FTT: Industrial Heat

Final report – August 2023

Final report – August 2023



Cambridge Econometrics’ mission is to provide clear and useful insights, based on rigorous and independent economic analysis, to address the complex challenges facing society.

www.camecon.com

Cambridge Econometrics Limited is owned by a charitable body,the Cambridge Trust for New Thinking in Economics.

www.neweconomicthinking.org

Contributors

Authors

Rosie Hayward – rh@camecon.com

(Cambridge Econometrics)

Authorisation and version history

|  |  |  |  |
| --- | --- | --- | --- |
| Version | Date | Authorised for release by | Description |
| 1.1 |  |  |  |
| 1.0 | 28/11/23 | Rosie Hayward | First draft. |
|  |  |  |  |
|  |  |  |  |

Contents page

[1. Introduction 5](#_Toc157601673)

[1.1. Motivation 5](#_Toc157601674)

[1.2. Decarbonising industry 5](#_Toc157601675)

[2. Sources 6](#_Toc157601676)

[2.1. Data sources 6](#_Toc157601677)

[2.2. Data processing 6](#_Toc157601678)

[3. Theoretical background 15](#_Toc157601679)

[3.1. General FTT theory 15](#_Toc157601680)

[3.2. Additional terms in the shares equation 20](#_Toc157601681)

[3.3. Implementing Polices 22](#_Toc157601682)

[4. References 25](#_Toc157601683)

Tables

[Table 1: 7](#_Toc157532982)

[Table 2: Market share caps for CHI 8](#_Toc157532983)

[Table 3: Market share caps FBT 9](#_Toc157532984)

[Table 4: Market share caps MTM 9](#_Toc157532985)

[Table 5: Market share caps NMM 10](#_Toc157532986)

[Table 6: Market share caps OIS 10](#_Toc157532987)

Figures

[Figure 3.1: , the probability density distribution which tells us about the relative likelihood that a technology has a particular cost. 17](file:///S:\E3ME_new\Documentation\FTT%20Documentation\FTT%20IH%20Report%20and%20Documentation.docx#_Toc157532988)

[Figure 3.2: , the consumer preferences function 18](file:///S:\E3ME_new\Documentation\FTT%20Documentation\FTT%20IH%20Report%20and%20Documentation.docx#_Toc157532989)

# Introduction

## Motivation

Why did we build FTT: Industrial Heat?

FTT Industrial Heat was a key development in the REFEREE project. Initially, the intention was to build an FTT model for the chemicals sector, however, this information was not readily available.

A data set on useful energy demand for industrial processes was available and open source for the 2015 EU28, and so this because the foundation of the model. In order to focus on processes which could reasonably compete and substitute one another, the model was limited to industrial process heating.

## Decarbonising industry

The decarbonisation of industry is a complex problem, with the decarbonisation of different processes and industries facing unique challenges. This model focuses on industrial heat processing within different broad sectors, to ensure investors are comparing technologies which can be reasonably substituted for each other.

This model is likely unsuitable for capturing the challenges industry will face when it comes to decarbonisation, and will not account for techniques introduced after 2015, or changes in feedstock usage.

# Data

## Data sources

Three main sources of data were used in the development of FTT: IH:

1. The work of Silvia Madeddu et. al., *The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat), Environ. Res. Lett.* ***15*** *(2020) 124004.* The supplementary material which accompanies this paper was particularly important, and Silvia was also very helpful and responded to my emails.
2. The JRC-IDEES database: <https://data.jrc.ec.europa.eu/collection/id-0110>. The relevant data from this database and the relevant documentation has been downloaded and can be found in the development folder for FTT: IH, within the REFEREE project folder. This data is open source and compliant with Eurostat.
3. Technology Data for Industrial Process Heat, published by the Danish Energy Agency: <https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-industrial-process-heat>. A download of this data can also be found in the IH development folder. This dataset has been updated since FTT: IH was first developed. It would be worth checking it regularly.

## Data processing

In order to align cost data with energy demand data, and to ensure investor comparisons applied to reasonably similar technologies, the following five broad sectors were selected for the creation of sub-models within FTT: IH:

* + 1. Chemicals (CHI)
    2. Food, beverages, and tobacco (FBT)
    3. Non-Ferrous Metals, Machinery, and Transport Equipment (MTM)
    4. Non-Metallic Minerals (NMM)
    5. Other Industrial Sectors (OIS)

All models follow the same structure, using the same variables, and as such are distinguished using the numbering and abbreviations given above.

