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DEMOSOFC

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"DEMOnstration of large SOFC system fed with biogas from WWTP"

Deliverable number 6.1

SOFC-based CHP market potential analysis

(Task leader: Imperial College London - Start: M36 - End: M60)

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Abstract:

The analysis in WP6 (task 6.1) provided answers and insights to the below research questions related to SOFC adoption.

- What is the market share of SOFC in Europe?
- What are favourable markets conditions to accelerate adoption of SOFC?
- What is the best use of biogas (cogeneration or upgrade to biomethane)?
- How to reduce installation and investment costs?
- What incentives can drive deployment?

Novel and innovative aspects of the analysis done in WP6 (Task 6.1) are provided below

- Development of an optimisation-based decision-support framework to determine the best use of biogas from a WWTP, and provide a market outlook for each of the options. This work proposes a multi-period Mixed Integer Linear Program (MILP) model for dispatch and selection of technologies capable of exploiting biogas produced from sludge.
- Development of the market potential analysis (MPA) methodology to quantify the market share of the SOFC using the 6,181 plants. The MPA builds on detailed techno-economic assessment of a WWTP plant.
- Applied the MPA to quantify the impact of existing policy instruments, and business models on the diffusion of biogas-SOFC in WWTP.
- Applied the MPA to determine various pathways to commercialise SOFC.
- Developed of narratives for biogas-SOFC for three stakeholders: policy makers, technology manufacturers, and end-users (WWTP owners)

Keyword list: biogas, biogas exploitation, SOFC, market potential analysis, system design, techno-economic analysis, WWTP, optimization, business models, incentives, market share, commercialisation.

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1. Purpose of this document

Generation of heat and electricity from the same unit of fuel via combined heat and power (CHP) units have a high efficiency and less carbon dioxide emissions compared to separate technologies used for heat and electricity generation. CHP units can be fuelled by both renewable energy vectors and non-renewables like fossil fuels. DEMOSOFC is centred on biogas exploitation from wastewater treatment plants, therefore the report focuses on biogas fuelled CHP market analysis. The methods developed can be applied to other energy vectors. Effective utilisation of biogas is an important step in increasing usage of renewable energy, due to the great flexibility that solar and wind power in particular lacks. Biogas generated through anaerobic digestion (AD) of sewage sludge addresses environmental concerns together with creating electricity generation potential. WWTPs are energy intensive plants which require a high amount of energy to reach their goal (clean the inlet wastewater).

The aim of Work Package 6 (Task 6.1) is to deliver an independent analysis of the potential market share of distributed biogas-based SOFCs in European WWTP's. The market for the biogas-SOFC is WWTP in Europe having a population equivalent greater than 20,000, in total 6,181 plants (Water base, 2014) were considered. Discriminant placed on the minimum size of WWTP (i.e. 20,000 P.E.) based on the economic feasibility of installing an anaerobic digester.

The analysis in WP6 (task 6.1) provided answers and insights to the below research questions related to SOFC adoption.

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The rest of the deliverable is divided into six other sections. An overview of the methodology is presented in Section 2. Section 3 contains the methodology inputs and other assumptions used. We note that the inputs and assumptions are dynamic; however, the methodology is robust enough to be applied to updated inputs. Results and discussion is provided in Section 4, section 5 is on conclusions and future work. The Appendix in Section 7 contains a summary of the optimisation model, and the narratives for the three stakeholders – policy makers, technology manufacturers and end-users (WWTP owners). The 6,181 plants considered have a P.E. from 20,000 to 1,100,000 P.E. Results show that 7–25 % savings in operating costs are possible from integrating three systems to exploit biogas i.e. heat and electricity generation in solid oxide fuel cells (SOFC), internal combustion engines (ICE) and biogas upgrade to biomethane, and the trade-offs between capital and operating costs affect the choice of the optimal system.

2. Overview of methodology for SOFC market potential analysis

The methodology applied in WP6 (Task 6.1) begins with determining the optimal design of the plant with biogas SOFC integrated and other competitive technology. A techno-economic assessment of a WWTP plant is done to determine the economic viability of the biogas-SOFC. A MPA is done for plants in the EU i.e. 6,181 to determine the market share of the SOFC, and associated pathways to increase the market share. Whilst techno-economic assessment is able to determine if integrating a technology is economically viable – less expensive when compared to the business as usual technology or its competitor, they are not sufficient to determine the market share of a technology. A technology may be economically viable under different market conditions; hence, the MPA. An overview of the methodology is summarised in the below figure.

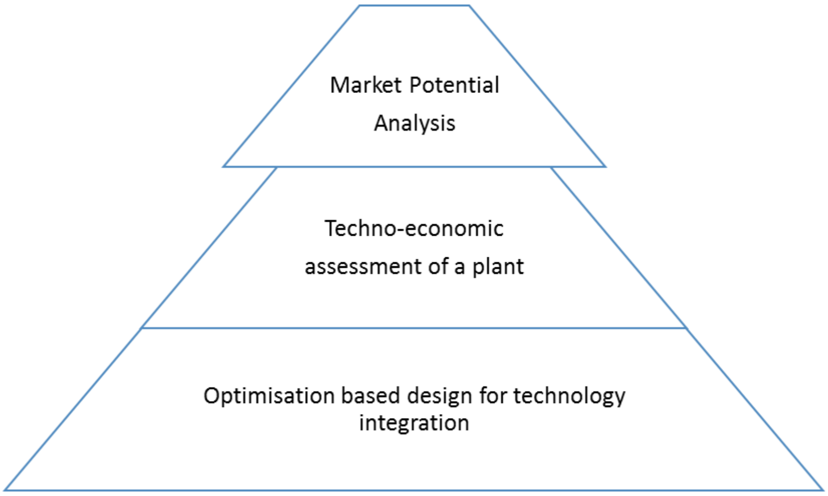

Figure 1 Overall methodology overview

2.1. Optimisation to support SOFC integration

A schematic of the energy system under consideration is in Figure 2. The system needs to satisfy the energy demands (i.e. heat and electricity) of the site. The site currently uses a biogas boiler for heat demand (backed-up by a natural gas boiler), and electricity is imported from the grid. Therefore, the conventional or business as usual system exploits biogas by burning in a boiler to provide heating. Integrating an SOFC or an ICE means some of the grid electricity and natural gas can be displaced. Upgrading biogas to biomethane, implies the site energy demand would need to be satisfied from a natural gas boiler and electricity imported; this is often neglected in studies on biogas upgrade. Each of the three exploitation paths is applied to all WWTPs to ensure that extrapolation to a country context accounts for scale. The methodology begins with an optimisation based design of the system in order to determine the optimal trade-offs between capital and operating costs (details of the optimisation model is presented in Appendix 7.1), this forms the basis of a techno-economic assessment of the plants, which form the basis of an analysis for plants in a country-wide context (section 2.4). Such an analysis takes into account plant size, and market conditions in determining the best exploitation strategy for biogas.

