regulations	Buildings	Gradual ban of fossil fuel boilers by 2050
Kick start for H2-DR-EAF	**Steel**	**A program to support H2-DR-EAF plants by setting up a small size demonstration plant in the first few years**
Subsidies on low-carbon steelmaking	**Steel**	**Like policy scenario I but a greater push towards hydrogen-based steelmaking**
Hydrogen use in other industries	**Industry**	**No FTT model, but we can assume that the share of hydrogen use in steel is a proxy for hydrogen use in other industries**
Processed emissions	Industry	Assume processed emission intensity reduced by 4% pa in the net zero scenario
Revenue recycling	Government	These policy packages come at a cost and the government is (assumed) to respond to the policy costs by changing fiscal tax rates (can act both ways!)
Hydrogen subsidies	**Hydrogen supply**	**Subsidised hydrogen prices if costs > prices (as taken from METI)**

Sector specific policies relating to hydrogen

FTT:Steel
- Carbon tax
- Phase-out of carbon intensive processes
- Initial kick-start program of hydrogen-based steelmaking
- Subsidies on low-carbon steelmaking

FTT:Power
- Follows the Government Power Mix Plan (GPMP)
- Carbon tax
- Subsidies
- Feed-in-Tariffs

FTT:Tr
- Ban on sale of ICE vehicles
- Road tax on ICE vehicles
- Fuel tax on petrol and diesel
- Biofuel blending mandate
- Government mandate on FCEVs (kick-start)
- Support of FCEVs

Non-FTT industry sectors
- Hydrogen demand follows trend in iron & steel

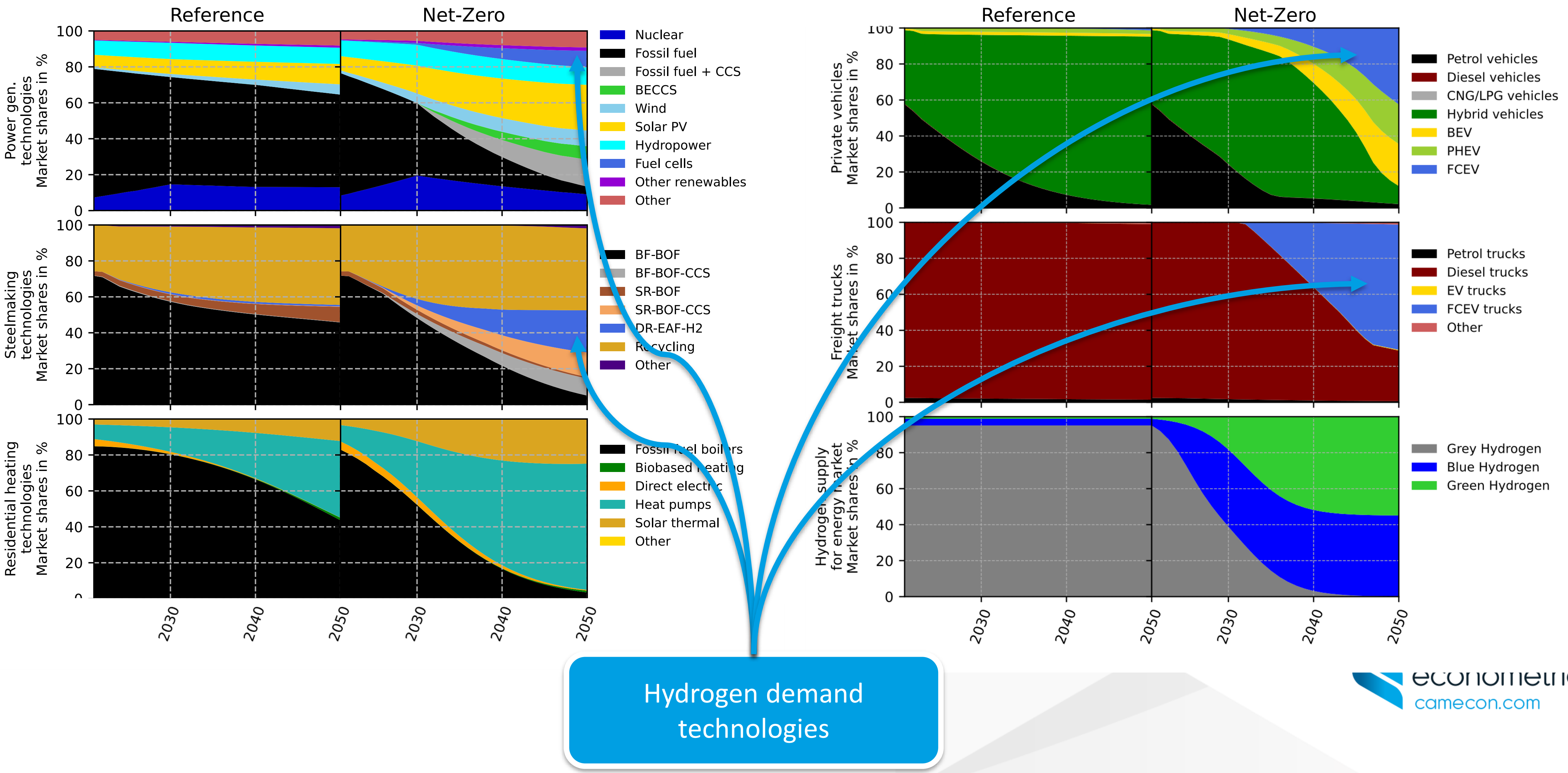
FTT:Freight
- Ban on sale of ICE trucks and vans
- Road tax on ICE trucks and vans
- Fuel tax on petrol and diesel
- Biofuel blending mandate
- Support of FCEVs trucks (30.000 $/veh on small trucks and 60.000 $/veh)
- Sales mandate of FCEV trucks (10% by 2030 and 20% by 2035)