Due to the variety of process heating technologies which exist in industry, as well as the restrictions imposed by the available data, comparisons of individual technologies was not a practical goal for these models. The key driver of decarbonisation in industrial process heating is the type of fuel used for these processes rather than the particular process, and therefore technologies were categorised based on their fuel source. A distinction was made between direct and indirect heating processes due to their extremely limited likelihood of overlap in use, with no substitutions between these two classes of technologies currently enabled in the model.

Steam Distributed heating is enabled in the model, but is removed from substitution, as the overlap of this heating methodology with others is unclear, and its use is likely dependent on other factors. Substitution could be enabled in future versions.

The following broad technology classification was created for FTT: Industrial Heat:

|  |  |
| --- | --- |
| No. | Technology |
| 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 |

The mapping of the JRC data set to these technologies was informed by the descriptive names of processes in the JRC data, and the supplementary material in Madeddu et. al. This mapping can be found in the workbook “JRC\_to\_ITTI.xlsx” [here](file:///J:\Projects\DG%20Research\REFEREE%20(P1451)\Deliverables\FTT%20and%20E3ME%20info\FTT%20Indy%20Dev\Data%20for%20market%20share%20calculations\Data%20Processing\JRC_to_ITTI.xlsx).

Note that low enthalpy heat was taken as space heating and not process heating, in line with the assumptions in Maddedu et. al., and so is not included in the mapping.

Learning and costs

Technologies are assumed to be mature in the case of industrial process heating, where electricity is already an established fuel. As such, minimal learning is assumed for all technologies other than heat pumps. An approximate value of -0.05 is taken for mature technologies, based on the median of investment learning rates used in FTT: Steel for mature technologies (-0.01 to -0.09).

Table 1:

|  |  |
| --- | --- |
|  | Learning exponents |
| Indirect Heating Coal | -0.05 |
| Indirect Heating Oil | -0.05 |
| Indirect Heating Gas | -0.05 |
| Indirect Heating Biomass | -0.05 |
| Indirect Heating Electric | -0.05 |
| Indirect Heating Steam Distributed | -0.05 |
| Heat Pumps (Electricity) | -0.43296 |
| Direct Heating Coal | -0.05 |
| Direct Heating Oil | -0.05 |
| Direct Heating Gas | -0.05 |
| Direct Heating Biomass | -0.05 |
| Direct Heating Electric | -0.05 |
| Direct Heating Steam Distributed | -0.05 |

Technology costs are available from the year 2020, and as such fuel costs are taken to be from the same year. Because of this, learning is delayed until after 2020.

Conversion Efficiencies

Conversion efficiencies are calculated as the ratio of useful energy demand to final energy demand as of 2015 in the JRC dataset.

Market share caps

The application potential of different fuels and their overlap is provided by broad sector within the DEA data set. This application potential varies with broad sector and by temperature. The potential overlap of the application of different fuels is provided for industry overall.

Furthermore, information on the breakdown of processes by temperature as well as the share of these processes in useful energy demand can be found in Madeddu et. al.

In most cases, market share caps for direct and indirect processes were taken as the theoretical maximum application potential, base on the application potentials for processes <150C and >150C in the DEA data. However, in cases where this contradicted the data available in the JRC-IDEES database, or the analysis by Maddedu et. al., other assumptions were made.

Table 2: Market share caps for CHI

|  |  |  |  |
| --- | --- | --- | --- |
|  | Full application potential (high temperature) % | Full application potential (med. Temperature) % | Cap used (before correction to account for direct/indirect heating splits) |
| Indirect Heating Coal | 100 | 100 | 1 |
| Indirect Heating Oil | 100 | 100 | 1 |
| Indirect Heating Gas | 100 | 100 | 1 |
| Indirect Heating Biomass | 100 | 100 | 1 |
| Indirect Heating Electric | 100 | 100 | 1 |
| Indirect Heating Steam Distributed | N/A | N/A | 1 |
| Heat Pumps (Electricity) | 0 | 17 (66 booster HP) | 0.17 |
| Direct Heating Coal | 0\* | 0\* | 0.01 |
| Direct Heating Oil | Unavailable | Unavailable | 1 |
| Direct Heating Gas | 20 | 100 | 1 |
| Direct Heating Biomass | 0\* | 0\* | 0.01 |
| Direct Heating Electric | 20 | 100 | 1 |
| Direct Heating Steam Distributed | N/A | N/A | 1 |