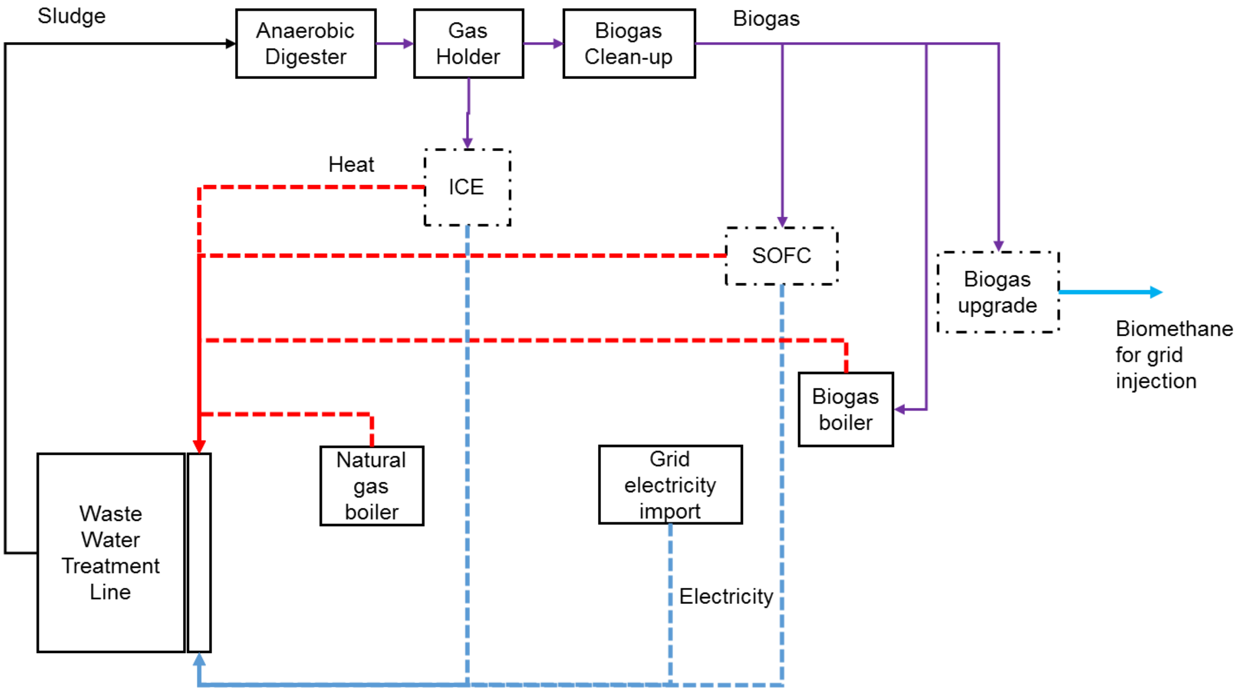

Figure 2 Energy system schematic

2.2. Analysis for all WWTP in EU

A preliminary work in WP6 (task 6.1) was to characterise all 6,181 WWTP into archetypes. Details of the methodology is contained in Sechi et al. (2018). The plants were grouped into 5 archetypes, XS – XL as shown in Figure 3 and Table 1. The number of plants in each archetype, and the archetype distribution by country is shown in Table 2 and 3 respectively. The case studies in the analysis correspond to five different size of WWTP selected from the Wastewater Database as explained below starting from the case study of the WWTP located in Collegno (IT) in which a CHP consisting of 3 SOFC generators will be installed (Santarelli, 2015).

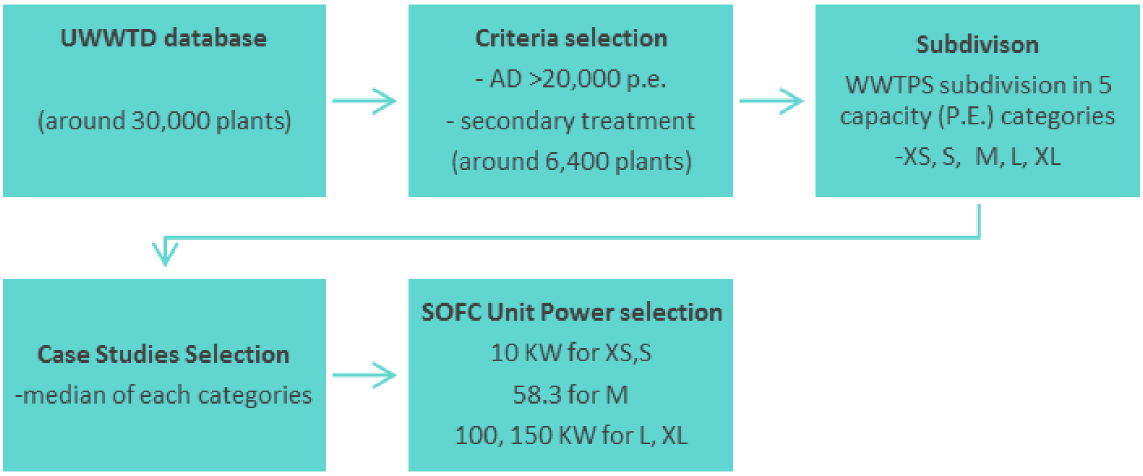

Figure 3 WWTP Archetypes XS – XL.

The Waterbase-UWWTD (Waterbases, 2014) contains all the data provided by all the member of the European States as provided for by the Urban Wastewater Treatment Directive which concerns the collection, treatment and discharge of waste water. The first discriminant in this selection was the economic feasibility of the anaerobic digestion process (AD), which it is not always present in the wastewater treatment plant; the minimum WWTP size identified by a Roland Berger study is 10,000 P.E. but in this analysis a more prudential and realistic number is adopted, in fact the minimum size to have the AD in Europe is 20,000 P.E. (communication with one of IEA task 37 member[1]). Moreover, it is necessary to select only the plants equipped with a secondary treatment which is fundamental to perform the stabilization of the sludges and hence the production of biogas in the AD reactor. The plants selected in such a way are around 6,181. A subdivision of the plants is performed to identify different segments of the potential market for the SOFC plants. To do this, five categories with roughly the same total capacity in terms of P.E., are selected and the median value of each of this is considered as reference case study. The archetypal scenarios for the biogas production and calculations for the thermal loads are obtained from the extension of the methodology identified in our preliminary analysis (Sechi et al., 2017). The archetypal profile for the XS, S and M sizes is set with the parameters (standard deviation and seasonal ratios) from the industrial data provided by the SMAT Collegno plant (180,000 p.e.); while for the larger sizes, L and XL, the characteristics of the Castiglione Torinese plants are set.

