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Analyses of models for promotion schemes and ownership arrangements

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Work Package 4

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(Risø DTU)

Risø DTU

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Acronyms

c€	(Euro)cent
CHP	Combined Heat and Power
CO_2	Carbon dioxide
EU	European Union
FC	Fuel cell
FIT	Feed in tariff
FITS	Feed in tariff with selfconsumption
i.e.	*id est* (that is)
kW	Kilowatt
kWh	Kilowatt-hour
mCHP	Micro-Combined Heat and Power
PEMFC	Proton Exchange Fuel Cell
	Polymer Electrolyte Fuel Cell
PV	Photovoltaic
SOFC	Solid Oxide Fuel Cell
TSO	Transmission system operator
TWh	Terawatt-hour

Foreword

This document is a result of the FC4Home research project (http://fc4home.com/) and accomplished in Work Package 4 Analyses of models for promotion schemes and ownership arrangements

The scope of the FC4Home project is to assess technical and economic aspects of the ongoing fuel cell based micro-combined heat and power demonstration projects by addressing the socio-economic and systems analyses perspectives of a large-scale promotion scheme of fuel cells. This was carried out by means of energy systems analysis and studies on central cases for each of the participating project partners.

Objectives of the work package:

The objectives of WP4 are to

- State the economic consequences of different constellations of promotion schemes and ownership conditions.
- Analyse how different kinds of ownership structures interact with different promotion schemes
- Analyse how different operational strategies influence the economy of the individual owners
- Perform energy system analyses of fuel cell based micro-combined heat and power systems as a function of the chosen operational strategies including the economic and environmental consequences.
- Analyse how the operational strategies and promotion schemes influence the energy systems, including environmental issues

Different combinations of promotion schemes and ownership arrangements form different incentive-structures. Utilising a partial-equilibrium model and structural analysis methods this WP handles quantitative and qualitative analyses addressing key economic criteria, among these an efficient deployment of fuel cells.

Project Partners:

- Risø National Laboratory for Sustainable Energy, Technical University of Denmark (Denmark)
- EDF / EIFER (France)
- Simbiente (Portugal)

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1 Executive Summary

Micro-Combined Heat and Power systems may contribute to changing the energy system at the residential level. Being a part of a distributed generation system, the stationary fuel cells constitute a promising element in a potentially sustainable and environmentally friendly energy system. Fuel cell based microCHP will be able to contribute to an innovative system where the customer produces his own heat and partly his own electricity. Furthermore, stationary fuel cells as a part of a distributed generation system are also regarded as a potential to improve the national security of supply as well as increase the national competitiveness.

The stationary fuel cell technology is still in a rather early stage of development and faces a long list of challenges and barriers of which some are linked directly to the technology through the need of cost decrease and reliability improvements. Others are linked to the political stage, where the necessary support schemes have to be in place in combination with guarantees that the political objectives for the future energy system does not change dramatically.

One of the main challenges of the fuel cell technology is the efficiency while others are the cost as well as the reliability of the fuel cell. It is questionable if investors such as households or energy companies are willing to engage in the fuel cell technology before these conditions have improved.

In order to assure actual market penetration of fuel cells, political objectives, which will contribute to assuring that the investors face long term planning perspectives and regulation in the field has to be clear and contribute to creating the market opportunities e.g. through investments in R&D. In this work package, we address the issues of necessary support schemes and the effect on the future energy system.

If the single countries should opt to support stationary fuel cells, we find that in Denmark it would be promising to apply the net metering based support scheme for households with an electricity consumption exceeding the electricity production from the fuel cell. In France and Portugal the most promising support scheme is price premium when the fuel cell is run as a part of a virtual power plant.

From a system perspective, it appears that it is more important which kind of energy system (represented by country) the FC's are implemented in, rather than which operation strategy is used. In an energy system with lots of fossil fuel (Denmark and Portugal), the potential CO2 emission reductions are relatively large compared to an energy system dominated by e.g. fossil-free nuclear.

2 Introduction

2.1 Fuel cells

It is now widely recognised that fuel cell based micro-Combined Heat and Power systems may contribute substantially to altering the energy system at the residential level. Traditionally the customers rely on centralised electricity producers delivering electricity through the grid. Fuel cell based microCHP will be able to contribute to an innovative system where the customer produces his own heat and partly his own electricity. Depending on who owns the fuel cell and who is in charge of operating it, some units can interact together, working as a virtual power plant, which could be operated by e.g. an energy company.

Being a part of a distributed generation system, the stationary fuel cells constitute a promising element in a potentially sustainable and environmentally friendly energy system. Furthermore, stationary fuel cells as a part of a distributed generation system are also regarded as a potential to improve the national security of supply as well as increase the national competitiveness.

Fuel cells are characterised by:

- High efficiency in both power and heat production
- Low CO_2-emissions
- No or very little SO_2 and NOx emissions
- No noise
- Modularity – can easily be adapted to local requirements
- High fuel flexibility – depends on type of fuel cell

For the stationary fuel cell there is a list of available technologies [1]:

- Phosphoric-acid FC (PAFC). The fuel for this type of FC is hydrogen and it has an electrical efficiency of 37-42 percent and an overall efficiency of 80-85 percent.
- Polymer electrolyte membrane FC (PEMFC). This fuel cell also runs on hydrogen.
- Molten carbonate FC (MCFC). The fuel for the MCFC is natural gas or bio gas and the electrical efficiency is 55 percent and the overall is 85 percent.
- Solid oxide FC (SOFC). The fuel for the SOFC is natural gas and the fuel cell has an electrical efficiency of 40 percent and an overall efficiency of 90 percent. A specific type of the SOFC, the CFCL fuel cell, has an electrical efficiency of 60 percent with an overall efficiency of 80 percent.

The stationary fuel cell technology is still in a rather early stage of development and faces a range of challenges. One of the main challenges of the fuel cell technology is the efficiency. Even though the fuel cell itself has overall efficiencies of more than 80 percent, you have to take into account that the fuel cells running on hydrogen are burdened by the production of hydrogen which has to be produced by reformation, partial oxidation, gasification, electrolysis or high temperature cracking of water [1]. The existing stationary fuel cells today are mainly using natural gas. National natural gas grids are already well established in many countries, which makes nationwide natural gas supply possible [1]. That the established fuel cells run on natural gas, on the other hand, is at the detriment of fuel cell as a clean and fossil-free technology. On the other hand, if the fuel cells ran on biogas the technology would be perceived as fossil free.

The companies engaged in the technology struggle hard to decrease the cost of the fuel cell in the same time as the reliability of the fuel cell needs to be improved [2]. It is questionable if investors such as households or energy companies are willing to engage in the fuel cell technology before these conditions have improved. A first market penetration of fuel cells might be just around the corner and a considerable market for fuel cells is expected to be established within the next five to 10 years.

In order to assure actual market penetration of fuel cells, clear political objectives for the future energy supply are needed, e.g. national independence. Clear political objectives will contribute to assuring that the investors face long term planning perspectives and regulation in the field has to be clear and contribute to creating the market opportunities e.g. through investments in R&D. As the costs of investing in fuel cells are still relatively high, private investors need financial incentives in order to invest in a fuel cell. These incentives could be provided either through operating support such as feed-in tariffs or through start-up financing such as investment support [1].

2.2 The report

It appears that the residential fuel cell technology faces a long list of challenges and barriers of which some are linked directly to the technology through the need of cost decrease and reliability improvements. Others are linked to the political stage, where the necessary support schemes have to be in place in combination with guarantees that the political objectives for the future energy system does not change dramatically.

This work package addresses one of these issues, namely the necessary support schemes and the effect on the future energy system. Based on a partial-equilibrium model and structural analysis methods, this WP will address how different combinations of support schemes and ownership structures affect different incentives structures. We have done the following:

- Analysed how different kinds of ownership structures is linked to different promotion schemes
- Performed private economic analysis of the necessary support levels for residential fuel cells of different constellations of promotion schemes and ownership conditions.
- Analysed how different operational strategies influence the economy of the individual owners through private economic analysis.
- Performed energy system analyses of fuel cell based micro-combined heat and power systems as a function of the chosen operational strategies including the economic and environmental consequences.
- Analysed how the operational strategies and promotion schemes influence the energy systems, including environmental issues.

The remainder of the report is structured as follows: In Section 3 we link the content of this work package to the rest of the project. In Section 4 we introduce the private economic analyses performed in this work package. The link between the operational strategies and the chosen support schemes are explained and the chosen combinations are presented. The private economic partial model is presented along with a number of the basic assumptions. In Section 5 the analyses for each country are presented including a summary and discussion of the private economic analyses. In Section 6 the effects of implementing the operational strategies on the various national energy systems are analysed using the STREAM energy system analysis tool. Finally, Section 7 concludes.

3 The role of WP 4 in the project

The private-economic analysis consists of a number of scenarios based on combinations of support schemes and ownership structures. The choice of combinations is based on the conclusions from Work Package 1 report "Support schemes and ownership structures - The Policy Context for Fuel Cell Based Micro-Combined Heat and Power" [3] and the Work Package 2 report: "Potential development, ownership models and support schemes – Analysing Actor Perceptions" [4] . Furthermore, the private economic analyses as well as the system analyses are based on results obtained in Work Package 5: Residential fuel cell micro CHP in Denmark, France and Portugal: Results simulation analysis [5]. Between the private economic analysis of support schemes and ownership structures and the control strategies, an iteration has taken place to a certain extent. This is explained in more detail later. Finally, the results obtained in Work Package 4 are used as input to the Work Package 6: National Cases combining promotion scheme, ownership and operational strategy [6] where the main contribution is a SWOT analysis of residential fuel cells in the three countries.

In the following, we summarise the main conclusions from Work Package 1 report "Support schemes and ownership structures - The Policy Context for Fuel Cell Based Micro-Combined Heat and Power" [3] and the Work Package 2 report: "Potential development, ownership models and support schemes – Analysing Actor Perceptions" [4] in order to motivate the choices and analyses made in this report.

3.1.1 Ownership arrangements

There are two perspectives when it comes to ownership structures: "consumer plug and play" and "company control". The focus group interviews in WP2 indicate that for Denmark both arrangements are relevant whereas in France the "consumer plug and play" solution seems to be the most realistic and in Portugal, it is the "company control" model that is the most probable.

Table 3-1 Ownership models and background motivation

	Denmark	France	Portugal
Ownership models	- Owned by households - Operated by users or an external service provider, e.g. gas supplier or grid company	- Owned and operated by households	- Owned by service providers (equipment manufacturers or utilities) - let to households
Background of this ownership model	- Some users expected as very active part in the energy system - Other users expected to be oriented towards minimising efforts and maximising gains	- Path dependency: installations traditionally owned by households - More active users expected in the future energy system - Energy companies reluctant to be owners	- Reducing households' transaction and maintenance costs - Reducing service providers' financial risk

Source: [4]

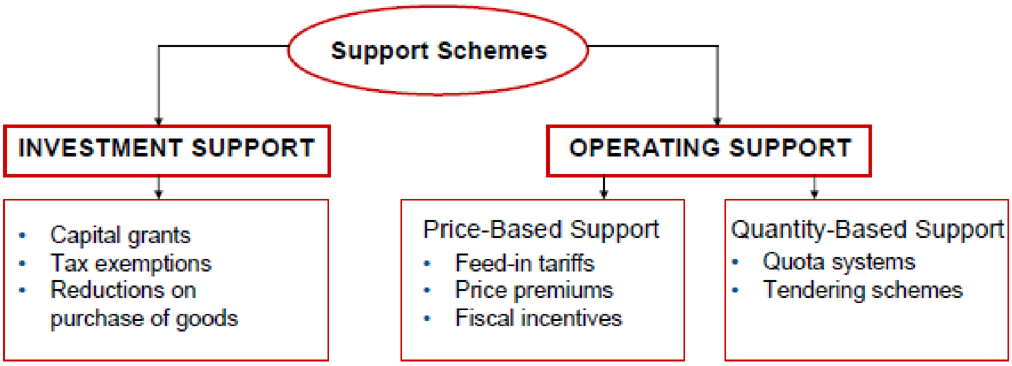
In Denmark this is motivated by the assumption that some users are "homo oecologicus activus", i.e. consumers who consider themselves as active promoters of environmental protection – mainly residential consumers – and others are "homo oeconomicus", i.e. users who, given the information at hand, are aiming to maximise their own economic benefits and minimising resources – mainly large companies (Huber et.al. 2010 [4]). In France installations have traditionally been owned by households and the indication is therefore a result of path dependency. In general, the focus group in Portugal is the one among the three countries being most skeptic towards fuel cell based mCHP. Therefore, the ownership structure with the least transaction and maintenance costs for the households and the least risk for the service providers is considered as the most appropriate one, i.e. the fuel cell will be owned and run by large companies.

3.1.2 Support schemes

The WP1 report gives an introduction to policy context for fuel cell based micro-combined heat and power and provides the rationale for support schemes and possible ownership arrangements for a future deployment of mCHP.

We distinguish between investment support – such as capital grants – and operating support (Figure 3-1). As for operating support we distinguish between price-based support schemes, e.g. feed-in tariffs, and quantity-based support schemes, e.g. quota systems [3].

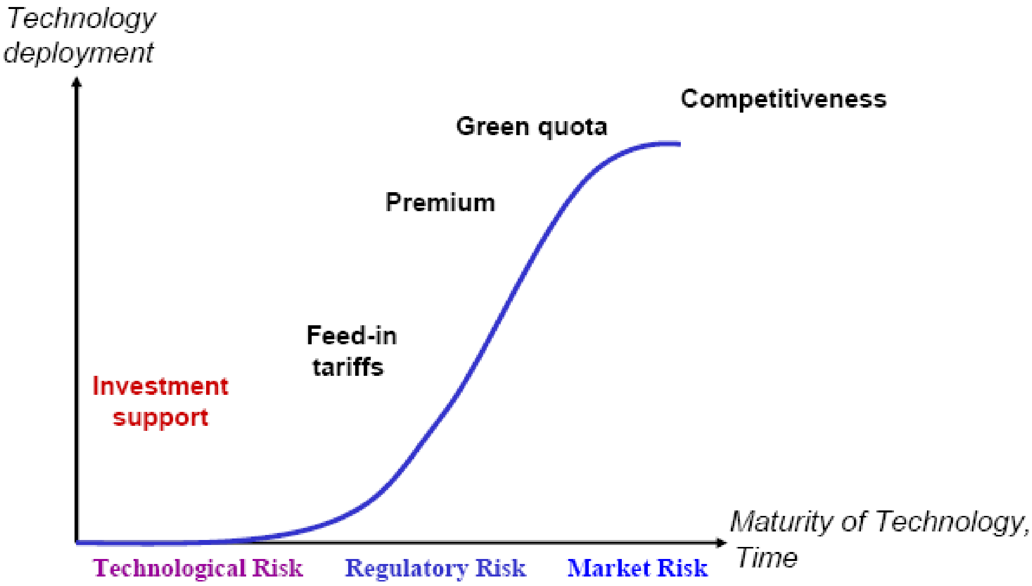
Figure 3-1 Overview of support schemes (CEC 2008)



Source: [3]

The choice of support scheme has to take into account a project developer's decision to invest in a new technology depending on the expected return of the investment and thereby the costs and risks of the investment. In the early stages of the development of a technology the technological risks and associated costs are very high (Figure 3-2). In this case a high degree of investment certainty might induce investments in the technology. As the technology matures the technological risk decreases and operational support schemes may be considered. In this stage it is the regulatory risk that is dominating. Finally, when the technology has reached the level of maturity that corresponds to competitiveness it will be market risk that dominates the technology.

Figure 3-2 Support schemes and maturity of technology



Source: [3]

The above mentioned analysis is mainly based on the point of view of a small private investor such as a household, and from that point of view fuel cell mCHP is located in the lower left corner with high technological risk pointing in the direction of investment support. However, you could easily suggest another kind of investor with higher demand for rate of return and more capital funds available. In this case, economies of scale could be realised by a single actor purchasing a large number of units. For this kind of professional investor, it would be more relevant to introduce a price premium. That way, the traditionally earlier step of feed-in tariffs might be omitted.

According to the focus group interviews, a "good cocktail" of investments support and some sort of operational support will be the proper way to induce investments in fuel cell based mCHP in Denmark and France. First of all the upfront investment support will reduce the investment costs and operational support will play an important role when taking the perspective of the system in order to add to grid balancing.

Table 3-2 Promotion schemes and background motivation

	Denmark	France	Portugal
Promotion schemes	- Upfront investment support plus premium on market price	- Upfront investment, e.g. capital allowance, plus - Operation support, e.g. premium on auto-consumption or fixed feed-in tariff	- Premium on top of the market price - Low tax rate
Motivations for this support scheme	- Reducing user's initial investment costs - System perspective: grid balancing	- Reducing user's investment costs - Compensating maintenance costs	- Most attractive to companies, reduces risk - Reflecting market prices

Source: [4]

3.1.3 Summary

The stakeholder analysis in combination with the introduction to policy context for fuel cell based micro-combined heat and power leads us to the following combination of ownership structure and support schemes for the three countries:

In Denmark, the residential fuel cell can either be owned by the household itself or a large company such as energy companies. The support schemes found the most appropriate for promoting residential fuel cells in Denmark are upfront investment support and price premium. In France, the fuel cell is expected to be owned and operated by household. The support schemes would be upfront investment, e.g. capital allowance, plus operation support, e.g. premium on auto-consumption or fixed feed-in tariff. In Portugal, the fuel cell is expected to be owned and run by a service provider supported by a premium on top of the market price maybe in combination with low tax rate.

4 Private-economic analysis

The purpose of the private economic analysis is to determine which support schemes are the most appropriate to apply.