Table 3: Market share caps FBT

|  |  |  |  |
| --- | --- | --- | --- |
|  | Full application potential (high temperature) % | Full application potential (med. Temperature) % | Cap used (before correction to account for direct/indirect heating splits) |
| Indirect Heating Coal | 100 | 100 | 1 |
| Indirect Heating Oil | 100 | 100 | 1 |
| Indirect Heating Gas | 100 | 100 | 1 |
| Indirect Heating Biomass | 100 | 100 | 1 |
| Indirect Heating Electric | 100 | 100 | 1 |
| Indirect Heating Steam Distributed | N/A | N/A | 1 |
| Heat Pumps (Electricity) | 0 | 24 | 0.24 |
| Direct Heating Coal | 0 | 0 | 0.01 |
| Direct Heating Oil | Unavailable | Unavailable | 1 |
| Direct Heating Gas | 100 | 100 | 1 |
| Direct Heating Biomass | 0 | 0 | 0.01 |
| Direct Heating Electric | 100 | 100 | 1 |
| Direct Heating Steam Distributed | N/A | N/A | 1 |

Table 4: Market share caps MTM

|  |  |  |  |
| --- | --- | --- | --- |
|  | Full application potential (high temperature) % | Full application potential (med. Temperature) % | Cap used (before correction to account for direct/indirect heating splits) |
| Indirect Heating Coal | 100 | 100 | 1 |
| Indirect Heating Oil | 100 | 100 | 1 |
| Indirect Heating Gas | 100 | 100 | 1 |
| Indirect Heating Biomass | 100 | 100 | 1 |
| Indirect Heating Electric | 100 | 100 | 1 |
| Indirect Heating Steam Distributed | N/A | N/A | 1 |
| Heat Pumps (Electricity) | 0 | 24 | 0.18 |
| Direct Heating Coal | 0 | 0 | 0.05 |
| Direct Heating Oil | Unavailable | Unavailable | 1 |
| Direct Heating Gas | 100 | 100 | 1 |
| Direct Heating Biomass | 0 | 0 | 0.01 |
| Direct Heating Electric | 100 | 100 | 1 |
| Direct Heating Steam Distributed | N/A | N/A | 1 |

Table 5: Market share caps NMM

|  |  |  |  |
| --- | --- | --- | --- |
|  | Full application potential (high temperature) % | Full application potential (med. Temperature) % | Cap used (before correction to account for direct/indirect heating splits) |
| Indirect Heating Coal | 100 | 100 | 1 |
| Indirect Heating Oil | 100 | 100 | 1 |
| Indirect Heating Gas | 100 | 100 | 1 |
| Indirect Heating Biomass | 100 | 100 | 1 |
| Indirect Heating Electric | 100 | 100 | 1 |
| Indirect Heating Steam Distributed | N/A | N/A | 1 |
| Heat Pumps (Electricity) | 0 | 24 | 0.17 |
| Direct Heating Coal | 0 | 0 | 1 |
| Direct Heating Oil | Unavailable | Unavailable | 1 |
| Direct Heating Gas | 100 | 100 | 1 |
| Direct Heating Biomass | 0 | 0 | 1 |
| Direct Heating Electric | 100 | 100 | 0.5 |
| Direct Heating Steam Distributed | N/A | N/A | 1 |

Table 6: Market share caps OIS

|  |  |  |  |
| --- | --- | --- | --- |
|  | Full application potential (high temperature) % | Full application potential (med. Temperature) % | Cap used (before correction to account for direct/indirect heating splits) |
| Indirect Heating Coal | 100 | 100 | 1 |
| Indirect Heating Oil | 100 | 100 | 1 |
| Indirect Heating Gas | 100 | 100 | 1 |
| Indirect Heating Biomass | 100 | 100 | 1 |
| Indirect Heating Electric | 100 | 100 | 1 |
| Indirect Heating Steam Distributed | N/A | N/A | 1 |
| Heat Pumps (Electricity) | 0 | 24 | 0.32 |
| Direct Heating Coal | 0 | 0 | 1 |
| Direct Heating Oil | Unavailable | Unavailable | 1 |
| Direct Heating Gas | 100 | 100 | 1 |
| Direct Heating Biomass | 0 | 0 | 1 |
| Direct Heating Electric | 100 | 100 | 1 |
| Direct Heating Steam Distributed | N/A | N/A | 1 |

These market share caps are adjusted based on the ratio of direct heating to indirect heating in every region.