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[1] This indication came also from the partner - SMAT

Table 1 Inputs of the model – Size of the WWTP selected for each of the five categories

WWTP categories	Case studies, P.E.	Electric Consumption, KWh/P.E./day
XS	30,000	48
S	90,000	42,3
M	210,000	37,6
L	450,000	37,6
XL	1,100,000	37,6

Table 2 Number of plants in each archetype

WWTP categories	Range (P.E.)	Number of Plants in each category – EU wide
XS	20,000-60,000	3828
S	60,001-150,000	1510
M	150,001-350,000	533
L	350,001-750,000	215
XL	750,000->1,100,000	95

Table 3 Archetype distribution by country

	XS	S	M	L	XL
Belgium	86	22	6	3	1
Bulgaria	15	16	8	4	1
Czech Republic	81	33	8	6	1
Denmark	58	42	9	4	0
Germany	963	293	106	36	17
Estonia	8	4	2	1	0
Ireland	29	9	3	1	1
Greece	68	20	6	1	2
Spain	319	163	72	33	21
France	498	181	48	21	8
Croatia	21	8	1	1	1
Italy	554	202	64	25	10
Cyprus	2	5	3	-	-
Latvia	12	3	1	-	1
Lithuania	21	3	4	3	0
Luxembourg	10	3	1	0	0
Hungary	81	30	11	6	2
Malta	2	1	-	1	0
Netherlands	124	72	28	10	1
Austria	135	42	10	6	2
Poland	123	65	25	6	4
Portugal	80	30	22	4	2
Romania	71	43	18	6	5
Slovenia	12	5	3	1	-
Slovakia	46	18	6	3	1
Finland	-	-	-	-	-
Sweden	68	26	10	4	2
United Kingdom	341	171	58	29	12

Each of the biogas exploitation technology is integrated into the WWTP (using the archetypes) and the optimisation methodology is Appendix 7.1.)

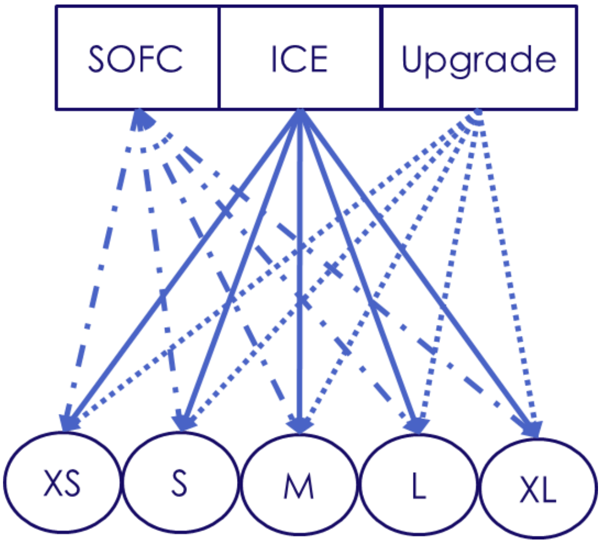

Figure 4 Competitive technologies considered in all WWTP archetypes.

2.3. *Techno-economic assessment*

The added value of the techno-economic assessment in WP6 (task 6.1) is an optimal system forms the basis. An optimal design ensure tradeoffs between capital and energy costs are captured such that the optimal operating strategy for the system is achieved at minimum cost. The economic assessment of an SOFC system using biogas from sewage plants in done in Hauptmeier et al., 2016 and Govender et al., 2019 However, an optimised plant is not the basis of their analysis. The techno-economic assessment measures the Total Annualized Cost (TAC), estimates the operating costs, and the savings/income from selecting the technologies. The savings is the difference between the operating costs of the selected system and the business as usual system. An income can be generated by injecting biomethane into the grid. The TAC is the sum of the annualized capital cost of the technology, the operating cost and maintenance cost. The operating cost is the sum of residual gas and electricity cost. Where the residual gas and electricity cost is for any energy demands not satisfied by the new technology. Assumptions for capital and operating costs are provided in section 3.1.

The electricity and heat produced from each technology i is determined using the optimal dispatch algorithm in Oluleye et al., 2019 (also provided in the Appendix 7.1).

2.4. *Market Potential Analysis*

Most techno-economic studies show whether integration of a technology in a plant is economically viable or not based on a comparison with the conventional technology or an NPV analysis, they do not determine the economic viability in different plants in a market aimed at providing a broader outlook. A technology even though economically not viable in a plant might be in another plant, hence, the market uptake could be greater than 0%.

Such an analysis is important to inform policy creation in form of subsidies and incentives, and also inform manufacturers cost reduction.

The MPA is a novel analysis that determines the market share of each technology under different scenarios, and the installation rate required to drive cost reduction in an economic market. The analysis takes into account competitive technology, for example for a biogas fuelled SOFC, its competitors are a biogas fuelled ICE and upgrading the biogas to biomethane. The market share is determined for market driven scenarios (i.e. based on combination of energy prices), incentivised scenarios, and scenarios with innovations in business models, as well a combination. The market driven case uses the influence of gas and electricity prices to push the technology into the market. For the incentivised case, the value and duration of incentives is varied to build robust insights and conclusions. For each of these cases, the technology cost reductions is taken into account. Innovations in Business Model (BM) can also create a market. An innovative BM is product sale and service with finance. Specifically, the end-user ploughs back the savings in operational expenses (from installing the SOFC) on an annual basis for the lifetime of the technology. A discount rate of 2.5 - 9% is applied to quantify the impact of this BM.

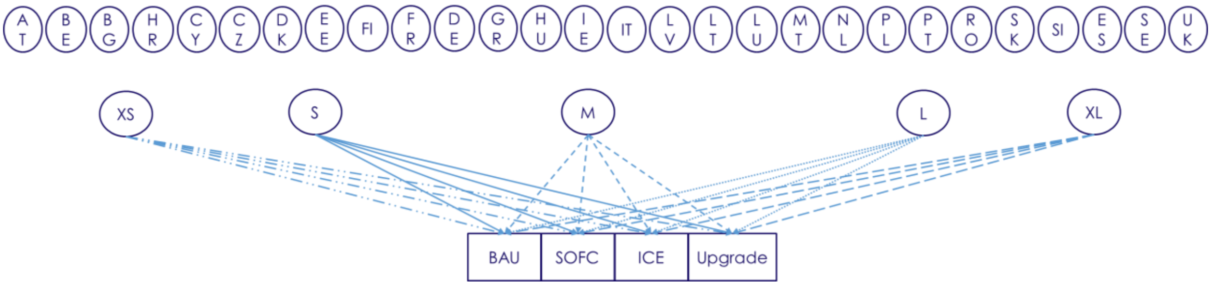

Figure 5 MPA overview – the four technologies applied to all WWTP archetypes using market conditions in all countries.