In order to perform the analyses we have defined a range of scenarios depending on ownership arrangement, control strategy and support scheme. When it comes to ownership arrangements, we distinguish between consumer plug and play on the one hand and company control on the other hand. The control strategy can either be thermal control or virtual power plant control (VPP). Furthermore, the thermal control strategies are divided into two: one with a single constant electricity price, and one where peak periods are taken into account. The motivation for including this possibility is the technology already in place in France and Portugal giving the consumers the opportunity to choose a price scheme based on a peak and off-peak tariff.

4.1 Scenario definitions

There are two ownership possibilities:

1. Consumer plug and play:

   The first one is ownership of the households, where the fuel cell is installed. We define this as "consumer plug and play" meaning that the consumer buys the fuel cell, installs and operates it.

2. Company control:

   The other possible ownership arrangement is that the fuel cell is bought and run by a company, it could be an electricity or gas provider, and then installed in the individual households.

Regarding control strategy there are three possibilities:

1. The simplest one is the thermal control strategy, where the fuel cell is running with the purpose of fulfilling as large a share as possible of the heat demand of the household. The electricity produced is either exported directly to the grid or consumed by the household. Whenever the fuel cell is not able to fulfil the heating need of the household (e.g. during the summer the fuel cell is turned off) a gas furnace provides the heat. The household is equipped with a heat storage of 200 l.

2. The second option is a thermal control strategy taking peak periods into consideration. As in the first control strategy the fuel cell is running with the purpose of fulfilling as large a share as possible of the heat demand of the household. However, when there is the opportunity to shift the running hours of the fuel cell, the control strategy shifts the running hours to the peak periods. In that way the household will be able to reduce electricity demand or – if the households does not have electricity demand – increase electricity export from the household during these periods where the electricity price is

high. The heat storage of 200 l can then be used actively to shift the usage of the fuel cell to periods with higher end user electricity prices.

3. The third control strategy is the virtual power plant (VPP). When the fuel cell functions as a VPP, it runs independent of the heating demand profile of the household. Instead the fuel cell only takes the electricity prices into account and will, independently of the heating need of the household, determine whether to run or not. In order to assure this independency, we have assumed that excess heat can be blown off costless such that the heat storage does not constitute a boundary on the use of the fuel cell. This means that whenever the fuel cell runs and there is not heating demand in the household and/or the heating storage is full, the excess heat will costless be send out in the air. The VPP strategy can either be based on the spot market for electricity or being run in order to act as balancing power on the regulating power market. In the latter case, the control strategy has been designed such that the fuel cell as default run 50 percent load in order to be able to work both as upward regulation as well as downward regulation. If the fuel cell was running according to the spot price when there was no need for regulating power, we would not be certain that the fuel cell could be a player on the regulating market.

We have decided to base our analyses on four different support schemes: net metering, feed-in-tariff direct export, feed-in-tariff with self-consumption and price premium:

1. In the net metering case, the electricity meter is designed such that the meter is able to run backwards whenever the electricity production from the fuel cell is higher than the electricity consumption in the household. Basically this means that the household receives the difference between the end consumer price and the market price of electricity as a variable (due to the variation in the market price) price premium. The regarded time period is one year. Net metering is only used for the thermal control scenarios.

2. The second support scheme is feed-in-tariff (FIT).[1] In practice this means that the household is equipped with two electricity meters – one for electricity import (consumption) and one for electricity export (production). For the electricity export the household is paid a fixed feed-in-tariff per kWh. The feed in tariff is only used for the thermal control scenarios.

3. The third support schemes are feed-in-tariff with self-consumption (FITS). In the case with self-consumption the household consume electricity (if there is an electricity consumption at the specific moment) whenever the fuel cell is running. If the electricity production from the fuel cell exceeds the consumption the household export the exceeding electricity to the grid. If, on the other hand, the electricity consumption exceeds the production, the household imports electricity from the grid at the regular end consumer price. In the peak period control strategies the household faces two

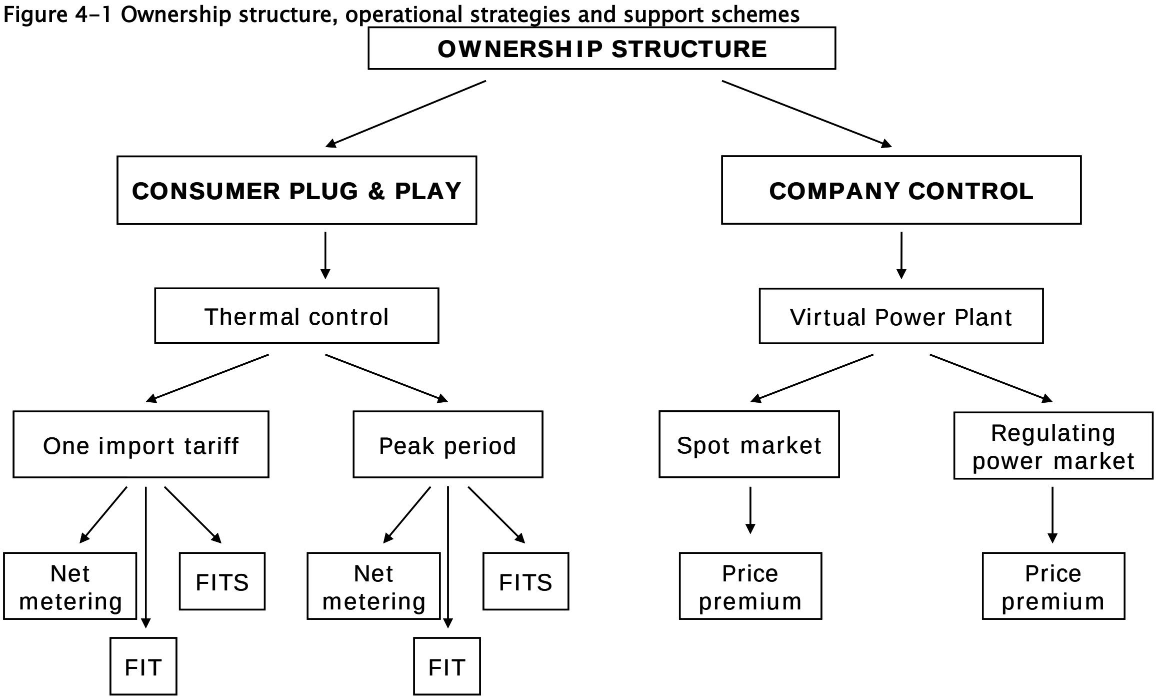
1 FIT: Without self-consumption meaning that all electricity produced by the fuel cell is sold to the grid.

different end consumer prices: peak and off peak. For the electricity exported to the grid the household is paid a fixed feed-in-tariff per kWh. In practice this means that the price the household faces for the self-consumed electricity corresponds to the feed-in-tariff. The feed in tariff with self-consumption is only used for the thermal control scenarios.

4. The last support scheme considered is price premium where all electricity is sold to the grid. The seller of the electricity receives a fixed premium on top of the market price of electricity. The price premium is only considered for the virtual power plant scenarios.

The discussions in Work package 1 and 2 have led us to define the following combinations of ownership structure, operational strategies and support schemes.

Figure 4-1 Ownership structure, operational strategies and support schemes



4.2 Model description

In order to analyse the need for financial support for promoting the diffusion of mCHP in individual households from a private economic perspective we have developed a model: Support Schemes for Fuel Cells (SS4FC). Its primary objective is thereby to give an indication of the required level of investment or price support in order to make the technology economically viable. The aim of the SS4FC model is thus to assess which support levels have to be granted under different promotion schemes and ownership arrangements.

Inputs to the SS4FC model comprise technical and economic data:

Table 4-1 Data input, SS4FC

Technical Data	**Unit**
System capacity	kW
Electrical efficiency	pct.
Thermal efficiency	pct.
Economic Data	
Capital Cost	€/kW
Operation and maintenance cost	€/kW/year
Stack change expenditures	€/kW
Lifetime	Years
Fuel cost, end consumer gas price	€/kWh
Electricity consumer price	€/kWh
Electricity consumer price, peak	€/kWh
Electricity consumer price, off peak	€/kWh
Power Exchange Price (average)	€/kWh
Real interest rate	pct.
Inflation rate	pct.
Opportunity cost (condensing boiler)	
Avoided investment cost	€/kW
Efficetivity	pct.

In the thermal control cases, we assume the fuel cell to have a capacity of 1 kW_e as compared to a capacity of 2 kW_e in the case of virtual power plant strategy. The 1 kW_e fuel cell is chosen in the thermal control case as the purpose is to assure as many load hours as possible in order to improve the profitability of the fuel cell. In the virtual power plant case, the purpose is to achieve the highest electricity production as possible and a higher capacity is chosen there. These strategies are supported by the choice of electrical and overall efficiencies. In the thermal control case the electrical efficiency is 40 percent and the overall efficiency is 90 percent, i.e. the heat efficiency is 50 percent supporting the satisfaction of the heat demand in the household. In the VPP case we assume another type of fuel cell is applied, the CFCL fuel cell. For the CFCL fuel cell the electrical efficiency is 60 percent whereas the overall efficiency is 80 percent, i.e. the heat efficiency is only 20 percent. Applying the CFCL with the higher electrical efficiency it is possible to achieve a higher electricity production.

The investment costs, operation and maintenance costs and stack change expenditures are all based on a number of studies ([8] -[20]) as well as information provided by the industry. We assume the investment costs to be 5000 €/kW. The assumption of proportional investment costs is rather conservative [21] and does not correspond to the assumption of the fuel cell producers. The fuel cell producers expect the price of the fuel cell to be less than twice as expensive when the capacity doubles. We have assumed that the operation and maintenance costs (excluding stack exchange) constitute to 140 €/kW/year being relatively optimistic. The stacks are initially expected to have a lifetime of 5 years and the stack exchange costs are assumed to be 1000

€/kW. In order to take uncertainties regarding these costs assumptions into account, we have preformed a number of analyses to enlighten the consequences of our choices.

All electricity prices as well as end consumer gas price is based on 2008 values. For all the scenarios we assume an interest rate of 5 percent.

If the household was not equipped with the fuel cell the alternative would be a gas furnace. The avoided investment costs as well as the effectivity rate are related to the alternative, i.e. the gas furnace.

4.2.1 Support level calculations

In order to illustrate the methodology of SS4FC three examples are provided below (Table 4-2, Table 4-3 and Table 4-4). In the first case (Table 4-2), the net metering is accompanied by investment support. The necessary investments support is dependent on the capital costs, the operation and maintenance (O&M) costs, the stack exchange costs and the fuel costs (gas consumption for the fuel cell). Furthermore, the avoided power costs (the electricity meter runs backwards), avoided heat costs (the heat produced by the fuel cell) as well as the avoided heat investments (the households does not have to invest in a new gas furnace) affect the necessary investment support. Finally, instead of investing in a fuel cell, the household could have invested the money elsewhere, and thus the opportunity costs of the investment also affects the necessary investment support.

Table 4-2, Support level example, net metering, (DK)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Investment, €/kW	-5000									
O&M, €/kW	-140	-143	-146	-149	-152	-155	-158	-161	-164	-167
Stack exchange costs, €/kW						-1104				
Fuel cost, €/kW	-1438	-1467	-1496	-1526	-1557	-1588	-1620	-1652	-1685	-1719
Avoided power costs, €	1255	1280	1305	1332	1358	1385	1413	1441	1470	1500
Avoided heat costs, €	799	815	831	848	865	882	900	918	936	955
Avoided heat investment, €	125									
Opportunity costs, €	-244	-261	-274	-288	-303	-319	-335	-352	-370	-389
Annual sums, €	-4643	224	220	216	212	-898	201	194	187	180
Annual sums (€2010)	-4643	220	212	204	196	-813	178	169	160	150
Sum (€2010)	-3968									
Necessary investment support(€/kW)	3968									
Annual generation (kWh/kW)	5432									
Total generation (kWh)	54323									

In the case of a feed in tariff (Table 4-3) the avoided power costs are not included in the analysis as the all the electricity produced is sold to grid. In order to obtain the necessary feed in tariff, the necessary support is divided by the total amount of electricity sold to the grid. In the case of feed in tariff without self-consumption, this equals the total generation of the fuel cell.

Table 4-3, Support level example, FIT (DK)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Investment, €/kW	-5000									
O&M, €/kW	-140	-143	-146	-149	-152	-155	-158	-161	-164	-167
Stack change costs, €/kW						-1104				
Fuel cost, €/kW	-1438	-1467	-1496	-1526	-1557	-1588	-1620	-1652	-1685	-1719
Avoided power costs, €	0	0	0	0	0	0	0	0	0	0
Avoided heat costs, €	799	815	831	848	865	882	900	918	936	955
Avoided heat investment, €	125									
Opportunity costs, €	-243.8	-261.1	-274.4	-288.4	-303.1	-318.5	-334.8	-351.8	-369.8	-388.6
Annual sums, €	-5898	-1056	-1085	-1115	-1147	-2283	-1212	-1247	-1283	-1320
Annual sums (€2010)	-5898	-1035	-1043	-1051	-1059	-2068	-1076	-1086	-1095	-1104
Sum (€2010)	-16515									
Necessary support(€/kW)	16515									
Annual generation (kWh/kW)	5432									
Total generation (kWh/kW)	54323									
Feed-In Tariff, €/kWh	0.30	0.31	0.32	0.32	0.33	0.34	0.34	0.35	0.36	0.36
Expenditure	1652	1652	1652	1652	1652	1652	1652	1652	1652	1652
	1652	1685	1718	1753	1788	1823	1860	1897	1935	1974
Feed-In Tariff (w/ inflation), €/kWh	0.333									

Finally, when using the price premium (Table 4-4) the power market income is taken into account in order to determine the total necessary support and hence the necessary price premium on top of the spot market price. Similar to the feed in tariff, the price premium is given by the total necessary support divided by the total generation.

Table 4-4 Support level example, Price Premium

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Investment, €/kW	-10 000									
O&M, €/kW	-280	-286	-291	-297	-303	-309	-315	-322	-328	-335
Stack change costs, €/kW						-2208				
Fuel cost, €/kW	-3144	-3207	-3271	-3337	-3403	-3471	-3541	-3612	-3684	-3757
Avoided power costs, €	0	0	0	0	0	0	0	0	0	0
Avoided heat costs, €	699	713	727	741	756	771	787	803	819	835
Avoided heat investment, €	250									
Power market income, €	990	1010	1030	1051	1072	1093	1115	1137	1160	1183
Opportunity costs, €	-488	-522	-549	-577	-606	-637	-670	-704	-740	-777
Annual sums, €	-11973	-2292	-2354	-2418	-2484	-4761	-2624	-2697	-2773	-2851
Annual sums (€2010)	-11973	-2247	-2263	-2279	-2295	-4312	-2330	-2348	-2366	-2386
Sum (€2010)	-34798									
Necessary support (€/kW)	17399									
Annual generation (kWh/kW)	17524									
Total generation (kWh/kW)	175242									
Price Premium	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.12	0.12
Expenditure	1740	1740	1740	1740	1740	1740	1740	1740	1740	1740
	1740	1775	1810	1846	1883	1921	1959	1999	2039	2079
Price Premium (w/ inflation)	0.11									

The annual values of fuel costs, avoided power costs, avoided heat investments and power market income are all founded in the technical simulations [5] and is based on calculations made on 10 minutes level.

5 Country cases

In the following we introduce the support scheme analyses for the three countries. Taking the point of departure in the results in WP1 and WP2 and the identified scenarios (Figure 4-1), a number of scenarios have been chosen for each country.

5.1 Denmark

For Denmark four combinations of ownership structure, operational strategies and support schemes are chosen (Figure 5-1):

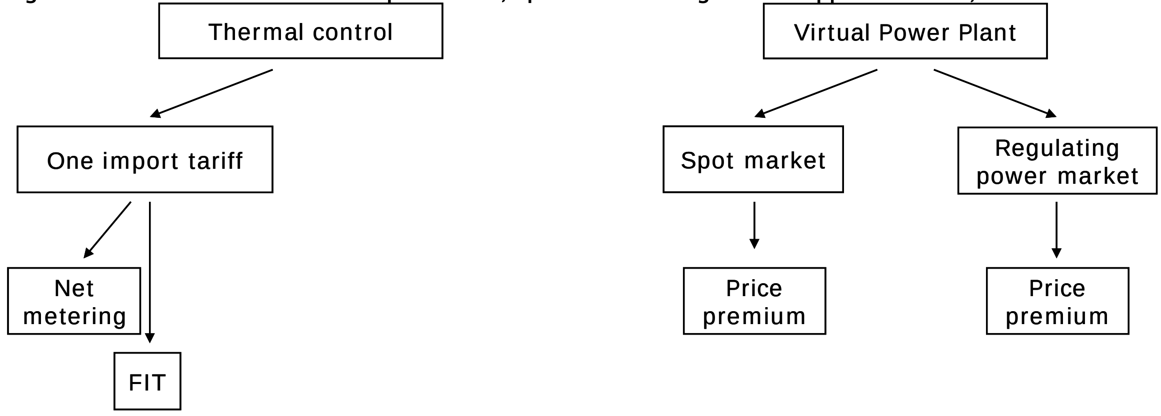
- Consumer plug and play – thermal control – net metering: the fuel cell is running in order to satisfy the heat demand of the household and the electricity meter runs backwards for the amount of electricity produced not exceeding the electricity consumption. For the electricity produced exceeding the electricity consumption on the annual basis, the owner of the fuel cell receives a fixed price of 8 c€/kWh. This assumption is in line with current Danish legislation for solar PV and a number of other small-scale renewable energy technologies [7].