Capacity factors

Due to limited data availability, capacity factors were estimated based on an average of planned and forced outage times in the DEA dataset. This calculation is shown in the tables below.

Table 7: Planned and forced outage

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Planned Outage (weeks per year) | Maximum planned outage (weeks per year) | Minimum planned outage (weeks per year) | Forced Outage (%) | Maximum forced outage (%) | Minimum forced outage (%) |
| Indirect Heating Coal | 0.9 | 1.1 | 0.8 | 1.2 | 2.2 | 0.1 |
| Indirect Heating Oil | 0.6 | 0.8 | 0.5 | 1.1 | 2.1 | 0.09 |
| Indirect Heating Gas | 0.4 | 0.6 | 0.3 | 1 | 2 | 0.08 |
| Indirect Heating Biomass | 3 | 3.5 | 2.6 | 3 | 3 | 3 |
| Indirect Heating Electric | 0.2 | 0.2 | 0.2 | 1 | 1 | 0.5 |
| Indirect Heating Steam Distributed |  | N/A |  |  | N/A |  |
| Heat Pumps (Electricity) | 0.5 | 1 | 0 | 0 | 1 | 0 |
| Direct Heating Coal | 3.5 | 5 | 2 | 0 | 1 | 0 |
| Direct Heating Oil |  | - |  |  | - |  |
| Direct Heating Gas | 0.5 | 1 | 0 |  | 0.5 | 0 |
| Direct Heating Biomass | 3.5 | 5 | 2 | 0 | 1 | 0 |
| Direct Heating Electric | 0 | 1 | 0 | 0 | 1 | 0 |
| Direct Heating Steam Distributed |  | N/A |  |  | N/A |  |

Table 8: Capacity factors

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate of CF (min outage) | Estimate of CF (average outage) | Estimate of CF (max outage) | Standard Deviation |
| Indirect Heating Coal | 0.984 | 0.970 | 0.957 | 0.0134 |
| Indirect Heating Oil | 0.989 | 0.977 | 0.964 | 0.0129 |
| Indirect Heating Gas | 0.993 | 0.981 | 0.968 | 0.0125 |
| Indirect Heating Biomass | 0.920 | 0.912 | 0.903 | 0.0087 |
| Indirect Heating Electric | 0.991 | 0.988 | 0.986 | 0.0029 |
| Indirect Heating Steam Distributed | N/A | N/A | N/A | 0.0000 |
| Heat Pumps (Electricity) | 0.990 | 0.984 | 0.971 | 0.0113 |
| Direct Heating Coal | 0.962 | 0.929 | 0.894 | 0.0340 |
| Direct Heating Oil | 0.962\* | 0.929\* | 0.894\* | 0.0340 |
| Direct Heating Gas | 1.000 | 0.988 | 0.976 | 0.0121 |
| Direct Heating Biomass | 0.962 | 0.929 | 0.894 | 0.0340 |
| Direct Heating Electric | 1.000 | 0.990 | 0.971 | 0.0169 |
| Direct Heating Steam Distributed | N/A | N/A | N/A | 0 |

## Model variables

The key data taken from the JRC-IDEES database to build the industrial heat models was useful energy demand (UED) by technology, final energy demand by technology (FED), and emissions by technology (EMI).

Useful energy demand was taken as the demand driver of the model, with the 2015 ratio of useful to final energy demand taken as efficiency.

Market shares are taken as shares of UED.