The system with the lowest TAC dominates the market, and this is applied to the country context under different scenarios based on sensitivity to energy prices and capital cost. An output of the MPA is pathways to commercialisation of a new technology showing how to achieve cost reductions from today until the technology is market driven i.e. economically viable. Analysis for all plants in a country, under each scenario is used to determine the market uptake of the exploitation pathways for biogas. The pathways that dominates a plant, has the lowest TAC, and this is determined for all plants in a country. The market share is then estimated based on this theorem. In explicit terms, for any country, where the total number of WWTP is known, and the number of plants in each archetypes also known. For the system with the minimum EAC in that archetype, the market share is the number of plants in each archetype divided by the total number of plants in the country. This is applied to all scenarios. For example assuming the total number of plants in country X is 50, and X has 10 plants in each archetype (XS, S, M, L and XL). Under the base scenario, if the minimum EAC option is upgrading to biomethane in the XS, M and L WWTP archetype, its market share would be 30/50.

2.5. Reducing CO_2 mitigation costs

The SOFC abatement cost is expected to come down based on new manufacturing techniques, favourable market factors, business models and policies. In WP6 (task 6.1), the impact of new business models (specifically looking at offsetting capital costs by ploughing back operational savings from a high-efficient SOFC) on reducing the abatement cost was quantified. The CO2 abatement cost is the annualised capital cost plus annual operating costs for the SOFC less annual operating costs for the business as usual case divided by the annual CO2 from the BAU less CO2 from the SOFC. i.e. the numerator is the difference between the total annualised cost for SOFC integration and the business as usual system and the denominator is the difference between CO2 emissions from the BAU and CO2 from the SOFC. The abatement costs were calculated relative to a business as usual scenario where biogas is combusted in a boiler to generate heat, and electricity imported from the grid. A positive abatement cost implies there is an added cost of reducing co2 emissions from integrating a biogas fuelled SOFC system. A negative abatement cost implies there is benefit from reducing CO2 emissions i.e. the cost of the business as usual system is lower than the SOFC system. In most cases with the SOFC, the abatement cost is positive. Case studies are presented in section 4.4. for WWTP's with population equivalent 60,000 – 350,000 in twelve European countries (totalling 977 plants). Results show the new business models reduces the abatement cost from 122 to 56 € per ton CO_2 in Bulgaria, 160 to 92 € per ton CO_2 in Czech Republic, 73 to 26 € per ton CO_2 in Greece, 150 to -90 € per ton CO_2 in the UK, 99 to -98 € per ton CO_2 in Germany, 210 to 84 € per ton CO_2 in Hungary, and 192 to 7 € per ton CO_2 in Cyprus. More results are provided in Section 4.4.

WP6 (task 6.1) makes an assessment of the suitability of the SOFC for reducing emissions in the wastewater treatment sector. Accurately estimating carbon dioxide (CO_2) abatement costs, and effectively identifying the factors impacting those costs, can improve the applicability and effectiveness of policy implementation.

2.6. Survey to support MPA analysis

A survey was released online but response was poor even after reducing the size of the survey.

3. Inputs for the SOFC Market Potential Analysis

The assumptions for technologies and energy prices are presented in Section 3.1, assumption used for policy instruments in Section 3.2 and inputs on the WWTP in section 3.3.

3.1. Assumptions for technologies and energy prices

The SOFC capital cost assumption under different scenarios is provided in table 4 below (Ammermann et al., 2015). The installation rate is the ratio of manufacturing volumes to the SOFC market demand. The installation rates calculated in the below table are based on an ideal market demand of 13,280 units for all 6,181 plants investigated in this study and it changes depending on the market size. The installation rate is the ratio of manufacturing volumes to the SOFC market demand.

Table 4 Assumptions on capital cost and manufacturing volumes per plant. The EU wide installation rate to achieve the cost is calculated from

	Very High	**High**	**Medium**	**Low**	**Short term**	**Target**
Module CAPEX projections (€/kW)	> 15,700	8,300–15,700	4,560–8,300	3,350–4,560	2,080–3,350	< 2,080
Manufacturing Volumes	1	1–100	100–780	780–1000	1000–10000	> 10000
EU wide installation rate for cost reduction	< 0.01	0.01 –0.8 %	0.8 – 6%	6 – 8%	8 – 75%	>75%

Table 5 Other assumptions for the SOFC cost (Giarola et al., 2018, Ammermann et al., 2015)

SOFC	**Unit**	**Low – Very high**	**Short term**	**target**
Stack lifetime	year	3-3-4-4	5-5-5	7-8
Module CAPEX	Euro/kW	> 4,560	3,350	2,080
Stack replacement	Euro/kW	1,223	540	478
Maintenance	Euro/kW-year	72	54	44
Gas clean-up CAPEX	Euro/kW	917	459	183
Gas clean-up OPEX	Euro/kW-year	76	57	38

On balance of plant cost: Auxiliary equipment and balance-of-plant components (i.e. heat exchangers, power conditioners, control unit, pumps, sensors, etc.) are also necessary for the operation of a fuel cell-based system. A factor of 1.5 times the CAPEX is applied for the balance of plant cost.

A competitive technology is the internal combustion engine, and upgrading biogas to biomethane. Assumptions applied for the cost are provided in Table 6 and 7 respectively.

Table 6 Techno-economic characteristics of the ICE-based CHP systems in the current, short-term and target scenario of technological development.

	Unit	**Current**
Unit CAPEX	€/kW	1,970
Maintenance	€ cents/kWh	2.80
Unit lifetime	Years	20

Table 7 Biogas upgrade to biomethane economic assumptions, upgrading via water scrubber (Ferella et al., 2019)

UPGRADE	**Unit**	**Current**
Unit CAPEX	€/kW	799
Unit lifetime	years	20
Gas Clean-up CAPEX	Euro/kW	917
Gas Clean-up OPEX	Euro/kW-year	76

The market force is determined by the energy price. The gas and electricity price assumed for the M archetype is shown in Figure 6. Grid emission factors for all countries are provided in figure 7.