- Consumer plug and play – thermal control – FIT: the fuel cell is running in order to satisfy the heat demand of the household having the heat storage both as a buffer for hot water supply as well as a mean to increase the usage of the fuel cell. All the electricity produced on the fuel cell is exported directly to the grid and the household is paid a fixed feed-in-tariff per kWh.

- Company control – VPP – day ahead: the fuel cell runs independent of the heating demand profile of the household and excess heat can be blown off without costs. The seller of the electricity sells the electricity on the spot market and is paid a fixed price premium on top of the market price of electricity.

- Company control – VPP – regulating power market: the fuel cell runs independent of the heating demand profile of the household and excess heat can be blown off without costs. The seller of the electricity sells the electricity on the regulating power market. The control strategy has been designed such that the fuel cell as default run 50 percent load in order to be able to work both as upward regulation as well as downward regulation. The seller of the electricity is paid a fixed price premium on top of the market price of electricity as well as the stand by payment.

Figure 5-1 Combination of ownership structure, operational strategies and support schemes, Denmark



The stakeholder analysis in combination with the introduction to policy context for fuel cell based micro-combined heat and power leads us to the following combination of ownership structure and support schemes in Denmark: the residential fuel cell will either be owned by the household itself or a large company such as energy companies. The support schemes found the most appropriate for promoting residential fuel cells in Denmark are upfront investment support and price premium.

We have nevertheless chosen also to analyse a feed in tariff. This choice is made because there is a tradition in Denmark for using feed in tariffs in the rather early stage of a new technology, e.g. wind power

In the two thermal control scenarios we assume to install a 1 kW_e low electric efficiency SOFC fuel cell with an electric efficiency of 40 percent and an overall efficiency of 90 percent, i.e. a heat efficiency of 50 percent (Table 5-1). This capacity has been chosen in order to assure that the fuel cell would run as many hours as possible in order to improve the profitability. The type of fuel cell determining the electric and overall efficiency is chosen because the primary purpose of the fuel cell in scenario 1 and 2 is to satisfy the thermal demand of the household whereby a high heat efficiency is attractive relative to electric efficiency. The 1 kW_e fuel cell is not able to fulfil the heat demand of the household and therefore the households in addition has a gas boiler which covers the remainder of the heat demand.

For the two VPP scenarios we perform the analyses for a 2 kW_e fuel cell. The electric efficiency is assumed to be rather high, 60 percent, whereas the overall efficiency is only 80 percent. As the primary purpose of the fuel cell in the VPP scenarios is to deliver electricity to the grid when other renewable energy resources are not available, we analyse the situation of a 2 kW_e fuel cell. Especially in the case when the fuel cell is supposed to operate on the regulating power market we assume it will be profitable to install a 2 kW_e fuel cell in order to obtain the possibility to act on both the up regulating as well as the down regulating market. In this case the fuel cell will as default run on a 50 percent basis and then be able to scale up or down corresponding to 1 kW_e. The high electric efficiency is chosen as the main purpose is to produce electricity whereby the heat production is secondary.

All analyses are performed for both an old house and a new house.

Table 5-1 Technical specifications, Denmark

Control strategy	Support scheme	Capacity (kW)	Housetype	Fuel cell	Efficiency, electrical/overall
Thermal control	Net metering/FIT	1	Old and new	Low electrical efficiency - SOFC	40/90
VPP - spot market/ regulating power market	Price premium	2	Old and new	High electrical efficiency - SOFC	60/80

The background data of the Danish analyses are given in Table 5-2. The end consumer electricity price of Denmark is rather high compared to France and Portugal. In Denmark it is 0.3 €/kWh whereas in France it is 0.11€/kWh and in Portugal 0.15 €/kWh. An old house in Denmark is assumed to consume approximately 20 000 kWh per year whereas the heat consumption of a new house is assumed to be approximately 10 000 kWh. These levels of heat consumptions are covering room heating as well as hot water supply. The annual electricity consumption is assumed to be 3752 kWh independent on housetype.[2]

Table 5-2 Background data, Denmark

Fuel cell		
Lifetime	10	Y
Capital Cost	5000	€/kW
O&M Cost	140	€/kW p.a.
Stack change (lifetime 5 years)	1000	€/kW
Energy prices		
Fuel cost, end consumer gas price	0.11	€/kWh
Electricity consumer price	0.3	€/kWh
Power Exchange Price (average)	0.057	€/kWh
Interest rate etc.		
Real interest rate	5	Pct. p.a.
Inflation rate	2	Pct. p.a.
Consumer data		
Electricity demand, annual	3752	kWh
Heat demand, annual, new house	10 541	kWh
Heat demand, annual, old house	19 660	kWh

[2] www.dongenergy.dk/privat/energiforum/tjekditforbrug/typiskelforbrug/Pages/hus.aspx

5.1.1 Thermal control

In the thermal control scenarios the consumer is assumed to own and run the fuel cell. As the individual consumer is not expected to react to the change in electricity and gas prices the fuel cell is expected to run according to what we define as thermal control, i.e. in order to fulfill the heating need of the individual household. The scenarios is run for a 1 kW_e FC in an old house and a new house. Two support schemes are chosen:

1. Net metering, covering the situation where the electricity meter runs backwards for the amount of electricity produced not exceeding the electricity consumption on a yearly basis.[3] For the electricity produced exceeding the electricity consumption the owner of the fuel cell receive a fixed price of 8 c€/kWh.

2. Feed in tariff (FIT) where all the electricity produced is sold to the grid for a fixed tariff per kWh.

The results from the analysis, summarised in Table 5-3, shows that the electricity production of the fuel cell installed in the old house exceeds the electricity production of the fuel cell installed in the new house. This result is not surprising since the fuel cell has to run more hours in order to fulfil the (larger) heating need of the household in the old house illustrated by the number of full load hours being 4957 in the new house as compared to 5432 in the old house. The share of the heat demand covered by the fuel cell is larger in the new house, 60 pct., compared to the old house, where the fuel cell only covers 35 pct.

The fuel cell is slightly more profitable in the case of the old house since the break even investment costs (the highest tolerable investment cost for the investment to break even under net metering) is 2495 €/kW and 2460 €/kW for the new house. I.e. the owner of the new house would only invest in the fuel cell if the price is 2460 €/kW or below whereas the owner of the old house would invest if the price was just 2495 €/kW or below. These break even investments should be related to the assumed investment cost of 5000 €/kW.

Without support, the internal rate of return in both cases is below zero.

[3] This is unlike the scenario for France where the meter runs backwards indenpendent of the consumption

Table 5-3 Thermal control – overview – Denmark

	New house	Old house
Electricity production	4957 kWh	5432 kWh
Electricity export (netmetering)	1220 kWh	1696 kWh
Full load hours	4957	5432
Heat demand covered by FC	60 pct.	35 pct.
Internal Rate of Return (nominal)	< 0 pct.	< 0 pct.
Break even investment costs	2460 €/kW	2495 €/kW
FIT	35.8 c€/kWh	33.3 c€/kWh

The analyses show that a feed in tariff of 33.3 c€/kWh is necessary for the fuel cell to be profitable in an old house whereas in a new house the feed in tariff has to be 35.8 c€/kWh. This is a very high level in comparison with current support for most renewable energy technologies such as wind or biomass, but these technologies advanced considerably since their market introduction decades ago. Historically, higher feed-in tariffs of approximately 50 c€/kWh have been seen in countries like Germany and induced cost decreases in the long run.

Large electricity consumption

For the Danish case, unlike the French, the net metering has the restriction that for the electricity production exceeding the electricity consumption on a yearly basis the fuel cell owner only receives 8 c€/kWh. If we instead assumed that we were dealing with a household with an identical heating profile but with an electricity consumption exceeding the electricity production from the fuel cell, then we would obtain other results (Table 5-4).

Table 5-4 Thermal control – large electricity consumption – overview – Denmark

	New	Old
Electricity production	4957 kWh	5432 kWh
Electricity export (netmetering)	≤ 0 kWh	≤ 0 kWh
Full load hours	4957	5432
Heat demand covered by FC	60 pct.	35 pct.
Break even investment costs	4209.18 €/kW	4904.635 €/kW
Internal Rate of Return (nominal)	5.1 pct.	6.8 pct.

The Table shows that assuming that the electricity consumption on a yearly basis exceeds the electricity production, we have a significantly different situation. In this case the break even investments almost corresponds to the assumed investment cost of 5000 €/kW. Furthermore, the internal rate of return turns out to be rather beneficial for the old house.

Sensitivity analysis

In order to test the validity of our basic assumptions and therefore the above mentioned results we have performed a number of sensitivity analyses changing the preconditions for important parameters:

- We have analysed the situation where the fuel cell has a life time of 20 years instead of 10.
- We have looked in to the situation where the O&M costs are more than twice as high as in the base case scenario, i.e. 300 €/kW/year.
- We have analysed the consequences of a lifetime of the stacks of two years compared to the initially assumed five years.
- We have also analysed the consequences of a lifetime of the stacks on 10 years – i.e. that the stacks do not have to be replaced.
- Finally, we have analysed the consequences of an additional increase of one percent point in the electricity and gas price relative to the elsewhere assumed inflation.

Table 5-5 Thermal control, sensitivity analyses - Denmark

	Old house (base case)	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
Break even investment costs	2495 €/kW	2705 €/kW	1485 €/kW	600 €/kW	3125 €/kW	2670 €/kW
Internal Rate of Return (nominal)	< 0 pct.	3.33 pct.	< 0 pct.	< 0 pct.	< 0 pct.	< 0 pct.
Feed in tariff	33.3 c€/kWh	33.7 c€/kWh	36.5 c€/kWh	39.3 c€/kWh	31.3 c€/kWh	31.9 c€/kWh

The analysis shows that the profitability of the fuel cell increases with the lifetime. Even though the stacks have to be changed twice in the prolonged period, the break even investment costs increases to 2705 €/kW. Comparing this result to the case where the stacks have a lifetime of 10 years and therefore do not have to be changed in the entire period, the break even investment is 3125 €/kW. However, the nominal internal rate of return is only positive in the case of a lifetime of 20 years of the fuel cell.

If the lifetime of the stacks decreased to two years, the breakeven investment costs would decrease to approximately 600 €/kW and with the initial assumption of 5000 €/kW the profitability of the investment would be below zero. Further, if the operation and maintenance costs increased to 300 €/kW/year the break even investment costs falls to 1485 €/kW.

In coherence herewith, the necessary feed in tariff increases significantly in the cases of higher O&M costs as well as shorter lifetime of the stacks. In case of a longer lifetime of stacks as well as in the case on higher electricity and gas prices, the feed in tariff is slightly lower compared to the base case scenario (old house). In the case of a lifetime of 20 years of the fuel cell, the nominal value of the necessary feed tariff increases slightly – however – in fixed 2010-price the feed in tariff falls slightly compared to the base case.

5.1.2 Virtual power plant - spot market

In the virtual power plant scenarios the fuel cell is assumed to be owned and controlled by a company such as an electricity supplier or gas supplier but still to be installed in a private household. The fuel cell is assumed to run independent of the heating profile of the household, i.e. the fuel cell does not run in order to fulfil the heating need of the household. Instead the control strategy only takes the electricity prices into account and will, independently of the heating need of the household, determine whether to run or not. The technical simulations have thus been run assuming that excess heat can be blown off costless. This means that whenever the fuel cell runs and there is no heating demand in the household and/or the heating storage is full, the excess heat is deposed of without expenses. In this scenario we assume that the fuel cell has the capacity of 2 kW_e.

The necessary price premium has been determined by running the technical simulations under the assumptions of a number of different price premiums.[4] The technical simulations show that assuming a price premium of 10 c€/kWh the fuel cell will run almost as much as possible and increasing the price premium further does not affect the technical simulation significantly.

In order to determine the necessary price premium we have made the private economic analyses based on the results from the technical simulation for the entire range of assumed price premiums. Assuming a technical strategy correspondent to a price premium of 10 c€/kWh (i.e. the technical strategy where the fuel cell run almost around the clock) it is necessary to introduce a price premium of 21.7 c€/kWh in order to make the investment in the fuel cell profitable. As the fuel cell at this level already runs as much as possible, the same results would be obtained doing the private economic analyses using the results from the technical simulations assuming 15 as well as 20 c€/kWh. The total necessary support is then 8784 €/kW. Technical simulations based on lower price premiums result in a lower level of electricity production and a resulting higher necessary support level.

In the following the results for the VPP based on the spot market for electricity are presented.

Table 5-6 Virtual power plant – spot market – overview – Denmark

	New house	Old house
Electricity production	17451 kWh	17524 kWh
Full load hours	8725 h	8762 h
Heat demand covered by FC	55 pct.	30 pct.
Price premium	21.7 c€/kWh	21.7 c€/kWh

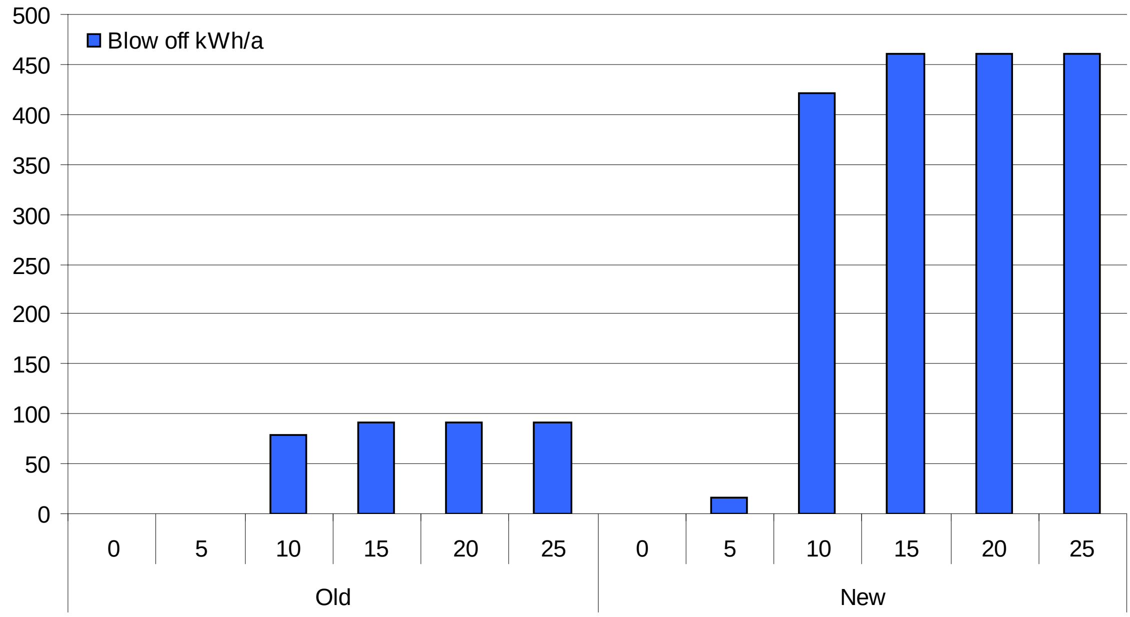
The analyses show that under the virtual power plant based on the spot market, there is hardly any difference between the control strategies for a new house compared to an old house. The amount of electricity produced exceeds the electricity consumed by a factor five whereas the fuel cell only covers 55 percent and 30 percent of the heat consumption in a new and an old house respectively.

Even though the fuel cell does not cover the total heat demand of the household the fuel cell will still run in periods where there is no heating need in the house in combination with a full

4 0 c€/kWh, 5 c€/kWh, 10 c€/kWh, 15 c€/kWh and 20 c€/kWh

heating storage. In these situations the technical simulations simply assume a heat blow-off, which is illustrated in Figure 5-2, showing that the amount of blow off is largest for the new house and that the amount of blow off is almost maximal for both and old and a new house for a price premium of 10 c€/kWh.

Figure 5-2 Blow off dependent on price premium and house types - Denmark



Source: [5]

The fuel cell runs almost around the clock and despite the amount of blow off the fuel cell is not able to fulfil the heating demand of the household. The logic behind this is that the fuel cell in some periods produce even though there is no heating demand and the storage is full (blow off). In other times of the day the heating demand exceeds the production of the fuel cell including the storage and the gas boiler runs in order to fulfil the heating demand. This affect would be altered if the heat storage was larger.

Sensitivity analysis

We have performed the same sensitivity analyses as for the thermal control strategy. We see that the necessary price premium is mostly affected by a decrease in the lifetime of the stacks. In that case the necessary price premium increases to 25.5 c€/kWh compared to the situation where the stacks do not have to be replaced where the necessary price premium is only 20.5 c€/kWh.