# Theoretical background

## General FTT theory

An introduction to how decisions are made in FTT

The following is a walkthrough of how investor or consumer decisions are calculated in FTT, however this follows an approximate, illustrative approach to aid understanding of what is happening. This is not a full derivation. The following academic texts should be referred to for a deeper understanding:

* Mercure, J. F. (2015). An age structured demographic theory of technological change. *Journal of Evolutionary Economics*, *25*(4), 787-820.
* 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.
* Knobloch, F., Pollitt, H., Chewpreecha, U., Lewney, R., Huijbregts, M. A., & Mercure, J. F. (2021). FTT: Heat—A simulation model for technological change in the European residential heating sector. *Energy Policy*, *153*, 112249.
* Mercurea, J. F., & Lamb (2018), A. FTT: Transport-Detailed model description and data gathering procedure.
* Vercoulen, P., Lee, S., Suk, S., He, Y., Fujikawa, K., & Mercure, J. F. (2019). Policies to decarbonize the steel industry in East Asia. *Energy, Environmental and Economic Sustainability in East Asia: Policies and Institutional Reforms*, 110-137.

#### End of lifetime replacements

The theoretical framework of FTT is based on consumer or investor preferences. These preferences are based on an imperfect comparison of the cost difference between two technologies, and the resulting function will provide a fraction of technology j which will be transferred to technology i.

However, this fraction only applies to the proportion of technology j which is coming to the end of its lifetime (in most FTT models, early scrapping of technologies is not taken into consideration). Furthermore, the ability of technology i to replace technology j is dependent on the current production capability of technology i. Technology i may not have the production capital to cover all of the end-of-lifetime replacements of technology j, and therefore we limit any substitutions based on the fraction of production capital belonging to each technology – this is important as it approximates a real world constraint in how quickly we can build and deploy new technologies.

Therefore, the amount of technology j which can switch to technology i is as follows:

|  |  |
| --- | --- |
|  | (3.1) |

To illustrate this process, consider the following scenario:

We have a system of three technologies: heat pumps, gas boilers, and wood stoves. The distribution of these technologies is as follows:

|  |  |  |
| --- | --- | --- |
|  | Number of units | Share of total number of units |
| Gas boilers | 150 | 0.75 |
| Wood stoves | 40 | 0.2 |
| Heat pumps | 10 | 0.05 |

The average lifetime of all of these technologies is approximately 20 years. We can assume the number of technologies coming to the end of their lifetime is proportional to the existing number of units, N, just as in radioactive decay. This means the ‘death rate’ of these technologies is equal to the inverse of the lifetime, *τ*:

The share of breakdowns for technology j multiplied by the total number of breakdowns is equal to the number of breakdowns of j.

|  |  |
| --- | --- |
|  | (3.2) |

If *τ =* 20, the ‘death’ rate, or breakdown rate, will be equal to 0.05. The total number of units of a single technology, j, is . Based on our breakdown rate, the total number of breakdowns of this year will be .

Let’s try to rewrite our equation so far:

|  |  |
| --- | --- |
|  | (3.3) |

We already know for our simple model, the number of gas boilers is 150. Hence, the total number of gas boiler breakdowns will be approximately 7.5.

If all consumers preferred heat pumps to gas boilers, and there were no constraints on how many heat pumps we could produce, then the number of units of gas boilers which were replaced by heat pumps this year would be 7.5 (let’s not worry about the fact we can’t replace half a boiler in the real world).

However, realistically this is not the case, and we need to estimate production capacity and consumer preferences.

#### Production capacity

Before we move on to quantifying consumer preferences, let’s think about how we can estimate production capital for these technologies. This data is likely to be hard to come by, and in fact is not currently available and used for FTT. Because of this, the fraction of production capital belonging to a particular technology is approximated to be equal to its current market share. This approximation is justified by the assumption that how easy it is to manufacture a new technology in response to demand will likely be proportional to its current popularity in the market.

We also take into account the maximum possible growth-rate of the market, to ensure the maximum possible share of production capacity is taken into account. To do this, the total number of units N\_j is divided by the ‘lead time’, which can be thought of as the fastest possible timescale taken to build a new unit of technology j. This is then divided by the total number of units, which is itself divided by the average lead time.

