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

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Introduction
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

2020

- Integration of R&D resources
- Trial design
- Tank, inboard transfer, storage, etc.
- Engine (single/dual fuel) and related technologies

2025

Pilot projects

- Experiment and demonstration of the use of alternative fuels (single/dual fuel combustion)
- Adoption of technologies from small coastal ships, to be scaled up into larger ocean-going vessels

2030

Advent of 1st-gen Zero Emission Ship

Expansion of Zero Emission Ships

Total: 50% reduction (carbon intensity: 80%)
(base year: 2008)

2040

Promoting Zero Emission Ships

- Incentive scheme
  (energy efficiency requirement, market mechanisms, financing, etc.)

2050

Establishment of Fuel supply

Regulatory developments

- Safety requirements
- Training and competency for seafarers
- Methodology to evaluate energy efficiency
Methodology
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
Introduction to E3ME-FTT

**Energy Resources**
- Natural resource use and depletion

**Energy Prices / Resource costs**

**E3ME**
- Macroeconometric model of the global economy

**FTT: Power**
- Power sector technology substitution model

**FTT: Transport**
- Transport technology substitution model

**FTT: Heating**
- Household energy use

**FTT: Steel**
- Steel sector technology substitution model

**Policy Assumptions**

**Economic feedbacks**

**GHG Emissions**

**GHG Concentrations**

**Future Technology Transformations**
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
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:
Levelised cost

**Net present value of expenses**

\[ NPV_{\text{expenses}} = \sum_{t=0}^{\tau} \frac{IC(t)}{CF(t)} + OM(t) + FC(t) + CO2T(t) + \cdots \left(1 + \frac{r}{1+r}\right)^t \]

**Net present value of benefits**

\[ NPV_{\text{benefits}} = \sum_{t=0}^{\tau} \frac{P(t) \times \text{Production}(t)}{(1+r)^t} = P \times \sum_{t=0}^{\tau} \frac{1}{(1+r)^t} \]

\[ \frac{NPV_{\text{expenses}}}{NPV_{\text{benefits}}} = 1 \]

**Break-even point**

\[ LC = P = \frac{\sum_{t=0}^{\tau} \frac{IC(t)}{CF} + OM(t) + FC(t) + CO2T(t) + \cdots}{\sum_{t=0}^{\tau} \frac{1}{(1+r)^t}} \]

**Levelised cost – mean (LC)**

\[ LC = \frac{\sum_{t=0}^{\tau} \sqrt{(\frac{sdIC}{CF})^2 + sdOM^2 + sdFC^2 + \cdots}}{\sum_{t=0}^{\tau} \frac{1}{(1+r)^t}} \]

**Levelised cost – st.dev (LC)**

\[ LC^{sd} = \frac{\sum_{t=0}^{\tau} \sqrt{(\frac{sdIC}{CF})^2 + sdOM^2 + sdFC^2 + \cdots}}{\sum_{t=0}^{\tau} \frac{1}{(1+r)^t}} \]
Investor preferences

Difference of the average LC

\[ \Delta C_{ij} = L_i - L_j \]

Gumbel distribution of LC

\[ f_i(C) = e^{-e^{-\frac{(C-L_i)}{L_i^{sd}}}} \]

Standard deviation

\[ F_{ij}^{SD} = \sqrt{2 \cdot L_i^{sd2} \cdot L_j^{sd2}} \]

Preferences as convoluted Gumbel distributions (yields a logistic distribution)

\[ F_{ij} = \int_{-\infty}^{+\infty} (f_i \ast f_j) d\Delta C = \frac{1}{1 + e^{\frac{\Delta C_{ij}}{F_{ij}^{SD2}}}} \]

Preferences for the alternative

\[ F_{ji} = 1 - F_{ji} \]

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

**Imperfect information / knowledge / foresight**

- Consumer choices
- Generalised cost $x$
- Frequency
- Cumulative Frequency
- People adopting $i$
- People adopting $j$

- $f_j(x)$, $f_i(x)$
- $\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2}$
- $F_{ij}(\Delta x) = 1 - F_{ji}(\Delta x)$

**Perfect information / knowledge / foresight**

- Consumer choices
- Generalised cost $x$
- Frequency
- Cumulative Frequency
- People adopting $j$
- People adopting $i$

- $f_j(x)$, $f_i(x)$
Market share dynamics

| Market share substitution between incumbent technology j and alternative i |
| Market share substitution between incumbent technology i and alternative j |
| Replicator function (core of the model) |
| Substitution frequency matrix (combines “births” and “deaths”) |

\[
\Delta S_{j \rightarrow i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \cdot \Delta t
\]

\[
\Delta S_{i \rightarrow j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \cdot \Delta t
\]

\[
\sum_j \Delta S_{j \rightarrow i} = \Delta S_i = \sum_j S_i S_j \cdot (F_{ij} A_{ij} - F_{ji} A_{ji}) \cdot \Delta t
\]

\[
A_{ij} = \frac{\kappa}{BT_i \cdot LT_j}
\]

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

Learning-by-doing

- 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 $C$.