Table 5-7 Virtual power plant – spot market – Sensitivity analysis – Denmark

	Old house (base case)	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
Price premium	21.7 c€/kWh	20.6 c€/kWh	23.7 c€/kWh	25.5 c€/kWh	20.5 c€/kWh	22.1 c€/kW

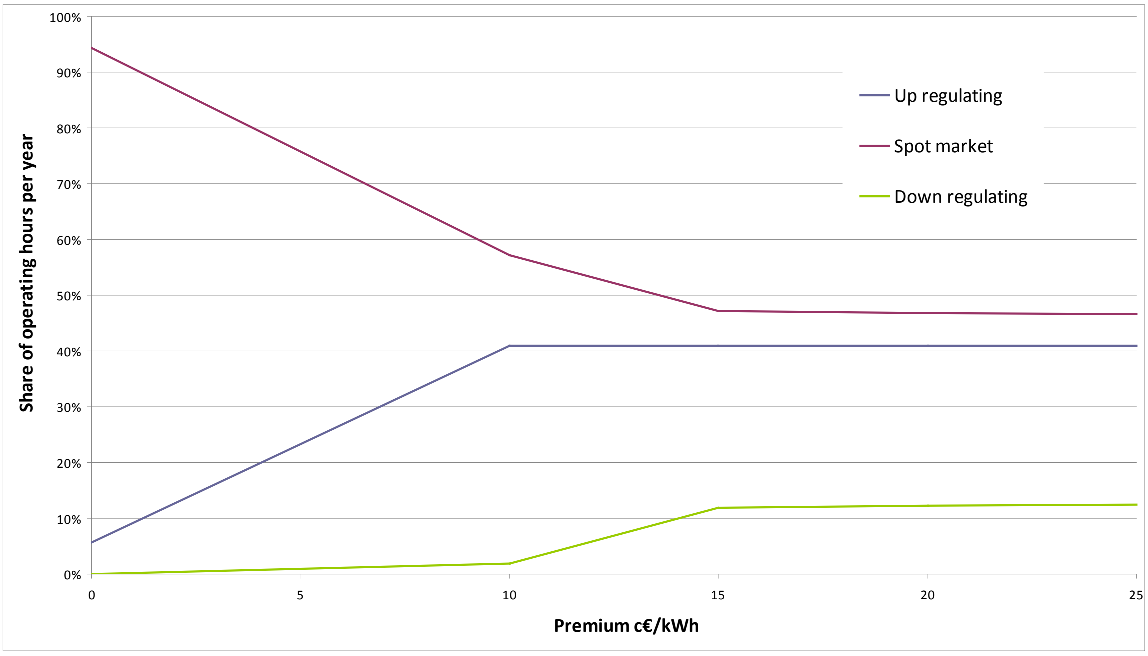
5.1.3 Virtual power plant – regulating power market

In the virtual power plant scenarios the fuel cell is assumed to be owned and run by a company such as an electricity supplier or gas supplier. The fuel cell is assumed to run independently of the heating demand of the household only taking electricity prices into account. In the following, the results for the VPP based on the regulating power market for electricity are presented. In order to run on the regulating power market we assume that the fuel cell runs 50 percent capacity per default, i.e. 1 kW_e as the fuel cell is assumed to be a 2 kW_e fuel cell. If there is need for up-regulating or down-regulating power, the unit is able to offer a downward regulation or upward regulation of 1 kW. As the fuel cell run 50 percent of its capacity per default the owner is able to achieve the stand by payment at any time as there is always the possibility to up or down regulate. If both down and up regulation is required within the same hour the fuel cell will up regulate or down regulate dependent on what is most profitable.

In order to determine the necessary price premium, the technical simulations have been run under the assumptions of a number of different price premiums. [5] The technical simulation shows that assuming a price premium of 15 c€/kWh the fuel cell maximises the share of hours for the upward regulating market. Assuming a price premium of 25 c€/kWh the fuel cell additionally maximises the share of hours on the downward regulating market only affecting the share of hours run on spot market (Figure 5-3).

[5] 0 c€/kWh, 10 c€/kWh, 15 c€/kWh, 20 c€/kWh and 25 c€/kWh

Figure 5-3 Premium-sensitivity on the mCHP optimisation-strategy related to the regulating market - Denmark



Source: [5]

The necessary price premium has been determined by doing the private economic analyses based on the results from the technical simulations on the range of assumed price premiums (Table 5-8). Doing the private economic analysis assuming the technical simulation under condition of a price premium of 15 c€/kWh we find that the necessary price premium is 26.3 c€/kWh. Using the technical simulations based on 20 c€/kWh as well as 25 c€/kWh we find that the necessary price premium is 26.4 c€/kWh. The total necessary support achieved is the lowest doing the private economic analyses based on the technical simulations assuming a price premium of 25 c€/kWh, which corresponds to a necessary price premium of 26.4 c€/kWh.

Table 5-8 Necessary support dependent on support assumed for technical strategy, €/kW - Denmark

Assumed support level	Total necessary support	Necessary Price Premium
0 c€/kWh	12437 €/kW	29.4 c€/kWh
10 c€/kWh	13455 €/kW	24.5 c€/kWh
15 c€/kWh	12317 €/kW	26.3 c€/kWh
20 c€/kWh	12285 €/kW	26.4 c€/kWh
25 c€/kWh	12278 €/kW	26.4 c€/kWh

Based on these considerations, we perform the further analyses based on a price premium of 26.4 c€/kWh. Under these conditions the amount of electricity produced exceeds the electricity consumed by a factor 2.5 whereas the fuel cell only covers approximately 30 percent and 15 percent of the heat consumption in a new and an old house respectively.

Table 5-9 Virtual power plant – regulating market – overview – Denmark

	New house	Old house
Electricity production	10252 kWh	10253 kWh
Full load hours	5126 h	5127h
Heat demand covered by FC	32.4 pct.	17.4 pct.
Price premium	26.4 c€/kWh	26.4 c€/kWh

Sensitivity analysis

We have performed the same sensitivity analyses as above: 20 years lifetime of the fuel cell, higher O&M costs, shorter lifetime of stacks, longer lifetime of stacks and finally higher electricity and gas prices. The results from the sensitivity analyses are summarised in Table 5-10.

The sensitivity analyses show that the results are rather robust towards changes in the basic assumption. Only changing the lifetime of the stacks to two years dramatically increase the necessary price premium. The most positive result is obtained if the lifetime of the fuel cell is assumed to increase to 20 years. In that case, the necessary price premium decreases to 23.4 c€/kWh.

Table 5-10 Virtual power plant – regulating power market – Sensitivity analysis – Denmark

	Old house (base case)	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
Price premium	26.4 c€/kWh	23.4 c€/kWh	29.9 c€/kWh	32.9 c€/kWh	24.3 c€/kWh	26.6 c€/kW

5.1.4 Summary Denmark

The analyses for Denmark showed that for households where the electricity consumption exceeds the electricity production of the fuel cell (i.e. the entire amount of electricity granted the support corresponding to the end consumer electricity price), the case with thermal control in combination with net metering would be very promising. In this case the household would only need an extra support corresponding to 200 €/kW al together. Assuming a feed in tariff the necessary feed in tariff is 33.3 c€/kWh independent on the electricity production.

Furthermore, comparing the two scenarios assuming the fuel cell is a part of a virtual power plant that the situation where the fuel cell is operates at the spot market makes is the most reasonable. In this case the necessary price premium is 21.7 c€/kWh whereas the fuel cell on the regulating power market would need a price premium of 26.4 c€/kWh. This covers the fact that for the spot market scenario, the total necessary support is 8784 €/kW whereas the for the regulating power market scenario, the total necessary support is 12278 €/kW.

5.2 France

For France six combinations of ownership structure, operational strategies and support schemes are chosen (Figure 5-4):

1. Consumer plug and play – thermal control one import tariff – net metering: the fuel cell is running in order to satisfy the heat demand of the household and the electricity meter runs backwards when the fuel cell is producing more than is being consumed.

2. Consumer plug and play – thermal control – FIT: the fuel cell is running in order to satisfy the heat demand of the household having the heat storage both as a buffer for hot water supply as well as a mean to increase the usage of the fuel cell. All the electricity produced on the fuel cell is exported directly to the grid and the household is paid a fixed feed-in-tariff per kWh.

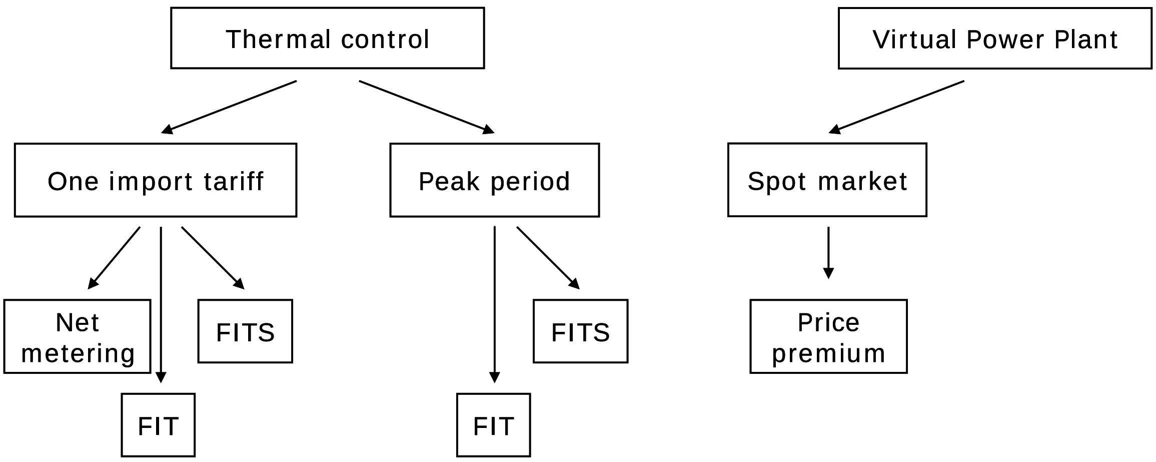
3. Consumer plug and play – thermal control one import tariff – Feed in tariff with self consumption (FITS): the fuel cell is running in order to satisfy the heat demand of the household having the heat storage both as a buffer for hot water supply as well as a mean to increase the usage of the fuel cell. Whenever the fuel cell is running and the household at the same time consumes electricity, the household self-consume. Within the hour the household export to the grid when the electricity production exceeds the consumption and import from the grid when the electricity consumption exceeds the production. For the electricity exported to the grid the household is paid a fixed feed-in-tariff per kWh (FITS)

4. Consumer plug and play – thermal control peak periods – FIT: the fuel cell is running in order to satisfy the heat demand of the household having the heat storage both as a buffer for hot water supply as well as a mean to increase the usage of the fuel cell as and as a mean for switching the usage of the fuel cell to hours with higher electricity prices. I.e., whenever it is possible to shift the usage of the fuel cell the operating hours will be shifted towards the peak periods. All the electricity produced on the fuel cell is exported directly to the grid and the household is paid a fixed feed-in-tariff per kWh.

5. Consumer plug and play – thermal control peak periods – FITS: the fuel cell is running in order to satisfy the heat demand of the household having the heat storage both as a buffer for hot water supply as well as a mean to increase the usage of the fuel cell as and as a mean for switching the usage of the fuel cell to hours with higher electricity prices. I.e., whenever it is possible to shift the usage of the fuel cell the operating hours will be shifted towards the peak periods. Whenever the fuel cell is running and the household at the same time consumes electricity, the household self-consume. Within the hour the household export to the grid when the electricity production exceeds the consumption and import from the grid when the electricity consumption exceeds the production. For the electricity exported to the grid the household is paid a fixed feed-in-tariff per kWh (FITS)

5. Company control – VPP – day ahead: the fuel cell runs independent of the heat demand profile of the household and excess heat can be blown off without costs. The seller of the electricity sells the electricity on the spot market and is paid a fixed price premium on top of the market price of electricity.

Figure 5-4 Combination of ownership structure, operational strategies and support schemes, France



The stakeholder analysis in combination with the introduction to policy context for fuel cell based micro-combined heat and power leads us to the following combination of ownership structure and support schemes in France: the fuel cell is expected to be owned and operated by household. The support schemes would be upfront investment, e.g. capital allowance, plus operation support, e.g. premium on auto-consumption or fixed feed-in tariff.

We have nevertheless also examined the situation where the fuel cell is at least operated if not owned by a large company e.g. an energy company in order to capture the possibility of residential fuel cells to work as a virtual power plant.

Table 5-11 Technical specifications, France

Scheme number	Support scheme	Capacity (kW)	House type	Fuel cell	Efficiency, electrical/over all
Thermal control	Net metering/FIT/FITS	1	Old/new	Low electrical efficiency - SOFC	40/90
Thermal control/peak periods	FIT/FITS	1	Old/new	Low electrical efficiency - SOFC	40/90
VPP - spot market	Price premium	2	Old/new	High electrical efficiency –	60/80

In the thermal control scenarios we assume to install a 1 kW_e low electric efficiency SOFC fuel cell with an electric efficiency of 40 percent and an overall efficiency of 90 percent (Table 5-11). For the VPP scenario, we perform the analyses for a 2 kW_e fuel cell with an electrical efficiency of 60 percent, whereas the overall efficiency is only 80 percent. All analyses are performed for both an old house and a new house.

The background data for France are given in Table 5-12. The end consumer electricity price of France is substantially lower compared to Denmark. In Denmark it is 0.3 €/kWh whereas in France it is only 0.11€/kWh. The heat consumption of an old house in France is assumed to be 18 925 kWh per year whereas the heat consumption of a new house is assumed to be approximately 8636 kWh. These levels of heat consumptions are covering room heating as well as hot water supply. The annual electricity consumption is assumed to be 2937 kWh independent on housetype.

Table 5-12 Background data, France

Fuel cell		
Lifetime	10	Y
Capital Cost	5000	€/kW
O&M Cost	140	€/kW p.a.
Stack change (lifetime 5 years)	1000	€/kW
Energy prices		
Fuel cost, end consumer gas price	0.0579	€/kWh
Electricity consumer price	0.1145	€/kWh
Electricity consumer price, day	0.1275	€/kWh
Electricity consumer price, night	0.0864	€/kWh
Power Exchange Price (average)	0.043	€/kWh
Interest rate etc.		
Real interest rate	5	pct. p.a.
Inflation rate	2	pct. p.a.
Consumer data		
Electricity demand, annual	2937	kWh/year
Heat demand, annual, new house	8636	kWh/year
Heat demand, annual, old house	18925	kWh/year

5.2.1 Thermal control – one import tariff

In the thermal control scenarios, the consumer is assumed to own and run the fuel cell and is not expected to react to the changes in electricity and gas prices. The fuel cell is expected to run in order to fulfill the heating need of the individual household. The chosen support schemes are netmetering, feed in tariff and feed in tariff with self-consumption.

The results show (Table 5-13) that in order to fulfil as much of the heat consumption as possible the fuel cell run more full load hours in the old house compared to the new house. Hence, the fuel cell in the old house produces more electricity compared to the fuel cell in the new house. The total electricity produced is 4206 kWh per year in the new house and 5231 kWh per year in the old house and thus exceed the electricity consumption for both type of houses.

The fuel cell is more profitable in the case of the old house since the break even investment costs[6] in this case is 266 €/kW whereas for a new house the break even investment costs is below zero indicating that the household would need to receive additional support even if the fuel cell was sold for free! The internal rate of return in both cases is below zero.

Table 5-13 Thermal control – one import tariff, overview, France

	New	**Old**
Electricity production	4206 kWh/year	5231 kWh/year
Electricity export (netmetering)	1269 kWh/year	2294 kWh/year
Self-consumption	1452 kWh/year	1658 kWh/year
Electricity export (self-consumption)	2754 kWh/year	3573 kWh/year
Full load hours	4206 h/year	5231 h/year
Heat demand covered by FC	56 pct.	34 pct.
Internal Rate of Return (nominal)	< 0 pct.	< 0 pct.
Break even investment costs	< 0 €/kW	266 €/kW
FIT	33.4 c€/kWh	28.2 c€/kWh
FITS	44.4 c€/kWh	35.5 c€/kWh

The necessary feed in tariff (with and without self-consumption) is lowest for the old house, 35.5 and 28.2 c€/kWh respectively. The reason why the necessary feed in tariff with self-consumption is higher compared to the necessary feed in tariff without self-consumption is that the electricity

6 the highest tolerable investment cost for the investment to break even under net metering

price in France is lower than the necessary feed in tariff without self-consumption. For the hours where the fuel cell owner self-consume (in the case with self-consumption) the fuel cell owner "only" receives what corresponds to the end consumer price. Since the end consumer price is lower than the feed tariff without self-consumption the owner has to be additionally compensated during the hours where he does not self-consume.

Sensitivity analysis

In order to test the validity of our basic assumptions we have performed the following sensitivity analyses:

- We have analysed the situation where the fuel cell has a life time of 20 years instead of 10.
- We have looked in to the situation where the O&M costs are more than twice as high as in the base case scenario, i.e. 300 €/kW/year.
- We have analysed the consequences of a lifetime of the stacks of two years compared to the initially assumed five years.
- We have also analysed the consequences of a lifetime of the stacks on 10 years – i.e. that the stacks do not have to be replaced.
- Finally, we have analysed the consequences of an additional increase of one percent point in the electricity and gas price relative to the elsewhere assumed inflation.

The results from the sensitivity analyses are summarised in Table 5-14 and show that only removing the stack change every 5 years or increasing the electricity and gas prices improve the profitability of the fuel cell. The least beneficial scenario is when the stacks has to be replaced every second year.

Table 5-14 Thermal control - one import tariff, sensitivity analyses, France

	Old	**20 years**	**Higher O&M costs**	**Stack change every 2 years**	**No stack change**	**Electricity and gas price increase**
Internal Rate of Return (nominal)	< 0 pct.	< 0 pct.	< 0 pct.	< 0 pct.	< 0 pct.	< 0 pct.
Break even investment costs	266 €/kW	<0 €/kW	< 0 €/kW	< 0 €/kW	900 €/kW	558 €/kW
FIT	28.2 c€/kWh	28 c€/kWh	31.6 c€/kWh	34.5 c€/kWh	26.1 c€/kWh	27.8 c€/kWh

FITS	35.5 c€/kWh	138.1 c€/kWh	40.4 c€/kWh	44.7 c€/kWh	32.5 c€/kWh	34.7 c€/kWh

The sensitivity analyses show us that our results are fairly robust towards changes in the assumptions. Stack exchange every two years as well as never, representing the worst case and best case scenarios, are equally unrealistic and affects the necessary feed in tariff with 22 and 7 percent respectively.