Our equation has now become:

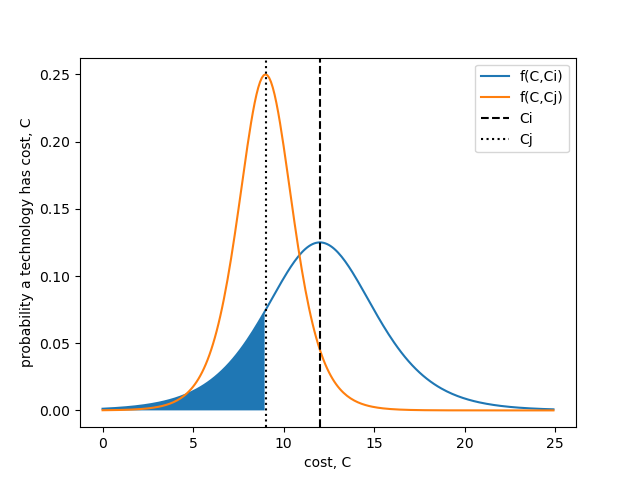
|  |  |
| --- | --- |
|  | (3.4) |

Which can be simplified to

|  |  |
| --- | --- |
|  | (3.5) |

where is the current market share of a technology, i.

#### Consumer preferences

Our last remaining component required to estimate transfers from technology j to technology i is the consumer preferences function.

For each technology, we can define a probability density distribution which tells us about the relative likelihood that a technology has a given cost, where Ci is the mean cost of that technology:

Figure 3.1: , the probability density distribution which tells us about the relative likelihood that a technology has a particular cost.

When building a new unit of a technology, if we want to calculate the probability that it is less than a certain cost, Cj, then we need to add up all of the probabilities up to that point. As we are working with continuous distributions, the is equivalent to calculating the area under our distribution up to point Cj:

We can calculate this area by integrating our probability distribution to find the cumulative probability distribution . This will give us the fraction of new units of i which will be less than the mean cost of technology j. This distribution is our consumer preferences function, .

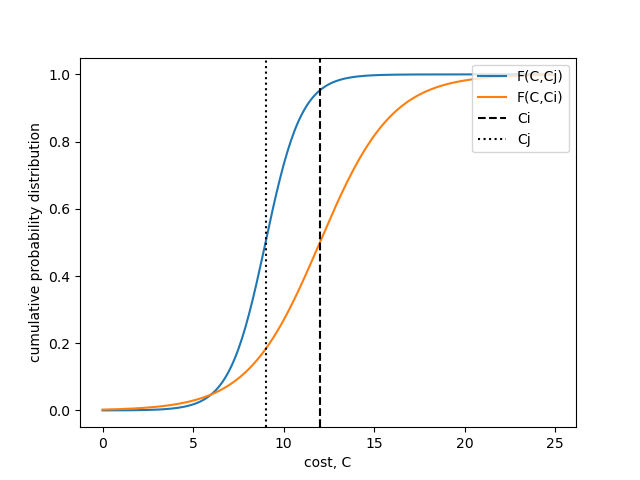


Figure 3.2: , the consumer preferences function

The function is typically a hyperbolic tangent in all existing FTT models:

|  |  |
| --- | --- |
|  | (3.6) |

where is the standard deviation of the distribution: .

#### Calculating substitutions

To estimate the overall change in technology i due to breakdown replacements of i and j alone, we need to calculate the net flow between i and j:

|  |  |
| --- | --- |
|  | (3.7) |

|  |  |
| --- | --- |
|  | (3.8) |

In terms of market shares, this becomes:

|  |  |
| --- | --- |
|  | (3.9) |

Taking the limit to *infinitesimal* changes in S and t, we can find the following differential equation:

|  |  |
| --- | --- |
|  | (3.10) |

This equation is the shares equation, and it is the core of every FTT model.

## Additional terms in the shares equation

An introduction to how constraints are introduced to the shares equation

These implementations are specific to FTT: Industrial Heat, however you may find similar implementation in other FTT models.

#### Market share caps

In order to translate market share caps into a practical policy constraint, we again use a hyperbolic tangent function:

|  |  |
| --- | --- |
|  | (3.11) |

where is the market share cap for technology i, is the current market share, and g is a scaling factor.

As the market share of technology i approaches the share cap, the function will approach zero, preventing further substitution. If it exceeds the cap, the function will be effectively zero. If the current market share is zero, the function will instead be very close to 1. The effect of this is a discouragement of investment as the share cap is approached.

This function appears next to consumer preferences in the shares equation.