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

\[
I_{i,t+1} = I_{i,t} + \Delta I_{i,t}
\]

\[
I_{i,t+1} = I_{i,t} (1 - b_i) \frac{\Delta C_{i,t}}{C_{i,t}}
\]
Calibration

- 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

\[ L\gamma = L + \gamma \]

- 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
Introduction to FTT

- Energy Resources
  - Natural resource use and depletion

- Energy Prices / Resource costs

- Policy Assumptions
- Economic feedbacks
- GHG Emissions
- GHG Concentrations

- FTT: Power
  - Power sector technology substitution model

- FTT: Transport
  - Transport technology substitution model

- FTT: Heating
  - Household energy use

- FTT: Steel
  - Steel sector technology substitution model

- FTT: H2
  - Exogenous representation

- E3ME
  - Macroeconometric model of the global economy
# Technological representation in FTT

<table>
<thead>
<tr>
<th>Technologies</th>
<th>FTT-Power</th>
<th>FTT-Transport</th>
<th>FTT-Heat</th>
<th>FTT-Steel</th>
<th>H2 supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs from E3ME</td>
<td>Electricity demand</td>
<td>Fleet/ car demand</td>
<td>Heat demand</td>
<td>Steel demand</td>
<td>Hydrogen demand</td>
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<tr>
<td></td>
<td>• Fuel demand and emissions</td>
<td>• Fuel demand and emissions</td>
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<td>• Fuel demand and emissions</td>
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<tr>
<td></td>
<td>• Electricity price</td>
<td>• Average car price</td>
<td>• Costs of boilers</td>
<td>• Steel investment</td>
<td>• Steel price</td>
</tr>
<tr>
<td></td>
<td>• Electricity investment</td>
<td>• Detailed PG employment</td>
<td></td>
<td>• Detailed steel employment</td>
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<tr>
<td>Output to E3ME</td>
<td></td>
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<td>Policies</td>
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<tr>
<td></td>
<td>• Tax (carbon, fuel, vehicle, boiler)</td>
<td>• Fuel demand and emissions</td>
<td>• Fuel demand and emissions</td>
<td>• Fuel demand and emissions</td>
<td>• Fuel demand and emissions</td>
</tr>
<tr>
<td></td>
<td>• Subsidy</td>
<td>• Average car price</td>
<td>• Costs of boilers</td>
<td>• Steel investment</td>
<td>• Steel price</td>
</tr>
<tr>
<td></td>
<td>• Regulations (phase out, limits)</td>
<td>• Detailed PG employment</td>
<td></td>
<td>• Detailed steel employment</td>
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<tr>
<td></td>
<td>• Turnover time</td>
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<td></td>
<td>• Discount rate</td>
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<td>• Feeds in tariff</td>
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<td></td>
<td>• Demonstration technology</td>
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<td></td>
<td>• Demand side policies e.g. building energy efficiency</td>
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</tbody>
</table>

Exogenous representation of Hydrogen supply (includes exogenous hydrogen prices)
Representation of the hydrogen economy
Hydrogen economy

(Figure 1) Extract from Environment Innovation Strategy materials

Resource: METI (Japan’s Roadmap to “Beyond-Zero” Carbon)
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
Scenario design
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

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<tr>
<th>Sectors</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon tax (from 2021 onward)</strong></td>
<td>All sectors</td>
</tr>
<tr>
<td><strong>Coal phase out regulation</strong></td>
<td>Power</td>
</tr>
<tr>
<td><strong>Nuclear assumptions</strong></td>
<td>Power</td>
</tr>
<tr>
<td><strong>Renewable subsidies and Feed-in-Tariffs</strong></td>
<td>Power</td>
</tr>
<tr>
<td><strong>Kick start for BECCS and Hydrogen</strong></td>
<td>Power</td>
</tr>
<tr>
<td><strong>Ban on petrol &amp; diesel engines by regulation</strong></td>
<td>Road transport</td>
</tr>
<tr>
<td><strong>Biofuel mandate</strong></td>
<td>Freight and air transport</td>
</tr>
<tr>
<td><strong>EV subsidies in private vehicles</strong></td>
<td>Private Road transport</td>
</tr>
<tr>
<td><strong>EV subsidies in HGV</strong></td>
<td>Freight Road transport</td>
</tr>
<tr>
<td><strong>FCEV mandates in HGV</strong></td>
<td>Freight Road transport</td>
</tr>
<tr>
<td><strong>Energy efficiency investment</strong></td>
<td>Buildings and industry</td>
</tr>
<tr>
<td><strong>Coal, gas and oil boiler regulations</strong></td>
<td>Buildings</td>
</tr>
<tr>
<td><strong>Kick start for H2-DR-EAF</strong></td>
<td>Steel</td>
</tr>
<tr>
<td><strong>Subsidies on low-carbon steelmaking</strong></td>
<td>Steel</td>
</tr>
<tr>
<td><strong>Hydrogen use in other industries</strong></td>
<td>Industry</td>
</tr>
<tr>
<td><strong>Processed emissions</strong></td>
<td>Industry</td>
</tr>
<tr>
<td><strong>Revenue recycling</strong></td>
<td>Government</td>
</tr>
<tr>
<td><strong>Hydrogen subsidies</strong></td>
<td>Hydrogen supply</td>
</tr>
</tbody>
</table>
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

**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)

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

**Residential heating**
- No representation of hydrogen-based technology
Simulation results
Energy demand

- Reference vs Net-Zero scenarios
- Power generation, steelmaking, residential heating, hydrogen supply
- Energy input in Mtoe
- Graphs showing changes over years 2030 to 2050
- Categories: Nuclear, Coal, Oil, Gas, Electricity, Biofuels, Hydrogen, Wind energy, Solar energy, Other
Hydrogen demand

Hydrogen demand and potential supply

- Power generation
- Iron & steel industry
- Road transport
- Households

Hydrogen price

- Market price
- Domestic producer price
- Maximum domestic supply
- Hydrogen imports

Mtoe

JPY/Nm³
Macro-economic impacts
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