5.2.2 Thermal control – peak periods

In the thermal control – peak period we assume that the fuel cell owner faces to end consumer electricity prices, i.e. peak and off peak. The support schemes found relevant to analyse are feed in tariff (FIT) and feed in tariff with self-consumption (FITS).[7] The main task of the fuel cell is still to fulfil the heat demand of the household. However, when it is possible to shift the operating hours of the fuel cell they will be shifted towards the peak periods. The effect of this is that the electricity import during the peak periods when the electricity is expensive will be reduced presumably improving the profitability of the fuel cell.

The results from the thermal control – peak periods analyses are summarised in Table 5-15 and show that the electricity production and therefore the electricity export is higher for the old house compared to the new house. The heat demand covered by the fuel cell is 54 percent in the new house whereas in the old house it is only 33 percent.

Table 5-15 Thermal control – peak periods, overview, France

	New	**Old**
Electricity production	4195 kWh/year	5116 kWh/year
Electricity export (netmetering)	1258 kWh/year	2179 kWh/year
Self-consumption	1538 kWh/year	1665 kWh/year
Electricity export (self-consumption)	2657 kWh/year	3450 kWh/year
Full load hours	4195 h/year	5116 h/year
Heat demand covered by FC	54 pct.	33 pct.
FIT	33.5 c€/kWh	28.7 c€/kWh
FITS	46.5 c€/kWh	37.4 c€/kWh

7 net metering has not been found relevant in this case

The better profitability for the old house is illustrated in the necessary feed in tariff with and without self-consumption. The table shows that the necessary feed in tariff without self-consumption is 28.7 c€/kWh and with self-consumption it is 37.4 c€/kWh.

Sensitivity analyses

We have performed the same sensitivity analyses as above and the results are listed in Table 5-16. As in the case with only one constant electricity price (Section 5.2.1), the major benefits arise when the lifetime of the stacks is prolonged such that the stacks do not have to be changed in the entire period as well as a larger price increase of electricity and gas. Increasing the lifetime of the fuel cell itself to 20 years decrease the necessary feed in tariff without self-consumption. However, the negative effect of the lower price of the self-consumed part of the electricity assuming self-consumption has a very large effect and severely increases the necessary feed in tariff when self-consumption is assumed.

Table 5-16 Thermal control – peak periods, sensitivity analyses, France

	Old	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
FIT	28.7 c€/kWh	24.5 c€/kWh	32.1 c€/kWh	35.1 c€/kWh	26.6 c€/kWh	29.4 c€/kWh
FITS	37.4 c€/kWh	145.6 c€/kWh	42.4 c€/kWh	46.9 c€/kWh	34.2 c€/kWh	38.4 c€/kWh

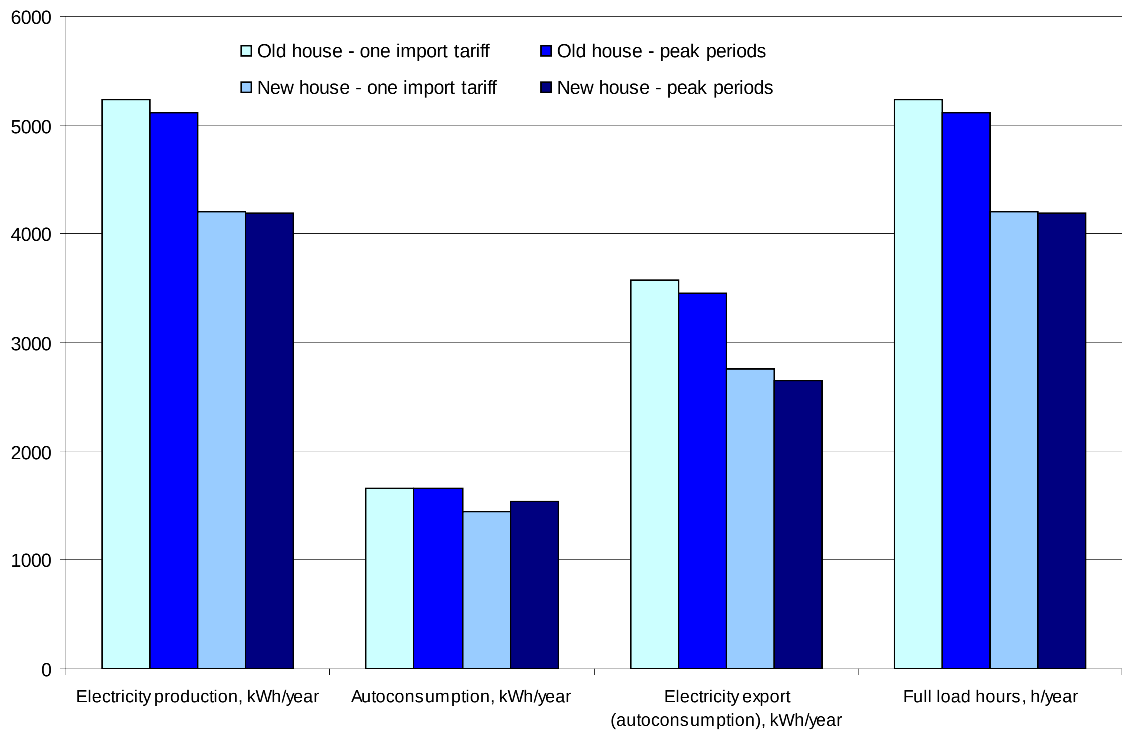
5.2.3 Comparing thermal control and thermal control – peak period

The alert reader would notice that the results from the two sections above do not differ significantly. In this section we will have a closer look into the differences and analyse why the differences are so small.

In Figure 5-5 the key numbers of the analyses is presented revealing that the overall picture is that there are hardly any differences between the results in the two thermal control cases for each of the house types. We see that the electricity production, electricity export and number of full load house are slightly higher in the case with one import tariff compared to the peak period case. The explanation is that under the peak period case the control strategy assures that the fuel cell shift the running hours to the peak periods. In this case the heat consumption in some periods exceeds the heat storage and therefore the gas boiler will cover the heat demand for a larger share (Figure 5-6) overall resulting in lower production from the fuel cell.

On the other hand, as the amount of self-consumption is identical in the old house for both of the scenarios and the share of the electricity produced being self-consumed in the peak period case exceeds the self-consumption in the case with one import tariff for the new house. This tells us, that a small amount of the running hours have been shifted towards the peak periods also being the periods where the household has the largest electricity consumption.

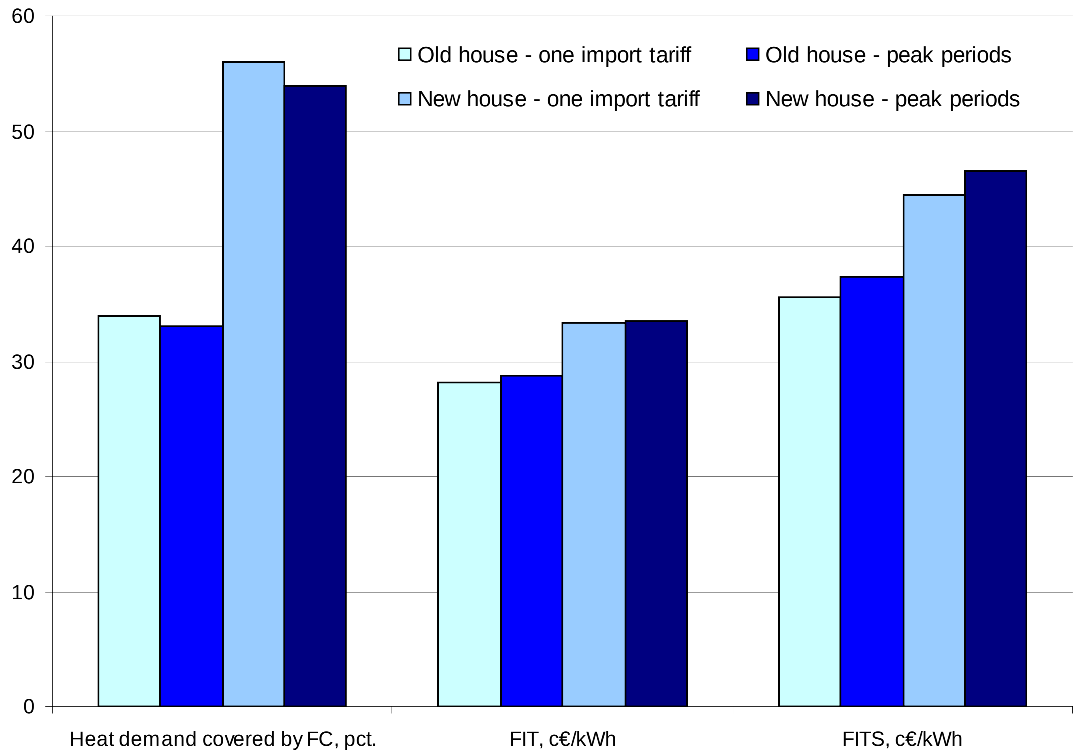
Figure 5-5 Key figures – old new house, one import tariff and peak periods, France



The resulting feed in tariffs mirror this as the necessary feed in tariffs in the peak period cases exceed the necessary feed in tariffs in the case with one import tariff in order to compensate for the lower electricity production.[8]

8 For the feed in tariff without self-consumption for the new house, the necessary feed in tariffs are 33.4 and 33.5 c€/kWh for the one import tariff and peak period cases respectively.

Figure 5-6 Heat demand, FIT and FITS – old new house, one import tariff and peak periods, France



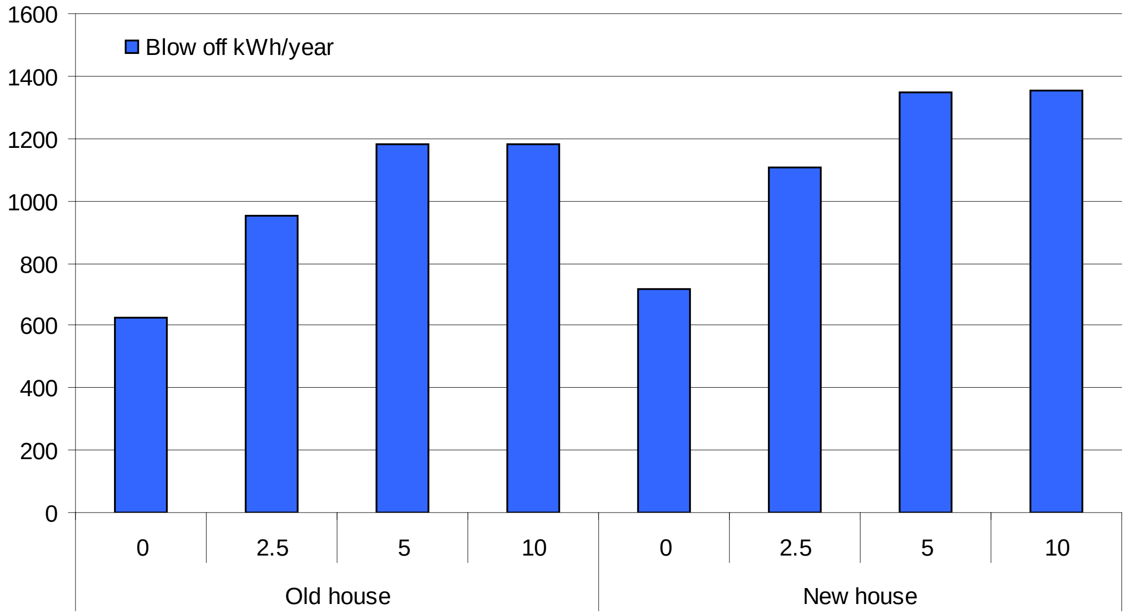
The comparison reveals that introducing peak periods in the control strategy does not affect the strategy significantly and definitely not in a more profitable direction for the fuel cell. This can be seen as the feed in tariffs taking the peak periods into account exceed the feed in tariffs not taking the peak periods into account.

5.2.4 Virtual power plant – spot market

In the virtual power plant scenarios, the 2 kW_e fuel cell is assumed to be owned and run by a company such as an electricity supplier or gas supplier. The fuel cell is operated independently of the heating demand of the household and only taking electricity prices into account. The technical simulations have thus been run assuming that excess heat can be blown off costless.

The necessary price premium has been determined by running the technical simulations under the assumptions of a number of different price premiums. The technical simulations show that assuming a price premium of 10 c€/kWh the fuel cell will run practically as much as possible and increasing the price premium further does not affect the technical simulation significantly. This is also seen from the amount of blow-off illustrated in Figure 5-7

Figure 5-7 Amount of blow off dependent on price premium and housetype, France



Source: [5]

From the analyses we found that assuming the technical strategy achieved for a price premium of 10 c€/kWh the price premium necessary in order to ensure profitability of the investor of is 13.3 c€/kWh. In the following the results for the VPP based on the spot market for electricity are presented.

Table 5-17 Virtual power plant – spot market – overview, France

	New	**Old**
Electricity production	17558	17559
Full load hours	8779	8780
Heat demand covered by FC	68 pct	31 pct.
Price premium	13.3 c€/kWh	13.3 c€/kWh

The Table shows that there is no difference between the technical simulation of the old house and the new house. [9] The fuel cell runs around the clock and despite the amount of blow off the fuel cell is not able to fulfil the heating demand of the household. The logic behind this is that the fuel cell in some periods produce even though there is no heating demand and the storage is full (blow off). In other times of the day the heating demand exceeds the production of the fuel

9 The minor differences are due to abbreviation

cell including the storage and the gas boiler runs in order to fulfil the heating demand. This affect would be altered if larger heat storage was introduced.

Sensitivity analysis

The sensitivity analyses show that the fuel cell improves the profitability assuming no stack change as well as a life time of 20 years of the fuel cell. However, in this analysis (spot market) the fuel cell runs all the time[10] which over all decreases the lifetime of the fuel cell. However, the basis assumption of investment costs of 5000 €/kW have been pointed out to be rather conservative [21] compensating for the high level of full load hours in these analyses.

Table 5-18 Virtual power plant - spot market - Sensitivity analysis, France

	Old house (base case)	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
Price premium	13.3 c€/kWh	11.3 c€/kWh	15.3 c€/kWh	17 c€/kWh	12 c€/kWh	13.3 c€/kWh

5.2.5 Summary France

The analyses for France showed that for the consumper plug and play scenarios the most promising one is the thermal control – one import tariff – FIT. The relatively low end consumer electricity price in France decreases the attractiveness of netmetering compared to Denmark. The same is true for the feed in tariff with self-consumption: since the end consumer electricity price is lower than the necessary feed in tariff (FIT) the necessary feed in tariff assuming self-consumption (FITS) has to be higher in order to compensate for the lower tariff (the end consumer price) indirectly received during self-consumption.

The private economic analyses based on the VPP strategy showed reason for cautious optimism regarding this promotion scheme. Thanks to a rather high electricity price in France the necessary price premium only constitutes 13.3 c€/kWh as compared to 21.7. c€/kWh in Denmark for the same support scheme.

10 In general fuel cells are assumed to run approximately 5000 full load hours per year.

5.3 Portugal

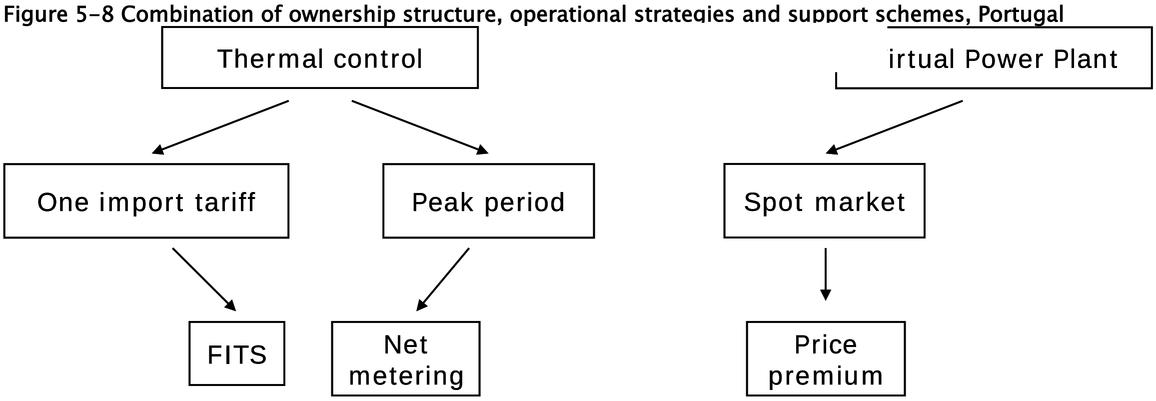
The combination of scenarios found relevant for Portugal are (Figure 5-8):

- Consumer plug and play – thermal control one import tariff – Feed in tariff with self consumption (FITS): the fuel cell is running in order to satisfy the heat demand of the household. The household export to the grid when the electricity production exceeds the consumption and import from the grid when the electricity consumption exceeds the production and self-consumes when you consume at the same time as you produce. For the electricity exported to the grid, the household is paid a fixed feed-in-tariff per kWh (FITS)

- Consumer plug and play – thermal control peak periods – netmetering: the fuel cell is operated in order to satisfy the heat demand of the household. However, when it is possible to shift the operating hours the operating hours will be shifted towards the peak periods. The electricity meter runs backwards when the fuel cell is producing more than is being consumed.

- Company control – VPP – day ahead: the fuel cell runs independent of the heating demand profile of the household and excess heat can be blown off without costs. The seller of the electricity sells the electricity on the spot market and is paid a fixed price premium on top of the market price of electricity.

Figure 5-8 Combination of ownership structure, operational strategies and support schemes, Portugal



The stakeholder analysis in combination with the introduction to policy context for fuel cell based micro-combined heat and power leads us to the following combination of ownership structure and support schemes: in Portugal the fuel cell is expected to be owned and run by a service provider supported by a premium on top of the market price maybe in combination with low tax rate.