#### Regulations

Regulations impose another constraint, also practically resulting in discouraging or preventing substitutions:

|  |  |
| --- | --- |
|  | (3.12) |

where is the current capacity of technology i, is the regulated capacity (the maximum allowed capacity), and is a scale factor.

isReg is a measure of how strictly shares need to be regulated to adhere to capacity constraints. As capacity approaches the regulation, isReg approaches 1, and will continue to approach one as the constraint is exceeded.

isReg is set to exactly 1 if the regulation is equal to zero, indicating a full phase out of the corresponding technology. This will mean substitution is discouraged, or fully prevented.

If isReg is zero, there is no interference with market share substitution.

It is important to note that regulations will only prevent substitutions between different technologies. This means that phase-outs may be delayed by an insufficient amount of production capacity for new technologies.

The consumer preferences function is modified by the isReg variable as follows:

|  |  |
| --- | --- |
|  | (3.13) |

If technology i is being regulated, and technology j is not, consumer preferences are set to zero. The consumer preferences in the opposite direction, , will equal one. This will mean all consumers prefer j over i.

If both technologies are maximally regulated, consumer preferences are 0.5 for both directions, indicating no preference.

If there are no regulations, consumer preferences are unchanged.

For isReg values between zero and one, consumer preferences are based on the isReg polynomial. To understand its effect, a table with example numbers is included below:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| isRegi | isRegj | Term1 | Term2 | Term3 | Fij | Fij Reg |
| 0.5 | 0.7 | 0.15 | 0.35 | 0.175 | 0.5 | 0.6 |
| 0.2 | 0.7 | 0.24 | 0.56 | 0.07 | 0.5 | 0.75 |
| 0.7 | 0.5 | 0.15 | 0.15 | 0.175 | 0.5 | 0.4 |
| 0.7 | 0.2 | 0.24 | 0.06 | 0.07 | 0.5 | 0.25 |
| 0.2 | 0.2 | 0.64 | 0.16 | 0.02 | 0.5 | 0.5 |
| 0.5 | 0.5 | 0.25 | 0.25 | 0.125 | 0.5 | 0.5 |
| 0.5 | 0.7 | 0.15 | 0.35 | 0.175 | 1 | 0.675 |
| 0.2 | 0.7 | 0.24 | 0.56 | 0.07 | 1 | 0.87 |
| 0.7 | 0.5 | 0.15 | 0.15 | 0.175 | 1 | 0.475 |
| 0.7 | 0.2 | 0.24 | 0.06 | 0.07 | 1 | 0.37 |
| 0.2 | 0.2 | 0.64 | 0.16 | 0.02 | 1 | 0.82 |
| 0.5 | 0.5 | 0.25 | 0.25 | 0.125 | 1 | 0.625 |
| 0.5 | 0.7 | 0.15 | 0.35 | 0.175 | 0 | 0.525 |
| 0.2 | 0.7 | 0.24 | 0.56 | 0.07 | 0 | 0.63 |
| 0.7 | 0.5 | 0.15 | 0.15 | 0.175 | 0 | 0.325 |
| 0.7 | 0.2 | 0.24 | 0.06 | 0.07 | 0 | 0.13 |
| 0.2 | 0.2 | 0.64 | 0.16 | 0.02 | 0 | 0.18 |
| 0.5 | 0.5 | 0.25 | 0.25 | 0.125 | 0 | 0.375 |

After introducing these constraints, equation (3.10) becomes:

|  |  |
| --- | --- |
|  | (3.10) |

## Modifications to the endogenous solution

An introduction to the available policies in FTT: IH, and how they modify the endogenous results

The solutions to the modified shares equation, equation (3.10), will give the endogenous solution for market shares.

However, certain policies in FTT: IH will make further changes to the endogenous solution. How these changes are implemented is detailed here.

#### Regulations

We have seen how regulations are implemented in the shares equation. Regulations will lace a constraint on the potential capacity of any technology, and should be use as a limitation or a ban. They will not encourage investment and cannot be used as a target.

Regulations can be set using the following variables:

Table 9: Regulation variables

|  |  |
| --- | --- |
| Model | Regulation Variable |
| 1 CHI | IRG1 |
| 2 FBT | IRG2 |
| 3 MTM | IRG3 |
| 4 NMM | IRG4 |
| 5 OIS | IRG5 |

These variables are in GW, the same unit as installed capacity.

# References