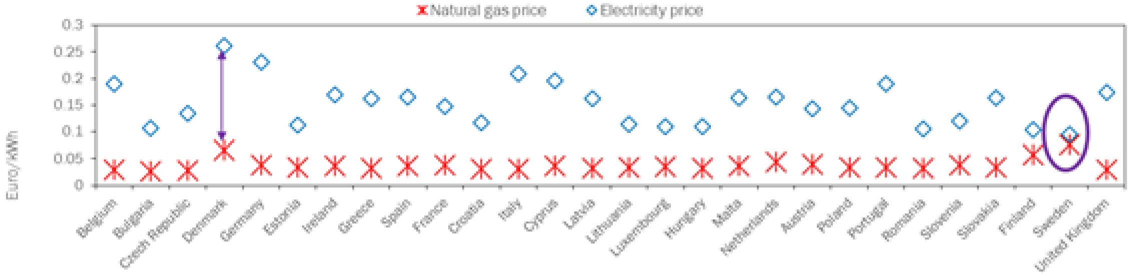

Figure 6 Energy price assumptions for a medium (M) archetype[23].

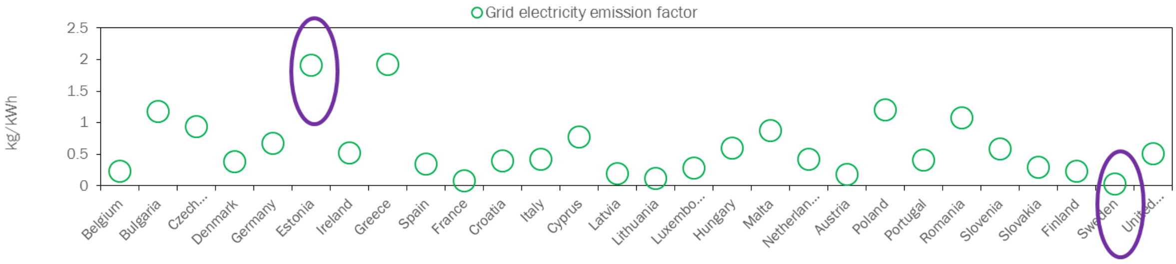

Figure 7 Grid electricity emission factor for EU-28[4].

The electricity and fuel prices varies in accordance with the size of the WWTP. Prices in selected countries are provided in Table 8.

Table 8 Fuel and electricity prices for different countries and WWTP archetype (Eurostat, 2017)

	€ cents/kWh	**XS**	**S**	**M**	**L**	**XL**
Italy	Natural gas price	5.06	5.06	3.20	3.20	3.20
	Electricity price	16.42	13.35	13.35	13.35	10.25
Greece	Natural gas price	3.40	3.40	3.12	3.12	3.12
	Electricity price	11.57	9.87	9.87	9.87	8.40
Germany	Natural gas	4.30	4.30	3.78	3.78	3.78

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[2] Natural gas prices for non-household consumers, first half 2017
http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics

[3] Electricity prices for non-household consumers, first half 2017
http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

[4] Electricity prices for non-household consumers, first half 2017
http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

	price					
	Electricity price	19.67	16.35	16.35	16.35	12.06
France	Natural gas price	4.78	4.78	4.13	4.13	4.13
	Electricity price	11.75	9.22	9.22	9.22	7.60
United Kingdom	Natural gas price	3.09	3.09	3.09	3.09	3.09
	Electricity price	16.03	15.22	15.22	15.22	15.15

3.2. Assumptions for Policy Interventions

Our own elaboration of policies for biogas, and biogas-CHP systems are provided in table 9. The value and duration of these instruments were applied to quantify the impact of policy interventions on the market share of biogas-SOFC as part of the MPA.

Table 9 representing an own elaboration from Res-Legal (15) and IEA (16) websites, an overview of financial schemes provided in 2018 for all the European countries is shown (adapted from Marco Thesis).

Countries	**Feed-in-Tariff**	**Feed-in-Premium**	**Tax mechanism**	**Quota system**
Austria	✓			
Belgium				✓
Bulgaria				
Croatia	✓			
Cyprus				
Czech Republic				
Denmark		✓	✓	
Estonia		✓		
Finland		✓		
France	✓	✓		
Germany				
Greece				
Hungary	✓	✓		
Ireland				
Italy	✓			
Latvia			✓	
Lithuania		✓		
Luxembourg	✓			
Malta				
Netherlands		✓	✓	
Poland	✓	✓	✓	
Portugal	✓			
Romania				✓
Slovakia	✓		✓	
Slovenia				
Spain				
Sweden			✓	✓
United Kingdom	✓	✓	✓	

3.3. Assumptions for WWTP's

The distribution of WWTP archetypes with P.E.> 20,000 in each country is shown in Figure 8. Figure 9 shows WWTP with P.E. < 20,000. Countries with the higher number of plants are Germany, Italy, France, Spain and the United Kingdom[5].