In spite of these recommendations we have still chosen to analyse two privately owned scenarios: the thermal control – feed in tariff with self-consumption and peak period – net metering. These analyses are made in order to determine the extent to which it is possible to maintain an incentive for private households to invest in a residential fuel cell.

As for Denmark and France the thermal control scenarios are run assuming a 1 kW_e fuel cell with low electrical efficiency, i.e. electrical efficiency of 40 and an overall efficiency of 90 percent. The VPP/spot market scenario is run assuming a 2 kW_e fuel cell with high electrical efficiency of 60 percent and an overall efficiency of 80 percent (Table 5-19).

Table 5-19 Technical specifications, Portugal

Control strategy	Support scheme	Capacity (kW)	House type	Type of the cell	Efficiency, electrical/overall
Thermal control	FITS	1	Old and new	Low electrical efficiency - SOFC	40/90
Thermal control – peak periods	Net metering	1	Old and new	Low electrical efficiency - SOFC	40/90
VPP – spot market	Price premium	2	Old and new	High electrical efficiency - SOFC	60/80

The background data for Portugal is given in Table 5-20. The end consumer electricity price for Portugal, being 15 c€/kWh, is marginally higher compared to the French (11 c€/kWh) and substantially lower compared to the Danish (30 c€/kWh). In the lack of Portuguese data for heat demand and electricity demand for the two house types the Portuguese analyses are made assuming similar electricity and heat profiles to the French cases as well as similar total annual demand. The annual heat consumption of an old house in Portugal is thus assumed to be 18 925 kWh per year whereas the heat consumption of a new house is assumed to be approximately 8636 kWh. These levels of heat consumptions are covering room heating as well as hot water supply. The annual electricity consumption is assumed to be 2937 kWh independent on housetype.

Table 5-20 Background data, Portugal

Fuel cell		
Lifetime	10	Y
Capital Cost	5000	€/kW
O&M Cost	140	€/kW p.a.
Stack change (lifetime 5 years)	1000	€/kW
Energy prices		
Fuel cost, end consumer gas price	0.0629	€/kWh
Electricity consumer price	0.15035	€/kWh
Electricity consumer price, day	0.1489	€/kWh
Electricity consumer price, night	0.08077	€/kWh
Power Exchange Price (average)	0.070	€/kWh
Interest rate etc.		
Real interest rate	5	pct. p.a.
Inflation rate	2	pct. p.a.
Consumer data[a]		
Electricity demand, annual	2937	kWh/year
Heat demand, annual, new house	8636	kWh/year
Heat demand, annual, old house	18925	kWh/year

a) consumer data for Portugal is similar to consumer data for France

5.3.1 Thermal control – one import tariff

In the thermal control scenarios the consumer is assumed to own and run the fuel cell. As the individual consumer is not expected to react to the change in electricity and gas prices, the fuel cell is expected to run according to what we define as thermal control, i.e. in order to fulfil the heat demand of the individual household. The chosen support scheme is feed in tariff with self-consumption where you self-consume when you consume at the same time as you produce. If the electricity production exceeds the consumption the excess electricity is exported to the grid and similar, if the electricity consumption exceeds the production the household import electricity from the grid. For the electricity sold to the grid we receive a fixed tariff. The scenario is run for a 1 kW_e FC in an old house and a new house.

The results from the analysis show that the fuel cell run 4200 full load hours in a new house and 5200 full load hours in an old house. The heat demand covered is 56 and 34 percent in a new and an old house respectively and 65 and 68 percent respectively of the electricity produced is exported.

Table 5-21 Thermal control – one import tariff

	New	Old
Electricity production	4206 kWh/year	5231 kWh/year
Electricity export (self-consumption)	2754 kWh/year	3573 kWh/year
Full load hours	4206 h/year	5231 h/year
Heat demand covered by FC	56 pct.	34 pct.
FIT Self-consumption	44.3 c€/kWh	34.6 c€/kWh

In the old house the necessary feed in tariff is 34.6 c€/kWh whereas the owner of the new house would have to be compensated by 44.3 c€/kWh pointing to the fact that as for the case with Denmark and France the fuel cell is more profitable to install in an old house compared to a new house as the number of full load hours is larger for an old house.

Sensitivity analysis

We have performed the same sensitivity analyses as above: 20 years lifetime of the fuel cell, higher O&M costs, shorter lifetime of stacks, longer lifetime of stacks and finally higher electricity and gas prices. The results from the sensitivity analyses are summarised in Table 5-22. As we have witnessed earlier with respect to the analyses for Denmark and France, eliminating the costs to stack exchange will do a great difference to the profitability of the fuel cell. Higher O&M costs as well as a more frequent stack exchanges, however, reduce the profitability of the fuel cell.

Table 5-22 Thermal control – one import tariff, sensitivity analyses

	Old	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
FIT Self-consumption	34.6 c€/kWh	1.34 c€/kWh	39.5 c€/kWh	43.8 c€/kWh	31.5 c€/kWh	34.8 c€/kWh

5.3.2 Thermal control – peak periods

In the thermal control – peak period we assume that the fuel cell owner faces two end consumer electricity prices, i.e. peak and off peak. The support scheme found relevant to analyse is net metering. The main task of the fuel cell is to fulfil the heat demand of the household. However, when it is possible to shift the operating hours the operating hours will be shifted towards the peak periods. The effect of this is that the electricity import during the peak periods when the electricity is expensive will be reduced presumably improving the profitability of the fuel cell.

The results from the thermal control – peak periods analyses are summarised in Table 5-23 and shows that the electricity production and therefore the electricity export is higher for the old house compared to the new house. The heat demand covered by the fuel cell is 56 percent in the new house whereas in the old house it is only 34 percent.

Table 5-23 Thermal control – peak periods – Portugal

	New house	**Old house**
Electricity production	4101 kWh	5230 kWh
Electricity export (netmetering)	1164 kWh	2293 kWh
Full load hours	4101	5230
Heat demand covered by FC	56 pct.	34 pct.
Internal Rate of Return (nominal)	< 0 pct.	< 0 pct.
Break even investment costs	< 0 €/kW	< 0 €/kW

The profitability of the old house is marginally better compared to the new house, as the necessary investment support is 200 €/kW lower for the old house, i.e. 9500 €/kW as compared to 9700 €/kW for the new house (not in Table).

Sensitivity analysis

None of the chosen elements to turn for this scenario improves the situation sufficiently to make this scenario promising.

5.3.3 Virtual power plant – spot market

In the virtual power plant scenarios the 2 kW_e fuel cell is assumed to be owned and run by a company such as an electricity supplier or gas supplier. The fuel cell is assumed to run independent of the heating demand of the household and only taking electricity prices into account. The technical simulations have thus been run assuming that excess heat can be blown off costless.

The necessary price premium has been determined by running the technical simulations under the assumptions of a number of different price premiums. The technical simulations show that assuming a price premium of 5 c€/kWh the fuel cell will run practically around the clock and increasing the price premium further does not affect the technical simulation significantly. From the economic analyses we found that assuming the technical strategy based on a price premium of 5 c€/kWh a price premium of 13.9 c€/kWh is necessary in order to ensure profitability of the investor.

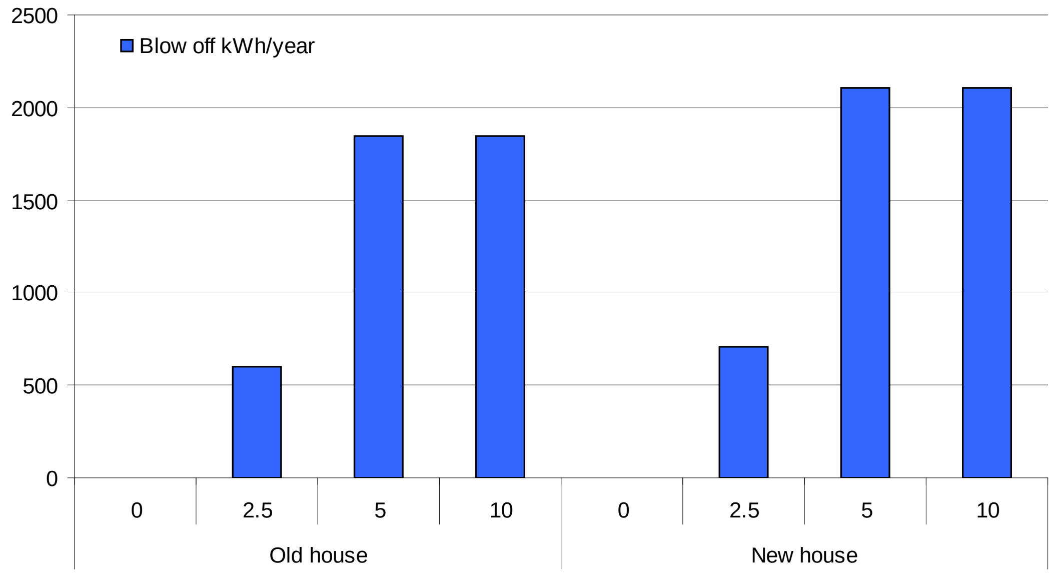
The results for the VPP based on the spot market for electricity are presented in Table 5-25 showing that the fuel cell operates round the clock 366 days a year. Nevertheless, the fuel cell only manages to cover 68 and 31 percent of the heat demand in a new and an old house respectively.

Table 5-24 Virtual power plant – spot market – overview Portugal

	New	Old
Electricity production	17566	17568
Full load hours	8783	8784
Heat demand covered by FC	68 pct	31 pct.
Price premium	13.9 c€/kWh	13.9 c€/kWh

In spite the fact that the fuel cell does not cover the entire heat demand of the household, there are also periods where the fuel cell produces electricity and hence heat even though there is no heat demand nor storage room. In these situations the heat is just assumed to be blown off. Figure 5-9 shows the amount of blow off dependent on the assumed price premium.

Figure 5-9 Amount of blow off dependent on price premium and housetype, Portugal



Source: [5]

Sensitivity analysis

We have performed the same sensitivity analyses as above: 20 years lifetime of the fuel cell, higher O&M costs, shorter lifetime of stacks, longer lifetime of stacks and finally higher electricity and gas prices. As is the case for the analyses above this sensitivity analyses shows that eliminating the stock exchange will improve the profitability of the fuel cell and higher O&M costs as well as more frequent stack exchange have the opposite effect (Table 5-25).

Table 5-25 Virtual power plant – spot market – Sensitivity analysis

	Old house (base case)	20 years	Higher O&M costs	Stack change every 2 years	No stack change	Electricity and gas price increase
Price premium	13.9 c€/kWh	12 c€/kWh	15.9 c€/kWh	17.6 c€/kWh	12.6 c€/kWh	13.9 c€/kWh

5.3.4 Summary Portugal

The private economic analyses for Portugal showed that none of the consumer plug and play scenarios (thermal control–one import tariff–FITS and thermal control–peak periods–net metering) are very promising. The relatively low end consumer electricity price in Portugal decreases the attractiveness of the feed in tariff with self-consumption as well as net metering: since the end consumer electricity price is lower than the necessary feed in tariff (FIT) the necessary feed in tariff assuming self-consumption (FITS) has to be higher in order to compensate for the lower tariff indirectly received during self-consumption. Similar for the net metering case: as the end consumer electricity price is relatively low the corresponding investment support has to be very high.

The private economic analyses based on the VPP strategy showed reason for cautious optimism regarding this promotion scheme. Thanks to a rather high electricity price in Portugal the necessary price premium only constitutes 13.9 c€/kWh as compared to 21.7. c€/kWh in Denmark for the same support scheme.

5.4 Summary and discussion

In the sections above we have presented a list of private economic analyses for Denmark, France and Portugal taking the results from the technical simulations presented in [5] for granted. The private economic analyses can be divided into two groups: *consumer plug and play* and *company control*.

The analyses for the consumer plug and play scenarios showed that for Denmark net metering is a very promising support scheme assuming that the electricity consumption of the households are somewhat larger than the average electricity consumption. In this case netmetering would be (almost) profitable and the household would only need an extra support corresponding to 200 €/kW al together.

For France the most promising one is the thermal control – one import tariff – FIT. The relatively low end consumer electricity price in France decreases the attractiveness of netmetering compared to Denmark. The same is true for the feed in tariff with self-consumption: since the end consumer electricity price is lower than the necessary feed in tariff (FIT) the necessary feed in tariff assuming self-consumption (FITS) has to be higher in order to compensate for the lower tariff indirectly received during self-consumption.

The private economic analyses for Portugal showed that none of the consumer plug and play scenarios (thermal control–one import tariff–FITS and thermal control–peak periods–net metering) are very promising. The relatively low end consumer electricity price in Portugal decreases the attractiveness of the feed in tariff with self-consumption as well as net metering

The private economic analyses based on the VPP strategy in France and Portugal showed reason for cautious optimism regarding this promotion scheme. Thanks to a rather high electricity price in France and Portugal the necessary price premium only constitutes 13.3 and 13.9 c€/kWh respectively as compared to 21.7. c€/kWh in Denmark for the same support scheme. However, the private economic analyses of the two VPP scenarios for Denmark showed that assuming that the fuel cell operates of the spot market is more economically reasonable compared to assuming the fuel cell operates on the regulating power market. In this case the necessary price premium is 21.7 c€/kWh whereas the fuel cell on the regulating power market would need a price premium of 26.4 c€/kWh. This covers the fact that for the spot market scenario the total necessary support is 8784 €/kW whereas the for the regulating power market scenario the total necessary support is 12278 €/kW.

6 System analysis

In this chapter the ownership, operational strategy and support scheme scenarios are analysed with regard to impact on the national energy systems by applying the energy system model, STREAM [22]. STREAM was originally developed for Denmark, but has also been applied in a European context [23].

The outline of the chapter is that first the reference scenarios are described, then the model is presented and finally the results are shown.

6.1 Description of the 2030 reference scenarios

The 2030 reference scenarios for Denmark, Portugal and France are based on the DG-TREN forecast of 2009 [24], as well as the 2009 STOA report "Future energy systems in Europe" [23]. Two distinct scenarios for future European energy systems were created for the STOA report; the Small Tech and the Big Tech scenario. The former focuses on distributed energy generation, energy savings and efficient utilisation of energy through smarter devices and combined heat and power generation [23]. The latter scenario emphasises centralised power plants and introduces an additional 40 pct. of nuclear energy compared to 2009 [23]. For both scenarios STREAM models were created, which simulate Europe's energy systems divided into five regions; central, south, north, east and west.

The STREAM models of this project are built on the regional models of the STOA report in a way which best accommodates assumptions of the DG-TREN forecast and the countries' geographical location as well as current energy system parameters, such as energy mix and final energy demand. Assessing these factors, the Small Tech scenario for northern Europe was chosen as baseline for Denmark, the Small Tech scenario for southern Europe for Portugal and the Big Tech scenario for central Europe for France. Country specific data from the 2009 DG-TREN report served as input for the years 2005 and 2030. Hourly values of national electricity demands of the year 2008 for Portugal and France were obtained from ENTSO-E, the European Network of Transmission System Operators [25] and from ENERGINET [26] for Denmark. These data are used to create electricity duration curves in the models. Hourly wind energy production was obtained from the national TSO's based on which own data compilations were made.

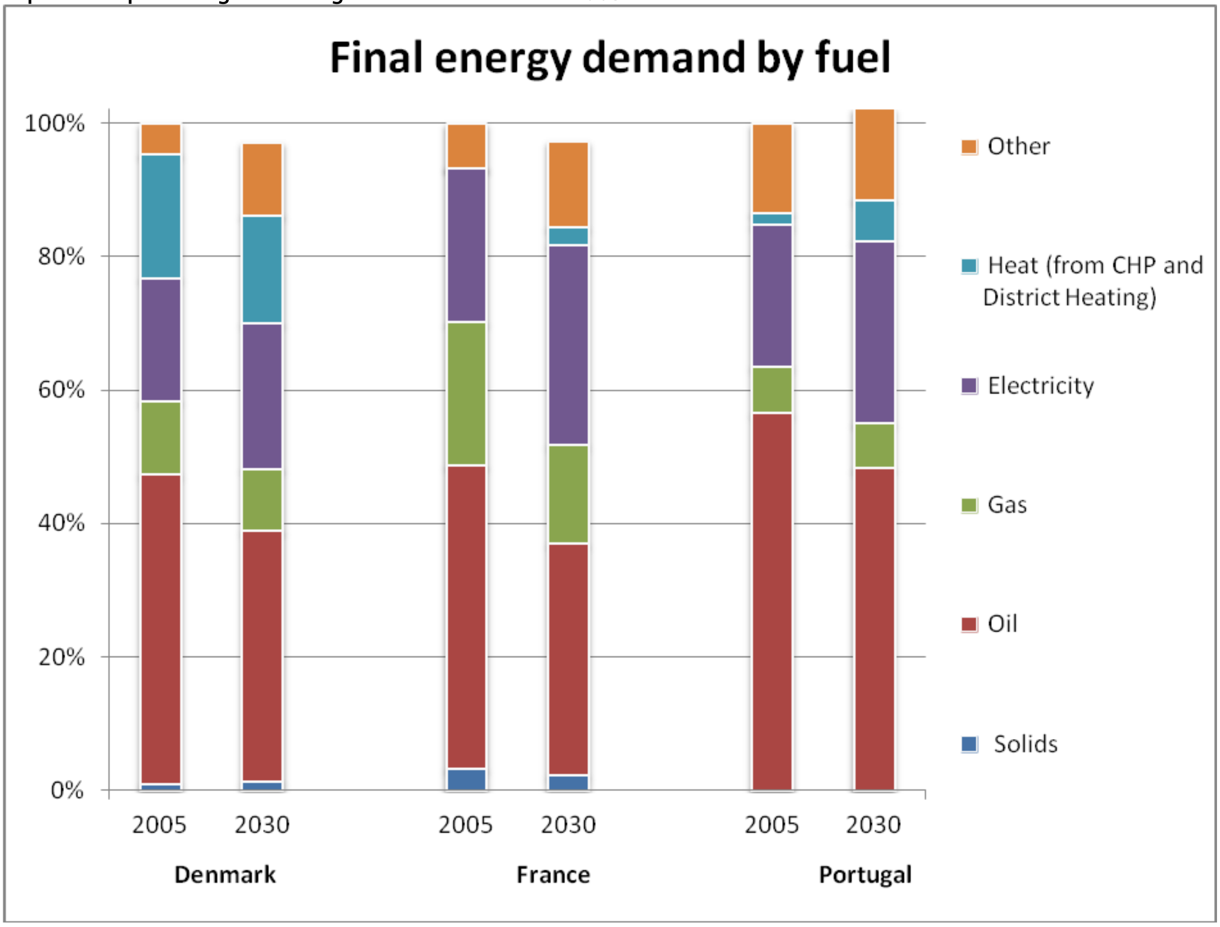
In order to illustrate the forecasts for 2030, key figures of the energy systems of the years 2005 and 2030 are compared below. The data are presented as percentages relative to the year 2005 in order to facilitate the comparison between the three countries.