Residential heating
- No representation of hydrogen-based technology

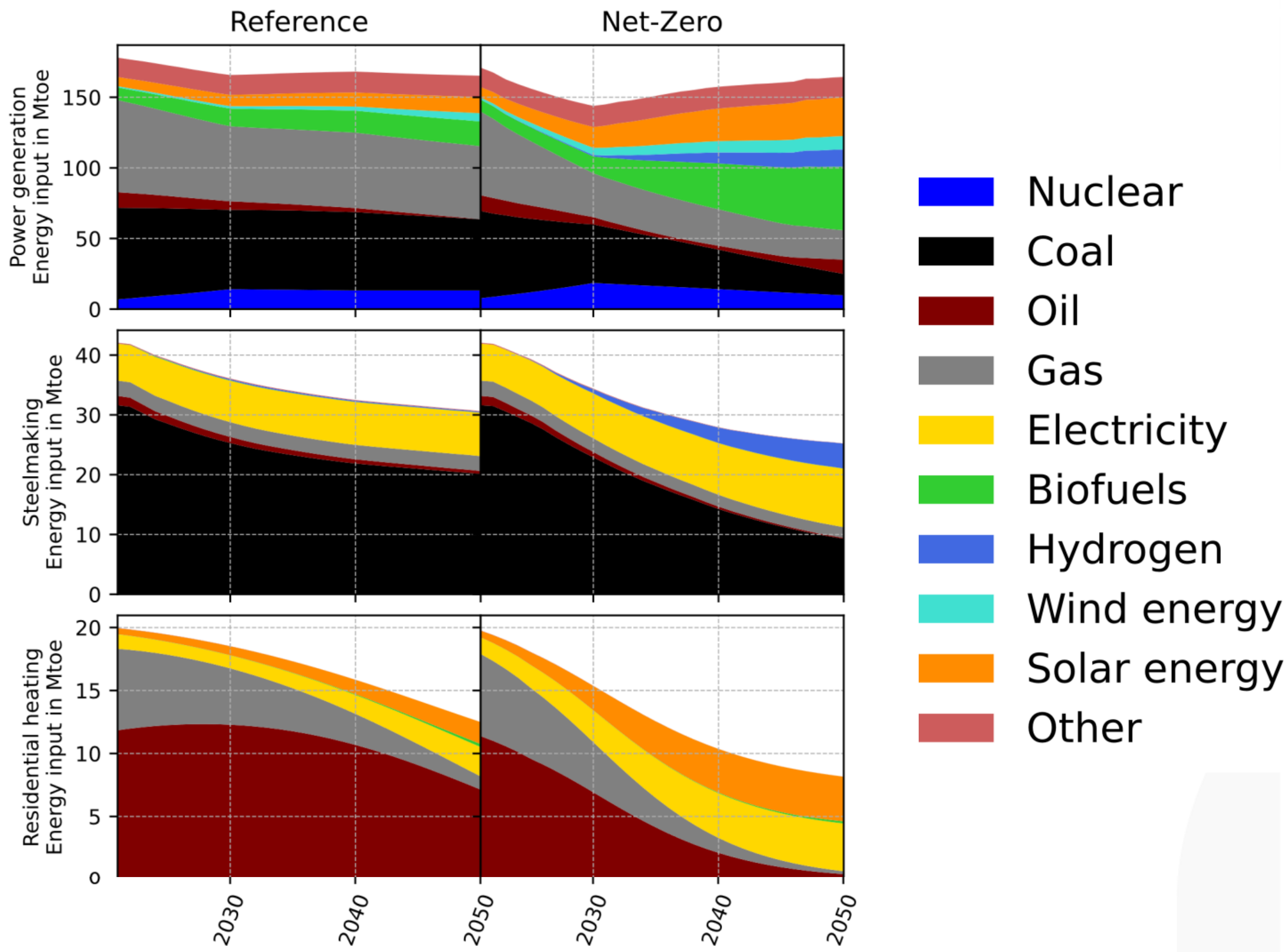
cambridge econometrics
camecon.com

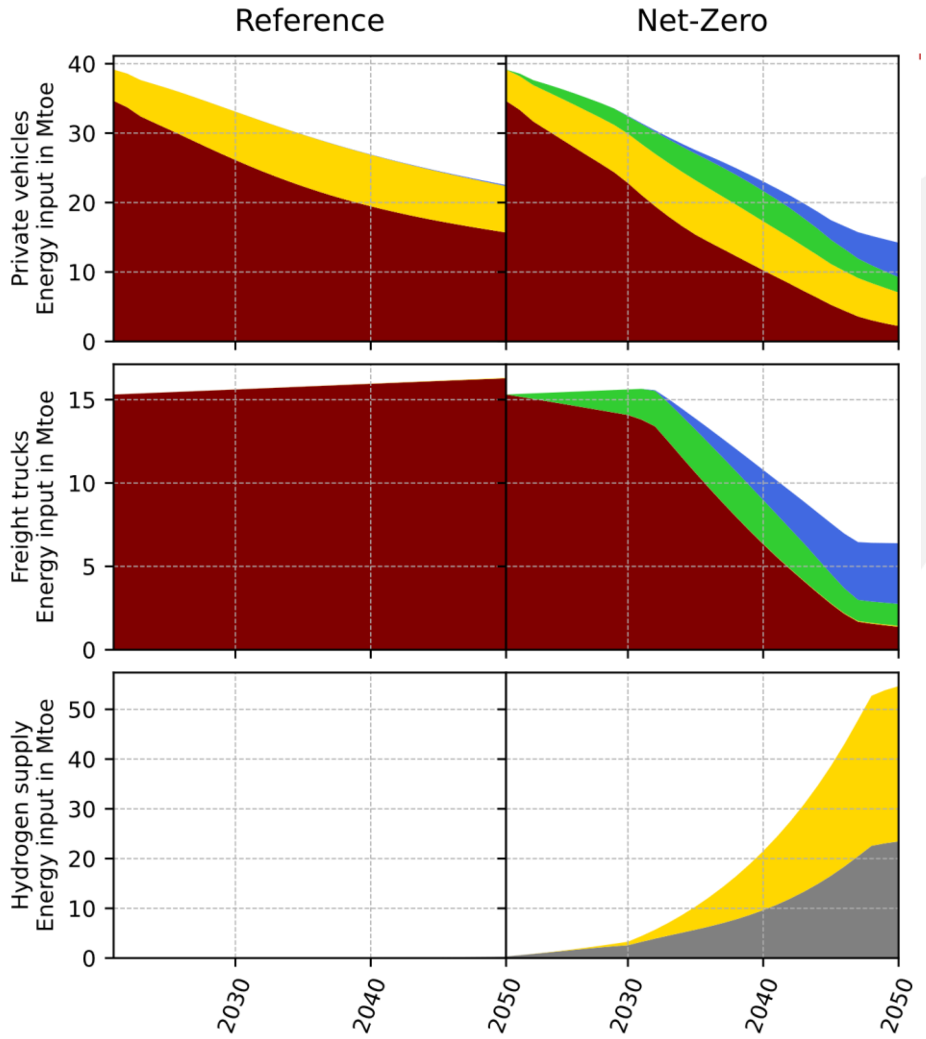
Simulation results

Technology diffusion



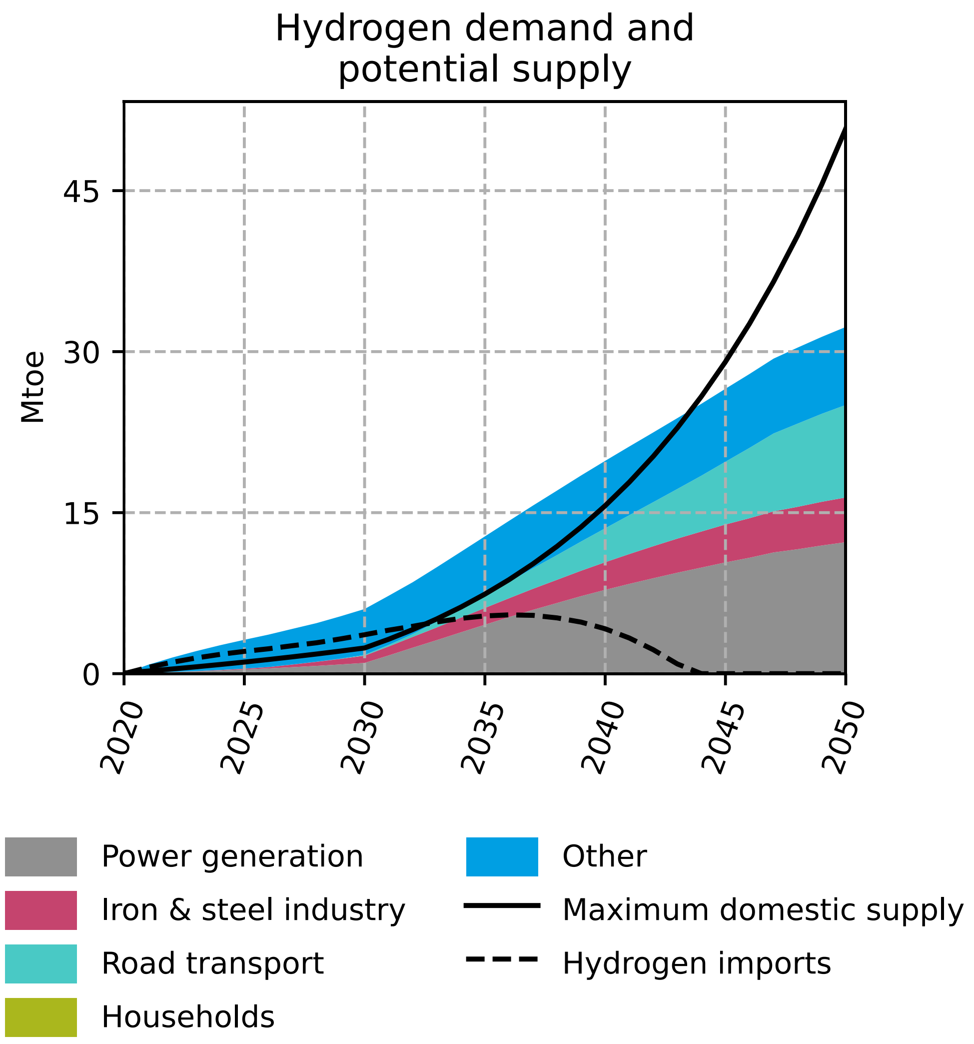
Energy demand

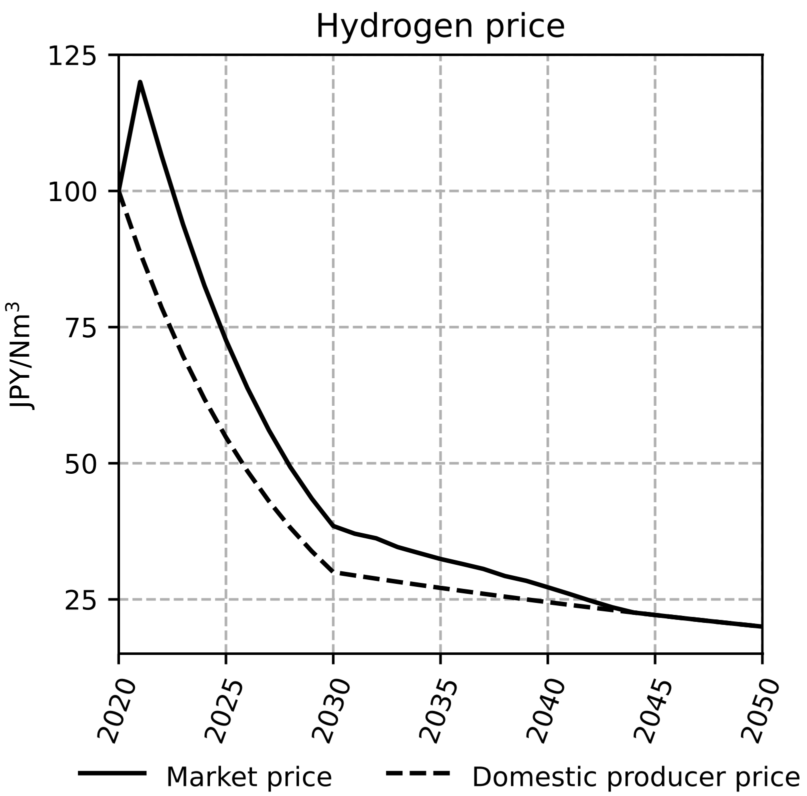




camecon.com

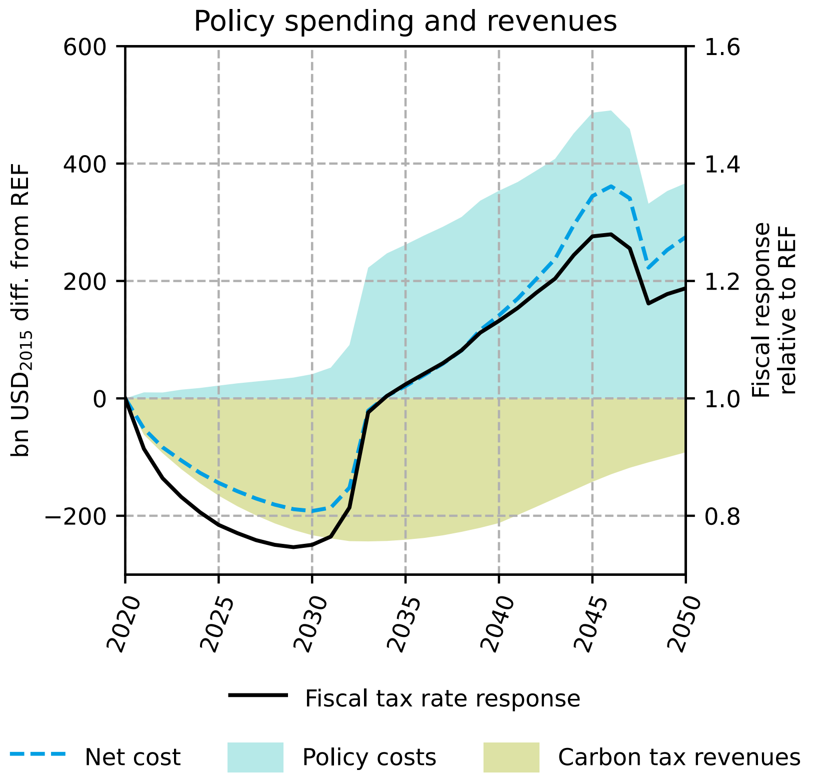
Hydrogen demand

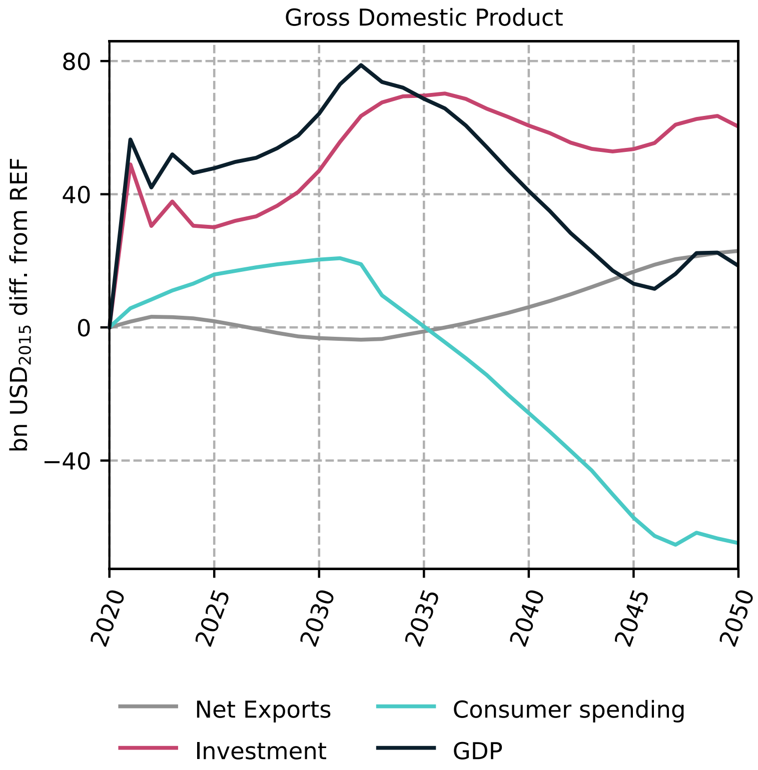


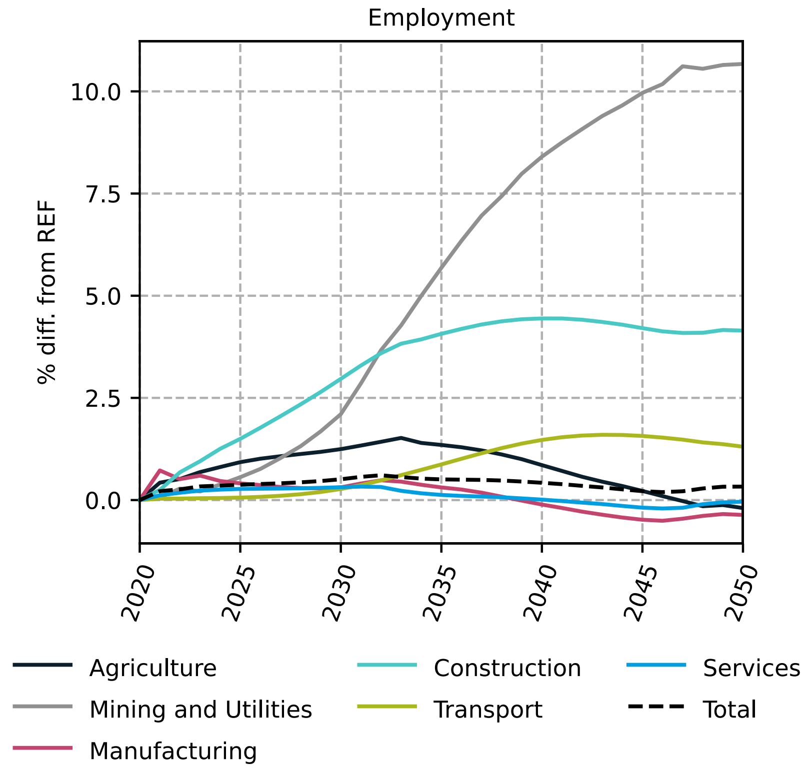


cambridge econometrics
camecon.com