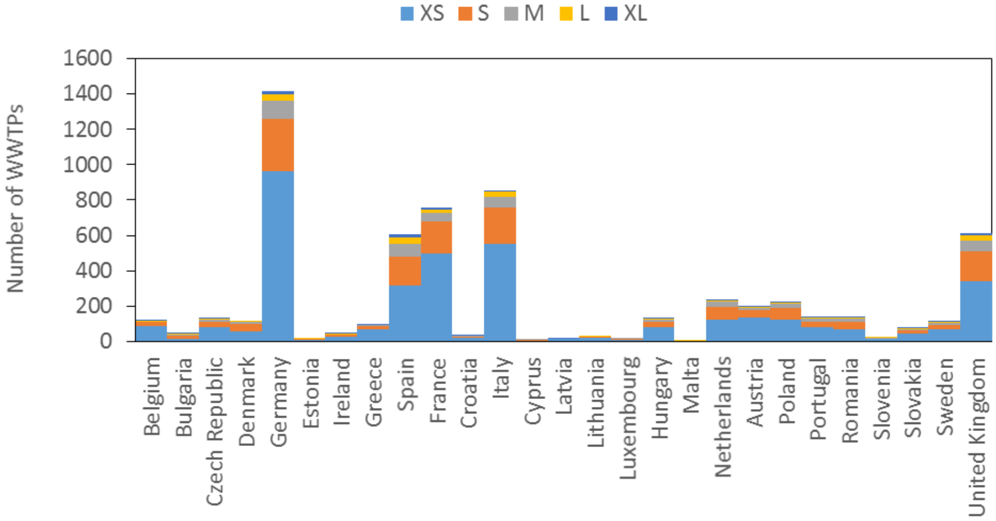

Figure 8 Distribution of WWTP with P.E. > 20,000 in the EU

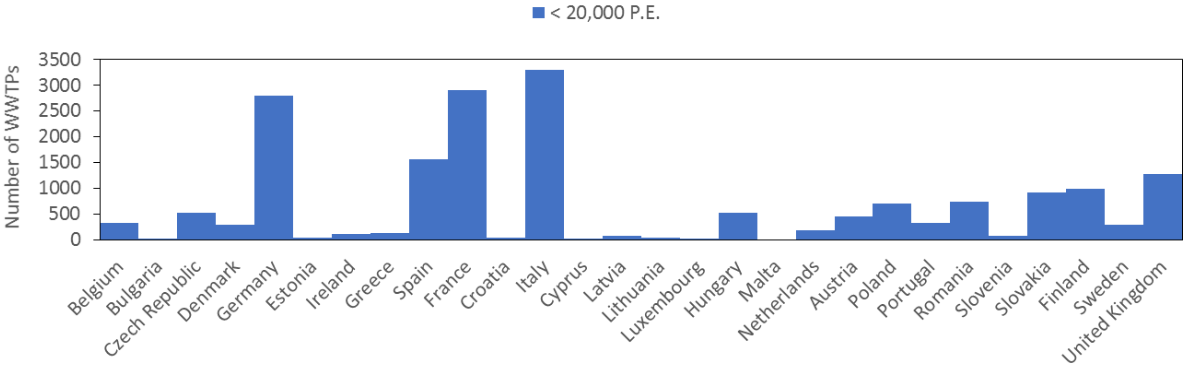

Figure 9 Distribution of WWTP with P.E. < 20,000 in the EU

The optimal SOFC number of units and energy demands in all archetypes is provided in table 10. The number of units of technology installed in determine via an optimisation framework in Giarola et al., 2018.

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[5] as at the time of WP6 (Task 6.1) analysis the United Kingdom was still a part of the European Union

Table 10 P.E., number of plants, biogas produced and energy demand in WWTPs

WWTP Archetype	Population Equivalent (P.E.)	Number of Plants in each category	Total biogas (GWh/y)	Total heat demand (GWh/y)	Total electricity demand (GWh/y)	SOFC size (58kW)
XS	20,000-60,000	3828	282	69	152	1
S	60,001-150,000	1510	309	83	164	2
M	150,001-350,000	533	229	47	92	3
L	350,001-750,000	215	214	58	114	11
XL	750,000-1,100,000	95	209	55	109	26

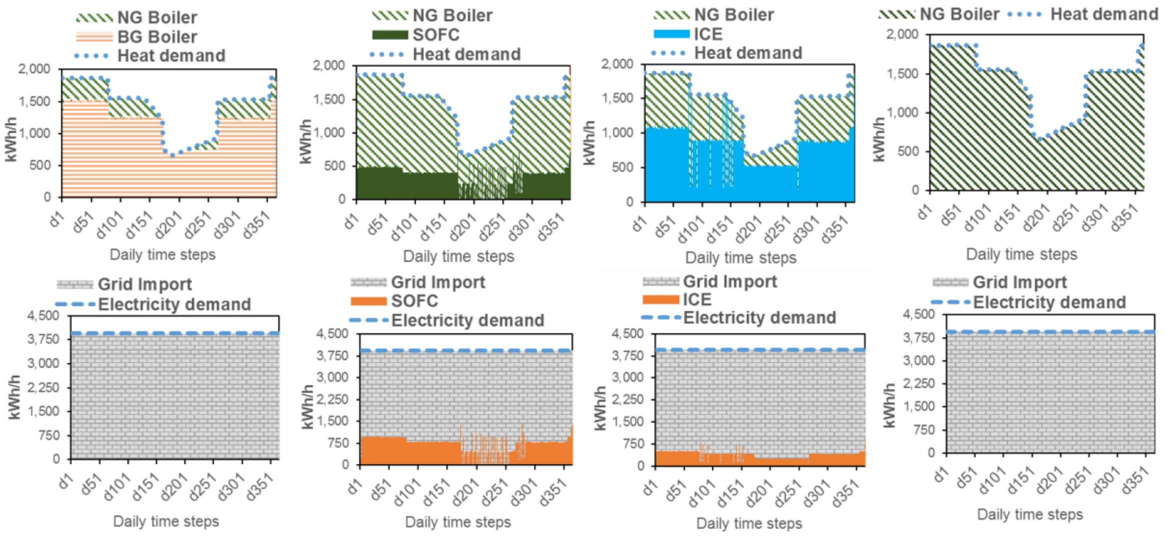
In total the demand for the SOFC in all archetypes is 13,282 SOFC modules of 58 kW_e. Since the competitive technologies are mature, the cost is the same for all scenarios. The market is therefore defined for 6181 plants producing biogas, and three competitive technologies to exploit biogas.

4. Results

The result section is divided into 6. Section 4.1 on the energy system dispatch, 4.2 on the economic results without policy interventions i.e. non-incentivised results, 4.3 on the incentivised MPA results, 4.4 on the impact of business models, and 4.5 on the pathways to commercialisation. Limitations of the work carried out in WP6 (Task 6.1) is provided in Section 4.6.

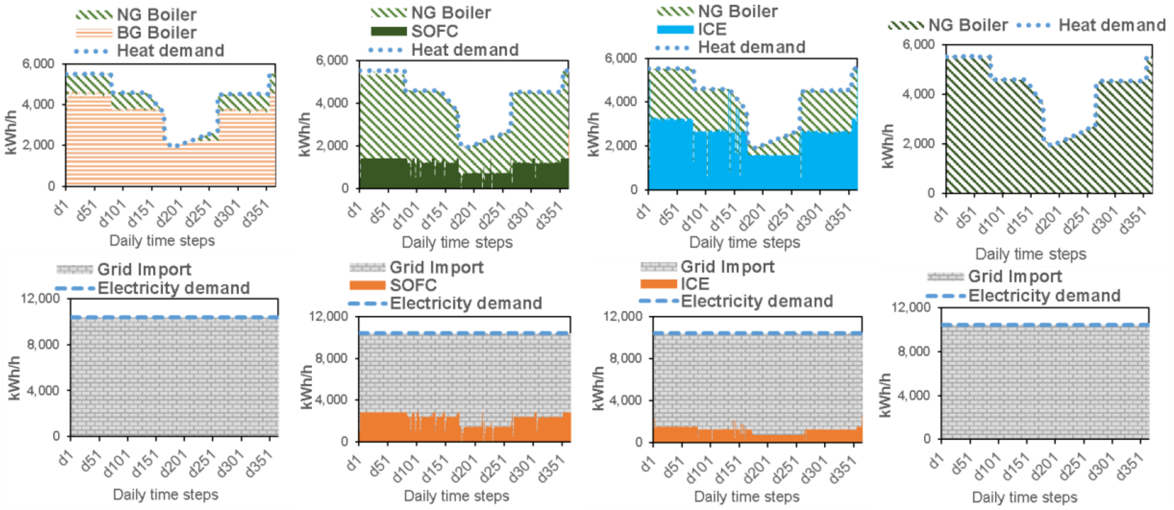
4.1. Energy System Dispatch

The novel optimisation framework is able to determine the dispatch strategy for the technologies considered. The dispatch for the extra small (XS) WWTP archetype is presented in Figure 10, Small (S) archetypes in Figure 11, Medium (M) archetype in Figure 12, large (L) archetype in Figure 13, and extra-large (XL) archetype in Figure 14. In each of these figures (10 – 14), ‘a’ depicts the operational schedule for the conventional system, ‘b’ for integrating SOFC, ‘c’ for biogas fuelled ICE and ‘d’ for biogas upgrade to biomethane. In the conventional/business as usual system the heat and electricity demands are met with a biogas boiler and grid electricity import. A NG boiler is used to provide back-up heating for all systems. Integrating an SOFC reduces the grid electricity import. Upgrading biogas to biomethane implies the heating demand needs to be satisfied by a NG boiler, and all electricity imported from the grid. The horizontal axis shows the daily time step.