6.1.1 Final energy demand

The final energy demand with regard to fuels will remain largely constant for all countries; decreasing by 3 pct. in France and Denmark, and increasing by 2 pct. in Portugal. The segmentation of the demand into fuels, or rather energy carriers, in Figure 6-1 shows that fossil fuels (oil, gas and coal) will still constitute around 50 pct. of the total demand for all countries.

The decrease in fossil fuel usage compared to 2005 is mainly achieved by reducing oil demands. In Denmark and France a noticeable increase of 6 pct. can be observed for other fuels, which encompasses mainly renewable resources. Heat demands are slightly decreasing in Denmark and increasing in France and Portugal. Electricity demands are growing in all countries, between 4 pct. and 7 pct. compared to 2005.

Figure 6-1 Shares of the final energy demand by fuel for Denmark, Portugal and France. Figures of 2030 are depicted as percentages with regard to the demand in 2005.

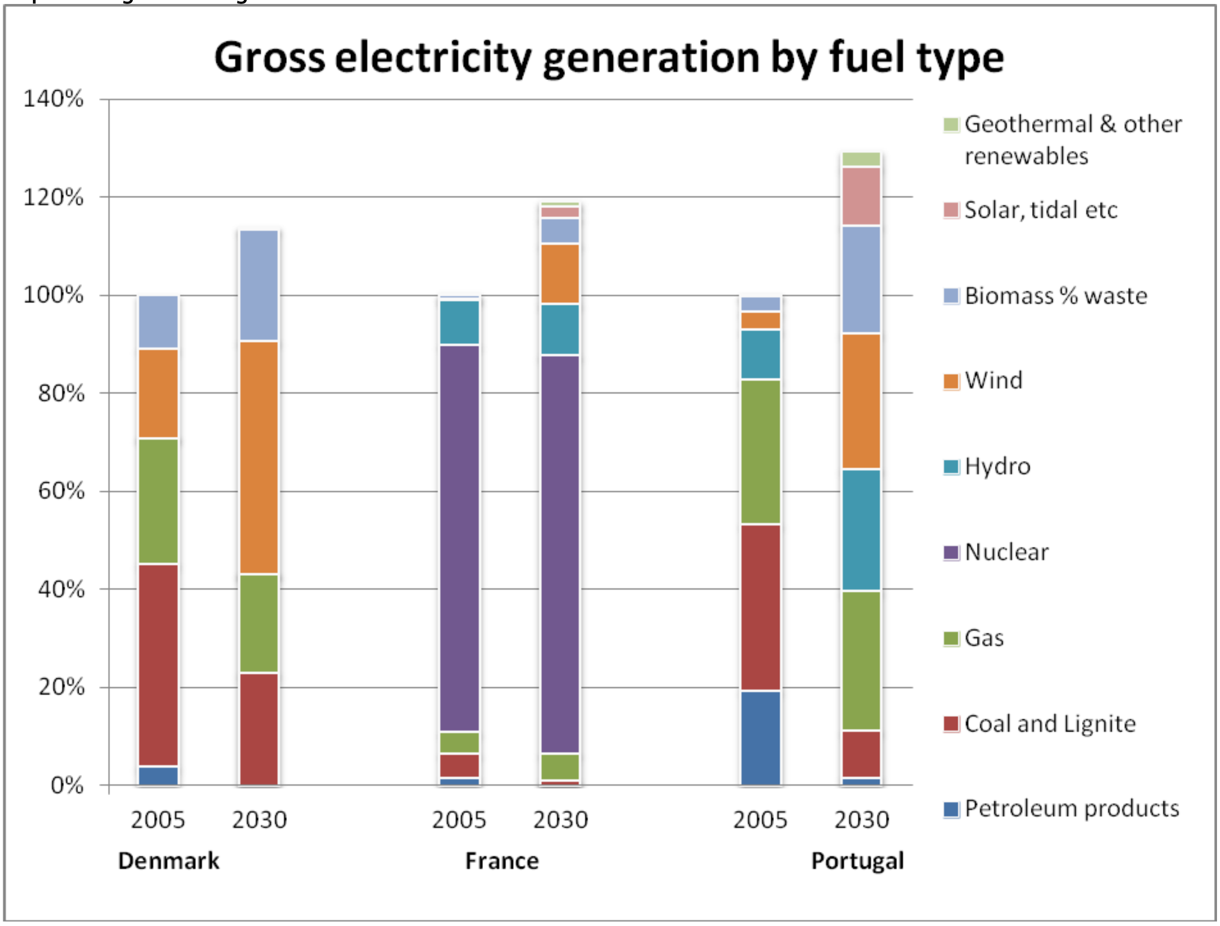


Source: [24]

6.1.2 Electricity

In accordance with the increasing electricity demand, the gross electricity generation is also rising for all three countries. Portugal is likely to experience the largest increase at a fraction of 29 pct. and Denmark the smallest with 14 pct. (See Figure 6-2). In all cases, the additional generation is largely covered by renewable resources, namely 62 pct., 27 pct. and 69 pct. of the gross electricity generation in Denmark, France and Portugal respectively. Wind energy is assumed to hold the largest potential among the renewable resources for all countries, followed by biomass and hydro. The fraction of nuclear energy is assumed to remain constant in France, still accounting for around 80 pct. of the total electricity production in 2030. No nuclear energy is introduced in Denmark or Portugal. Coal and petroleum products are significantly reduced in all cases whereas natural gas usage remains roughly constant. Portugal aims at the most even distribution of renewable resources, also incorporating solar, tidal and geothermal technologies to significant extents. Denmark will focus on wind energy, complemented by biomass as the only additional renewable resource.

Figure 6-2 Electricity generation by fuel type for Denmark, France and Portugal. Figures of 2030 are depicted as percentages with regard to the demand in 2005.

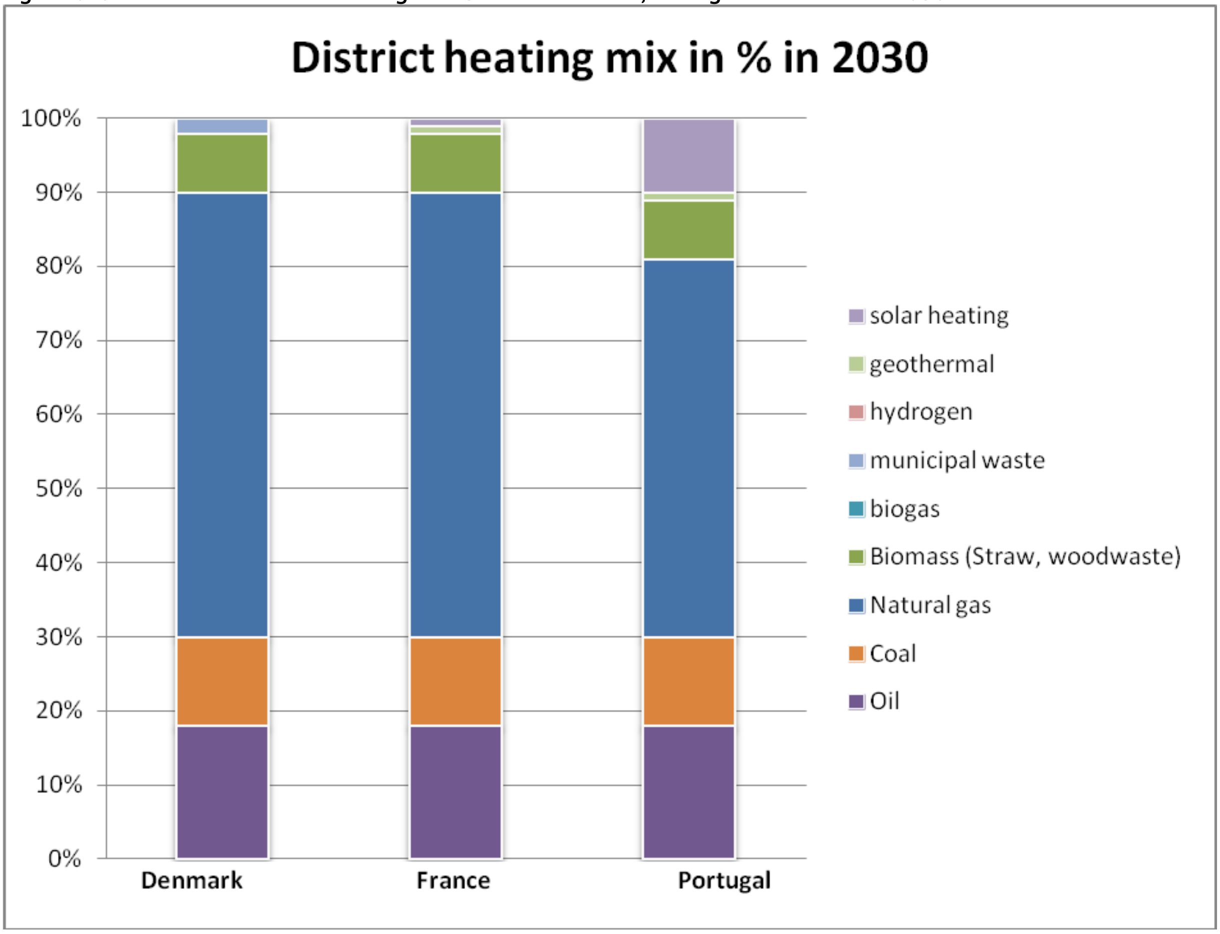


Source: [24]

6.1.3 District heat and CHP

From Figure 6-1 it is obvious that district heating and CHP is only a minor fraction in the final energy demand of France and Portugal, namely 3 pct. and 6 pct. respectively in 2030. In Denmark, the share of CHP and district heating production of the entire energy demand is expected to diminish from 19 pct. to 16 pct. of the final energy demand. The district heating mix of the three countries is based on the assumptions of the 2009 STOA report [23], where the Big Tech scenario served as a baseline for the French district heating system and the Small Tech scenario as a baseline for Denmark and Portugal. This distinction was made since the Big Tech scenario incorporates the continuous use of nuclear energy and large central fossil fuel power plants, which suits the assumptions of the [24]. Denmark and Portugal, however, are heading toward a more diversified energy mix without nuclear energy, incorporating decentralised energy generation technologies. The Small Tech scenario is therefore more suitable since it excludes nuclear energy and is based on large scale employment of decentralised energy generation facilities as well as enhanced application of district heating and CHP. The fuel mix for district heating and CHP in 2030 is depicted in Figure 6-3.

Figure 6-3 Fuel mix for district heating and CHP for Denmark, Portugal and France in 2030.



Source: [24]

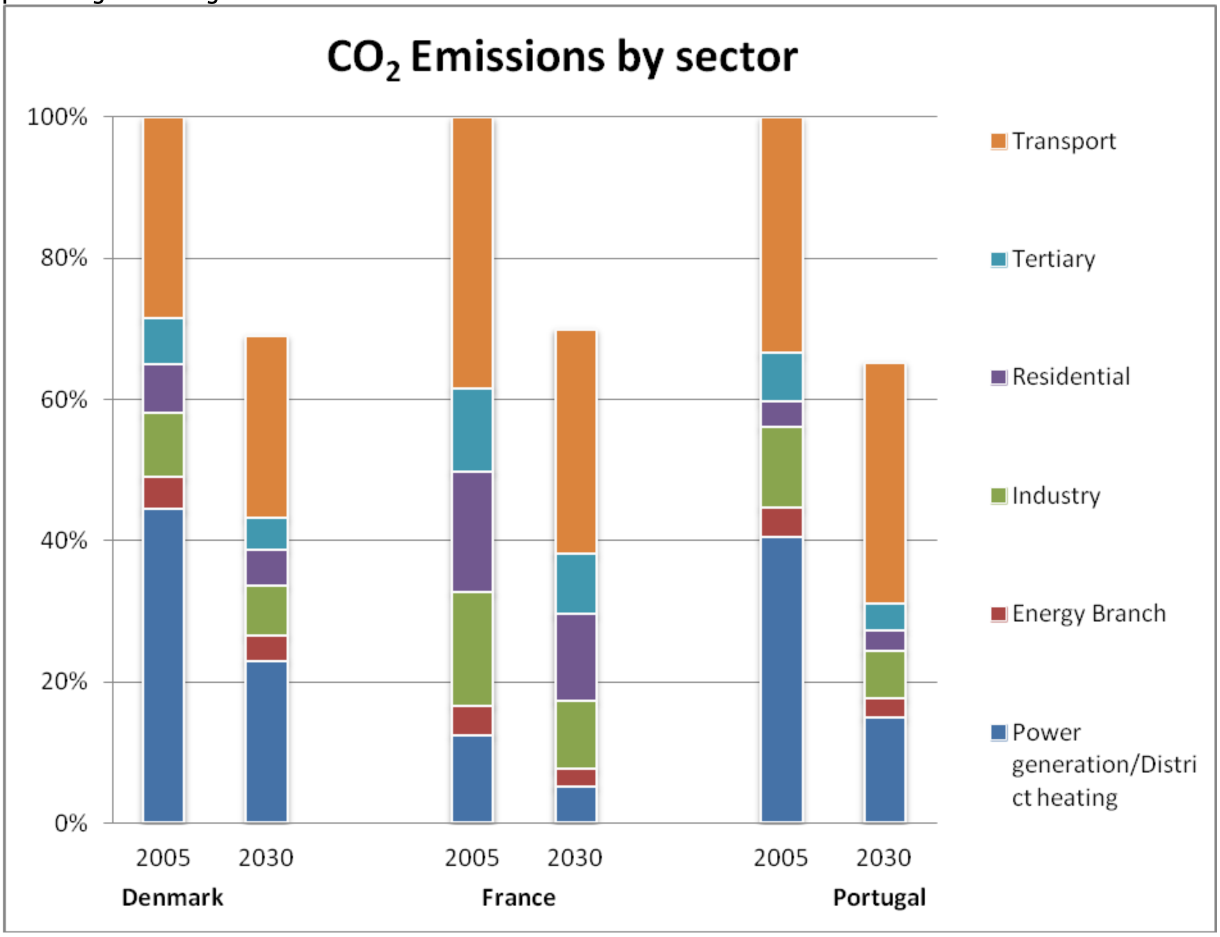
In Denmark and France, 90 pct. of the heat is assumed to be generated from CHP powered by fossil fuels. Portugal is expected to employ a larger fraction (10 pct.) of solar heating and thereby reduces the share of fossil fuels in the heating system.

6.1.4 Emissions

Figure 6-4 shows that, despite the nearly constant energy demand, CO_2 emissions are decreased by around one third in all countries. This is due to the large increase in the utilisation of renewable energy resources and the decrease in coal and petroleum usage, particularly in electricity generation.

Transport is the most emission intensive sector in all countries, followed by the power generation and district heating sector in Denmark and Portugal. Due to the large fraction of nuclear energy used for electricity generation in France, the power sector is less emission intensive than the residential, industry and the tertiary sector.

Figure 6-4 CO_2 emissions by sector for Denmark, Portugal and France. Figures of 2030 are depicted as percentages with regard to the demand in 2005.



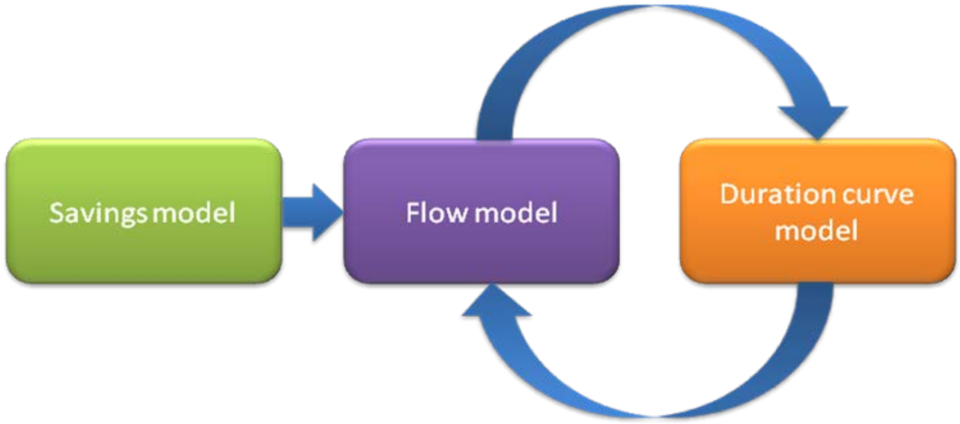
Source: [24]

6.2 The Model

STREAM is an energy system modeling tool which balances energy demands and supplies within the time frame of one year and delivers results on energy production, fuel consumption (resource utilisation), emissions and costs. It is typically used for predictive or explorative analysis of national energy systems but not capable of system optimisation. A reference scenario is devised by the user. The reference scenario is set up to predict the state of development of an energy system at a certain time in the future, usually based on current trends. The model scenario is placed in the same time frame but includes the intended changes in the system. Comparing the two scenarios gives an idea of the impacts of the implemented changes on the system.