Macro-economic impacts







cambridge econometrics
camecon.com

Conclusion & discussion

Main findings

- Deep decarbonisation via promotion of a hydrogen economy is possible!
- By 2050, 12% of all energy input to the Japanese economy is hydrogen, while 34% is electricity demand (of which a large portion is needed for hydrogen production)
- Promoting the hydrogen economy leads to positive GDP impacts, which are driven by investment boosts in new low-carbon technologies, while consumer expenditure takes a hit
- The costs of the subsidies are the main driver for negative consumer expenditure outcomes

Limitations & challenges

Limitations of E3ME

- The Net-Zero scenarios indicate systematic (sudden) change rather than marginal change; econometrics cannot deal with systematic change in terms of technology. Hence, why FTT is used instead.
- E3ME is agnostic on the source and availability of investment. Money is endogenous in Post-Keynesian economics and it can be created through lending; In E3ME it is implicit. There is no full crowding out. The model shows the investments required to achieve this representation of Net-Zero. It does not say anything on the availability of the funds.
- Any data intensive model will run into data quality and availability issues. E3ME covers more than 60.000 estimate parameters
- Value chain of hydrogen supply not properly represented in the model due to lack of existing sources
- Employment effects in the hydrogen supply sector highly uncertain

Limitations of FTT

- Only an exogenous representation of hydrogen supply
- Technology representation is always partial
- Breakthroughs inherently difficult to simulate
  - Innovator effect versus imitator effect
- In FTT, infrastructure and technologies are assumed to co-evolve
  - E.g. charging points for EVs, hydrogen fuelling stations
- Rate of electrolyser capacity expansion is uncertain
  - Odenweller et al. (2022) question the rate of scalability of electrolyser capacity needed to achieve green hydrogen targets
- Effectiveness of CC(U)S/BECCS is questionable

Q&A