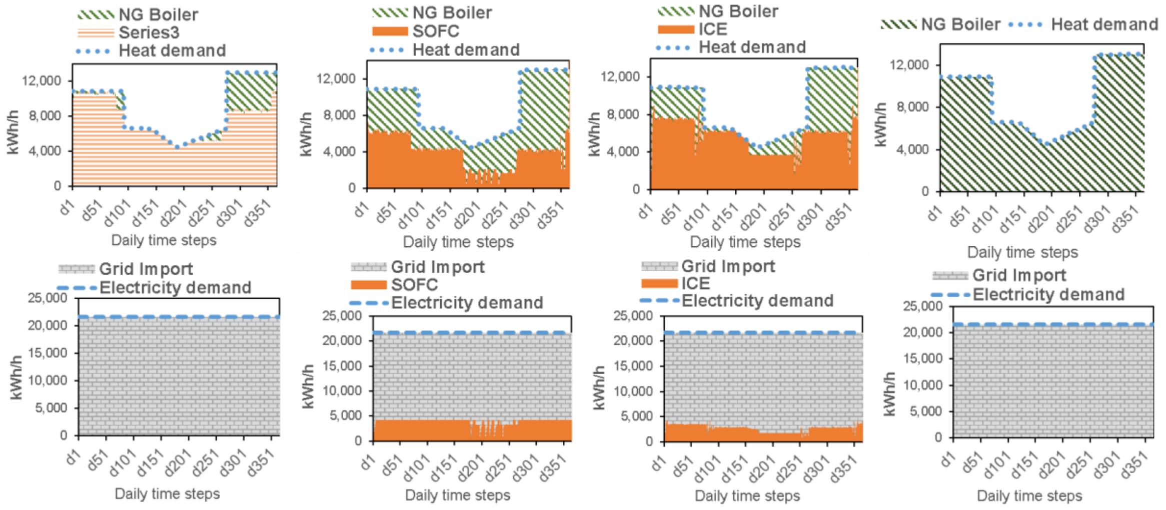
(a) (b) (c) (d)

Figure 10 Operating schedule for (a) conventional system, (b) SOFC integration, (c) ICE integration and (d) biogas upgrade. Top four figures are the heating profiles and bottom four are the electricity profiles for an Extra Small (XS) WWTP archetype.



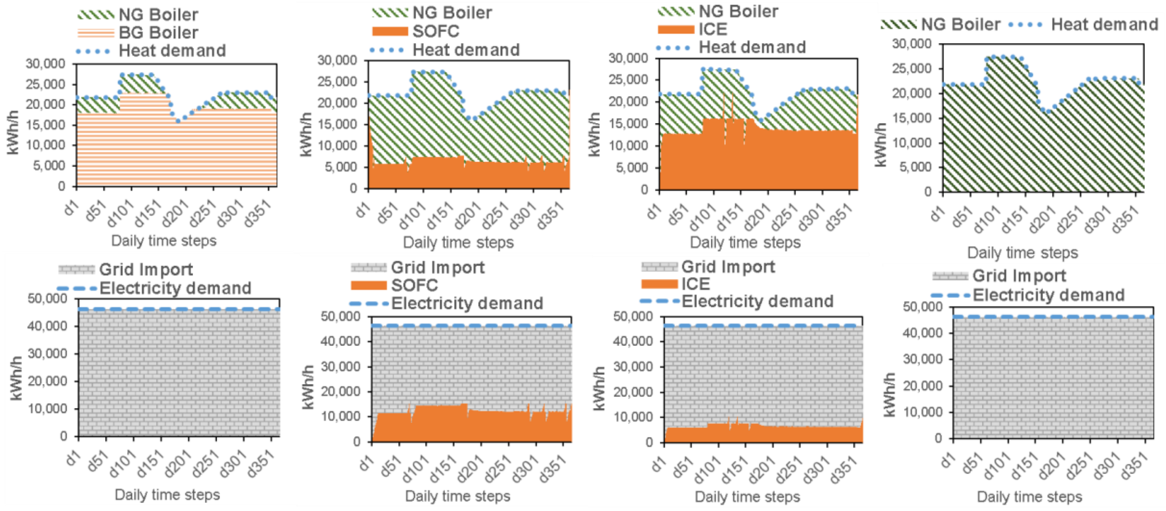
(a) (b) (c) (d)

Figure 11 Operating schedule for (a) conventional system, (b) SOFC integration, (c) ICE integration and (d) biogas upgrade. Top four figures are the heating profiles and bottom four are the electricity profiles for a Small (S) WWTP archetype.



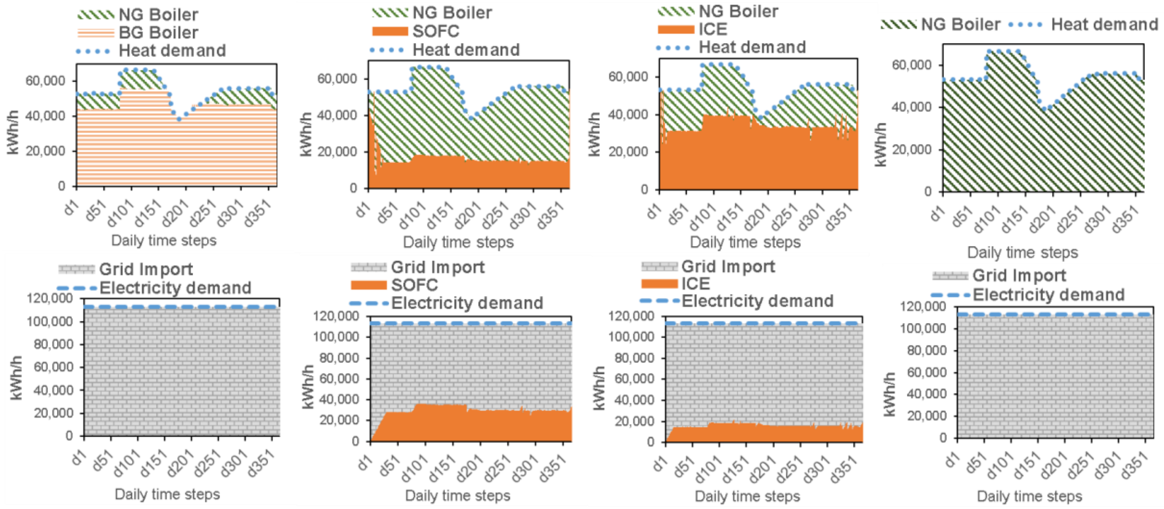
(a) (b) (c) (d)

Figure 12 Operating schedule for (a) conventional system, (b) SOFC integration, (c) ICE integration and (d) biogas upgrade. Top four figures are the heating profiles and bottom four are the electricity profiles for a Medium (M) WWTP archetype.