STREAM consists of three interacting excel spreadsheets, namely the energy savings model, the energy flow model and the duration curve model. The data flow between the models is depicted in Figure 6-5.

Figure 6-5 Interaction of the individual models in STREAM



Annual energy service demands are inserted into the savings model. These demands are adapted to the requirements and conditions of the scenarios and serve as an input to the flow model. In the flow model, the conversion of energy by various technologies and the extent to which each technology is deployed, are determined. The required energy production, given by the flow model, is passed to the duration curve model, where the load hours are determined for the various technologies. The output of the duration curve model is returned to the flow model. Installed capacities and required energy production are matched by iterative repetition of this operation.

6.2.1 Country scenarios

As explained earlier, different fuel cell scenarios have been analysed for the different countries. Table 6-1 summarises which scenarios have been analysed for which countries.

Table 6–1 Scenarios based on control strategies for Denmark, France and Portugal

Control strategy	Thermal control	Thermal control/ peak periods	Virtual Power Plant (VPP)
Fuel cell	1kW, 40 % el. eff.	1kW, 40 % el. eff.	2kW, 60 % el. eff.
Denmark	Sc 1,2		Sc 7 (spot market), Sc 8 (regulating market)
France	Sc 1,2,3	Sc 5,6	Sc 7 (spot market)
Portugal	Sc 3	Sc 4	Sc 7 (spot market)

6.2.2 The potential

The total potential for combined heat and power plants (mCHPs) for each country is dictated by the natural gas (NG) demand for space heating of all single family detached houses. It is assumed that one mCHP is installed in every single family detached house with access to NG gas. Heat demands as well as mCHP generation profiles and corresponding gas consumptions are divided into two building categories; new and old houses. It is therefore required to know the share of new and old buildings of this type. Based on the natural gas demand and the heating demand of this building type, the number of mCHP plants is calculated, for both, new and old buildings. The total national mCHP electricity generation profiles are calculated by multiplying individual generation profiles (new and old respectively) with the number of buildings and then summing up the profiles for new and old buildings according to

$$P_i^{total} = P_i^{old,ind} \times n_{old} + P_i^{new,ind} \times n_{new}$$

Where P_i^x is the electricity production of hour i and n_x is the number of buildings. The gas consumptions are given for each scenario, consisting of the boiler and the mCHP consumption. The boiler provides heat at either peak demands or when the mCHP is not operated. The electrical efficiency of mCHPs is assumed at 40 pct. and the thermal efficiency at 50 pct. for thermally controlled scenarios and at 60 pct. electrical and 20 pct. thermal efficiency for virtual power plant (VPP) scenarios. Efficiencies of NG boilers generally range between 80 pct. and 90 pct.. Hence, substituting NG boilers with mCHPs reduces the thermal efficiency and the overall fuel consumption in the sector of single family detached houses is increased. The fuel increase is calculated by subtracting the annual domestic heat demand from the annual NG consumption of boiler plus mCHP. Values are given for individual buildings and up-scaled by multiplying with the number of buildings. The assumed demands and number of buildings is illustrated in Table 6-2.

Table 6–2 Natural gas demand

2030	National demand (PJ)	Single family house demand (PJ)	% of residential demand	% of national demand	No. old/new single family houses with natural gas boilers
Denmark	102	6	64 %	6 %	86500/5500
France	1810	197	30 %	11 %	2728000/372000
Portugal	234	10	18 %	4 %	143200/19500

6.2.3 The modelling approach

For each scenario an individual model was created consisting of a flow model, a savings model and a duration curve model. All models of one country use the same reference, which is implemented in the respective flow models.

Required model inputs are

- mCHP Electricity generation profile
- Annual mCHP electricity generation (sum of profile)
- Additional NG consumption
- Annualised capital and operation and maintenance cost of mCHPs

The same modelling approach is taken for all scenarios (VPP and thermal controlled) of all countries. The power generated by mCHPs is considered as electricity saving in the domestic sector and modelled as a decrease in electricity consumption in the savings model. The resulting decrease in electricity production (calculated in the flow model) is distributed among non-renewable energy technologies, i.e. coal, oil, NG and in the case of France nuclear energy, and also biomass, as an average. Power production by renewable energy resources such as wind, solar power, geothermal and also municipal waste is maintained at a constant level with respect to the reference. The power generated by mCHPs, their NG consumption and additional costs are added in a separate spreadsheet, outside the STREAM model.

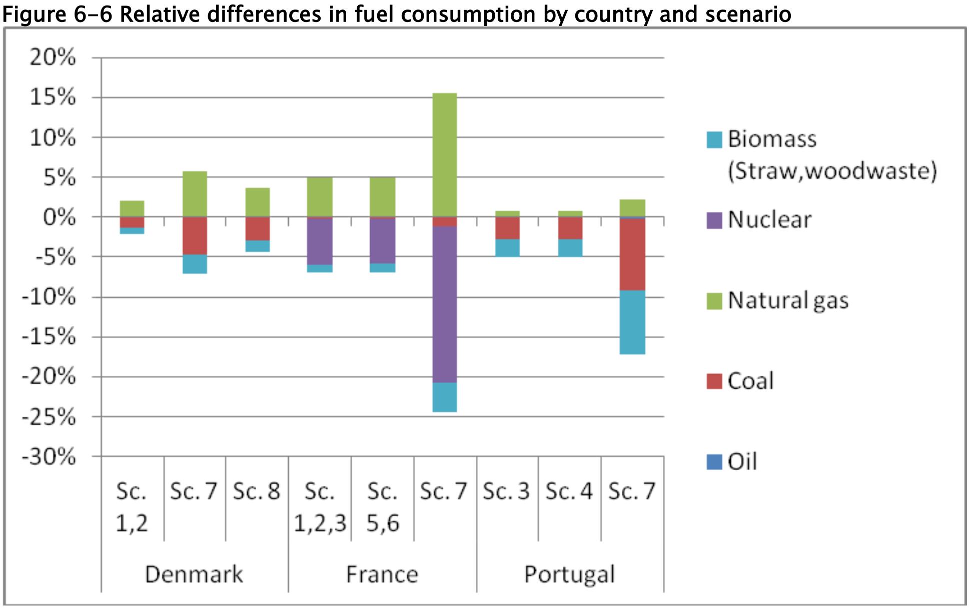
Variations in the electricity consumption profile are taken into account in the duration curve model. The electricity generation profiles of the mCHPs are incorporated into the national electricity demand profile so that the overall demand is maintained but variations due to mCHP production are regarded.

6.3 Results

To compare the effect of implementing the fuel cells in the different energy systems, analyses have been made of the changes in fuel consumption, in forced electricity export and share of condensing power as well as of costs and CO2 emissions. In all scenarios it is assumed that the full potential illustrated in Table 6-2 is utilised, that heat produced by the fuel cells substitute heat from natural gas fired boilers, and that the electricity produced by the fuel cells substitute averages of the national electricity production mixes of the respective countries. Electricity production from wind turbines, hydro power plants and waste incinerators are however maintained as it is assumed that the electricity production from these plants will remain unaffected.

For all the scenarios described in Table 6-1 the changes in the net fuel consumption changes are illustrated in terms of change in percentage of use of each fuel compared to the Reference (See Figure 6-6). In all fuel cell scenarios a net increase is seen in the consumption of natural gas. However, a net decrease is found in the overall consumption of fuels, with different fuels being substituted in the different countries. In France the decrease is mainly seen for the nuclear plants (around 20 pct. decrease compared to the use of nuclear in the reference). Nuclear is mainly affected as nuclear plants are still assumed to provide the main part of the electricity in 2030. The largest changes are found in France when the fuel cells are run as virtual power plants (Sc. 7). This is due to the large potential for installing fuel cells, which is assumed (11% of national natural gas consumption in 2030) combined with increased production of electricity as virtual power plants and the high electrical efficiency of the fuel cells in this scenario. In Portugal and Denmark decreases are mainly seen in the consumption of coal and biomass. Again, the largest changes are found in the virtual power plant scenarios (Sc. 7 & 8). In all countries a decrease is seen in the use of natural gas for electricity production. The net difference in total national fuel consumption is considerably lower than the difference in the use of each fuel, as shown in Figure 6-8.

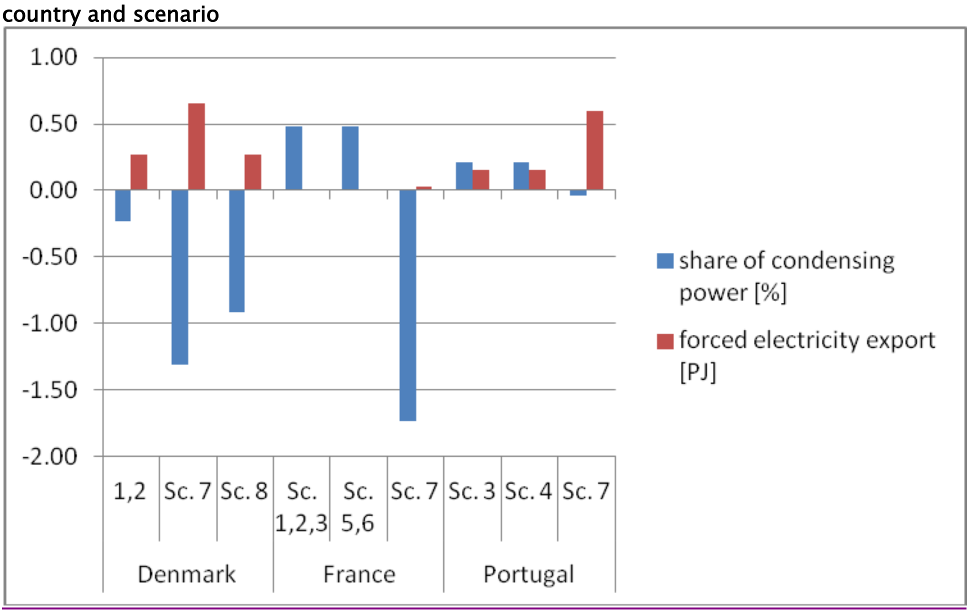
Figure 6-6 Relative differences in fuel consumption by country and scenario



The share of condensing power and the amount of forced electricity export are two measures of the efficiency and the match between energy production and consumption at each time step. As the STREAM model does not model electricity trade across borders the forced electricity export may not be an issue in real life and should only be seen as a measure of how well production and consumption fits in the model.

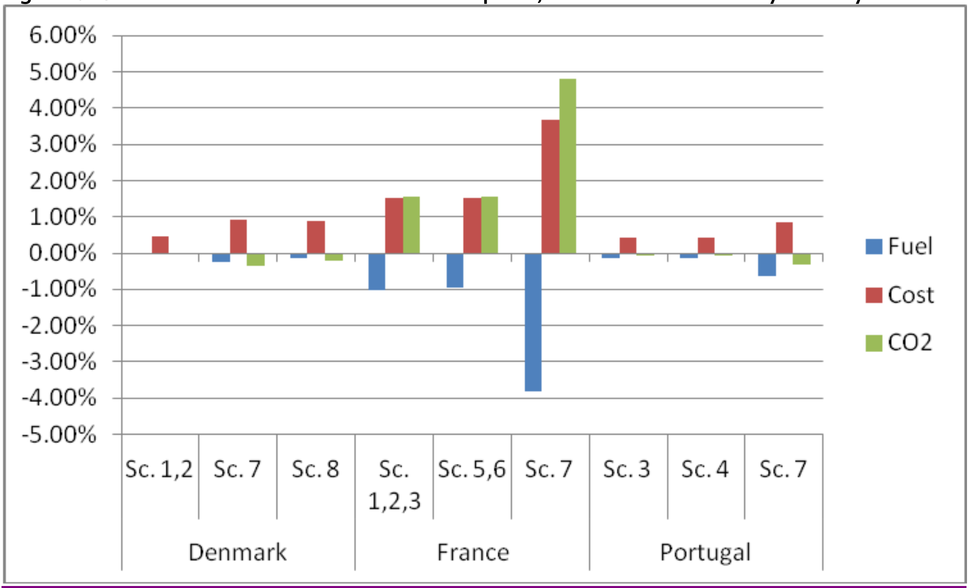
From Figure 6-7 it can be seen that the forced electricity export increases with the implementation of fuel cells in all scenarios although only marginally in France. In Denmark the forced electricity production follows the increased electricity production in all scenarios, whereas there is a marked difference in Portugal. Here the effect of adjusting the electricity production to the electricity prices in the virtual power plant scenario (Sc. 7) is seen as the forced electricity export only increases marginally here compared to the increase in thermal control scenarios (Sc. 3 & 4). In Denmark there is a correlation between the decrease in the share of condensing power and the forced electricity export. This means that the more power we produce at CHP plants the less our electricity production matches our electricity consumption and the more electricity we are forced to export. In Portugal there is a slight increase in the share of condensing power in the thermal control scenarios (Sc. 3 & 4) illustrating further the mismatch between demand and production, whereas there is a slight decrease in the scenario where the fuel cell operates as a part of a virtual power plant (Sc. 7). Apart from the effects of the production at nuclear plants an effect can be seen on the share of condensing power in France as there is an increase in the all thermal control scenarios (Sc. 1-6) and a decrease in the VPP scenario (Sc. 7).

Figure 6–7 Difference in share of condensing power (apart from nuclear) and in forced electricity export by country and scenario



In Figure 6-8 the differences in fuel consumption, costs and CO_2 emissions can be seen. As mentioned earlier there is an overall decrease in fuel consumption for all scenarios. This is however followed by an increase in costs, which is mainly due to the high investment costs of the fuel cells. In France an increase is seen in the CO_2 emissions as the production of nuclear power decreases and the consumption of natural gas increases. In Denmark and Portugal slight decreases are found in the emissions of CO_2.

Figure 6-8 Relative differences in fuel consumption, cost and emissions by country and scenario



All in all the results show that the effect of installing the fuel cells depend mainly on the energy system in which they are installed and secondly on which operation strategy is used when operating the fuel cells. Installing fuel cells lead to decreased fuel consumption and increased costs in all countries, but only to decreases in CO_2 emissions in Denmark and Portugal. Here the greatest reductions in CO_2 emissions are achieved when the fuel cells are operated as virtual power plants (Sc. 7 & 8).

7 Conclusions

Overall we find that some technological development within FC-based micro CHP is necessary in order to make the technology truly interesting as the expected prices the next 5-10 years are too high. However, the necessary support levels found in the analyses are not excessive compared to the initial support levels for e.g. PV's in Germany. Especially considering the opportunity for biogas in gas based FC's makes the found support levels promising.

Assuming that FC's are to be implemented the best solution for the three countries are:

Denmark: It seems promising to use the net metering as support mechanisms for FC based micro CHP in households with high electricity consumption, i.e. the electricity consumption exceeds the electricity production from the FC. This result is driven by the high end consumer electricity price in Denmark. The least interesting solution from a private economic perspective seemed to be the opportunity to operate as a part of a virtual power plant on the regulating power market. From a system perspective, the fuel consumption and CO_2 emissions decrease most in the virtual power plant case.

France: As the natural gas price in France are rather low (compared to Denmark and Portugal) an FC run as a virtual power plant (VPP) on the spot market seems to be the best solution in France. Despite a decrease in the fuel consumption, the CO_2 emissions increase in all scenarios as nuclear power is displaced by natural gas consumption. This is most dominant in the virtual power plant scenario.

Portugal: The electricity spot price in Portugal is relatively high resulting in results similar to those obtained for France - an FC run as a (VPP) on the spot market is the best solution. From a system perspective, the fuel consumption and CO_2 emissions decrease most in the virtual power plant case.

For France and Portugal we analysed the opportunity to apply the already available technology to distinguish between peak and off-peak electricity prices by introducing a feed in tariff in combination with self-consumption. We find that this is not an economically viable solution.

Furthermore we find that the fuel cell generally have to run many hours in order to improve the profitability. Especially for the cases with VPP the fuel cell either run (assumed support level above zero) or does not run (assumed support level = zero). This is a result of relatively stable electricity prices. Because the electricity price fluctuate so little the fuel cell goes from not running at all to running almost all the time when the support level reach a certain level. If the electricity price was more fluctuating (as for example as a consequence of more wind power) this result would be altered.

From a system perspective the results show that it is more important which kind of energy system (represented by country) the FC's are implemented in rather than which operational strategy that is basis of the analyses. In an energy system with lots of fossil fuel (Denmark and

Portugal) the potential CO_2 emission reductions are relatively large compared to an energy system dominated by e.g. fossil free nuclear.

The combined system costs are highest for the virtual power plant cases, however, there are many aspects regarding the opportunity to operate as a virtual power plant such as saved grid investments and saved investments in peak load which is not included in this analysis.

Under existing legislation within the EU, only large-scale power plants and industrial facilities are subject to CO_2 quota trading. Shifting a part of electricity generation from large-scale power plants to a decentral technology as mCHP fuel cells leads to additional CO_2 from the non-quota households, while the CO_2 being emitted from large-scale units stays constant. Therefore, the introduction of mCHP units could lead to additional CO_2 emissions if existing policy schemes do not account for this change. The authors suggest that the CO_2 cap must be reduced in line with expectations on the deployment of mCHP solutions.

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