(a) (b) (c) (d)

Figure 13 Operating schedule for (a) conventional system, (b) SOFC integration, (c) ICE integration and (d) biogas upgrade. Top four figures are the heating profiles and bottom four are the electricity profiles for a Large (L) WWTP archetype.



(a) (b) (c) (d)

Figure 14 Operating schedule for (a) conventional system, (b) SOFC integration, (c) ICE integration and (d) biogas upgrade. Top four figures are the heating profiles and bottom four are the electricity profiles for an Extra Large (XL) WWTP archetype.

The added value of considering the sizes of WWTP's is the ability to provide insights on its impact of the energy self-sufficiency in the biogas produced i.e. how much of the biogas can satisfy the energy demand of the site. The heat and electricity produced from biogas fuelled SOFC can satisfy 21.2% of the energy demand in the XS archetype, 23.4% in the S archetype, 26.41% in the M archetype, 27.7% in the L archetype, and 27.8% in the XL archetype. Therefore, even though energy demands increase from XS – XL the biogas produced from sludge due to additional P.E. also increases. The XS requires 1x58kWe module, the S requires 2, the M requires 3, the L requires 11, and the XL requires 26.

4.2. Economic Results without policy interventions

Results are first presented for five countries: Italy, Greece, Germany, France and the United Kingdom (Figure 15), and then for all countries considered.

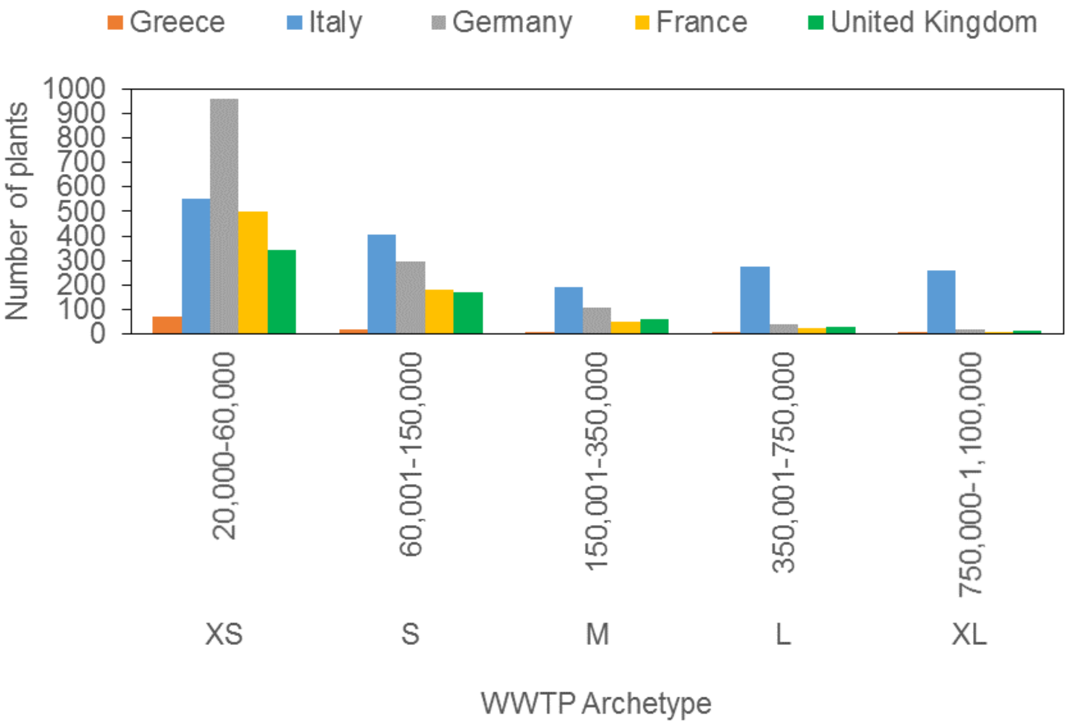


Figure 15 Number of WWTPs in each archetype for the five countries selected

Upgrading biogas to biomethane has the lowest annualized capital investment for the XS (Table 11), and the highest operating costs (for all archetypes) in all five countries studied since the energy demand needs to be met using heat from a NG boiler and grid electricity (Figures 10 – 14 'd'). The SOFC has the lowest operating cost in most archetypes and countries, expect for the M archetype in France (Figure 16). The M archetype in France has the lowest spark spread compared to other countries (Table 8). The lowest operating cost in all other countries is due to the SOFC's higher electrical efficiency compared to the ICE, resulting in more grid electricity displacement. However, the SOFC high capital investment in the current term reduces its economic attractiveness. The savings due to lower operating costs compared to the conventional system is also depicted in Figure 16 (negative axis). For each of the archetype category, the percentage of the operating costs that can be saved increases with the spark spread in the country. Savings from the SOFC are higher than the ICE expect in the M archetype located in France, Italy, Greece, Germany, and the UK. The percentage of the operating cost that can be saved on average for the SOFC in the 1685 plants in Italy is 17%, 97 plants in Greece if 15%, 1415 plants in Germany is 18%, 756 plants on France is 10.21%, and 611 plants in the UK is 20.2%. the savings from the ICE is lower expect in France, 11% in Italy, 11.5% in Greece, 11.5% in Germany, 10.5% in France and 11.6% in the UK. The savings reflect the market conditions in each country i.e. natural gas and electricity prices.

Without incentives for injection of biomethane to the grid income from upgrading biogas is zero. The sensitivity analysis conducted below considers biomethane injection tariff.

Table 11 Annualised Capital Investment (Euro/y)

	XS	S	M	L	XL
SOFC	97,726	195,452	293,178	1,074,985	2,540,873
ICE	17,682	36,547	57,726	201,265	476,656
Upgrade	15,382	39,472	81,545	201,446	487,258

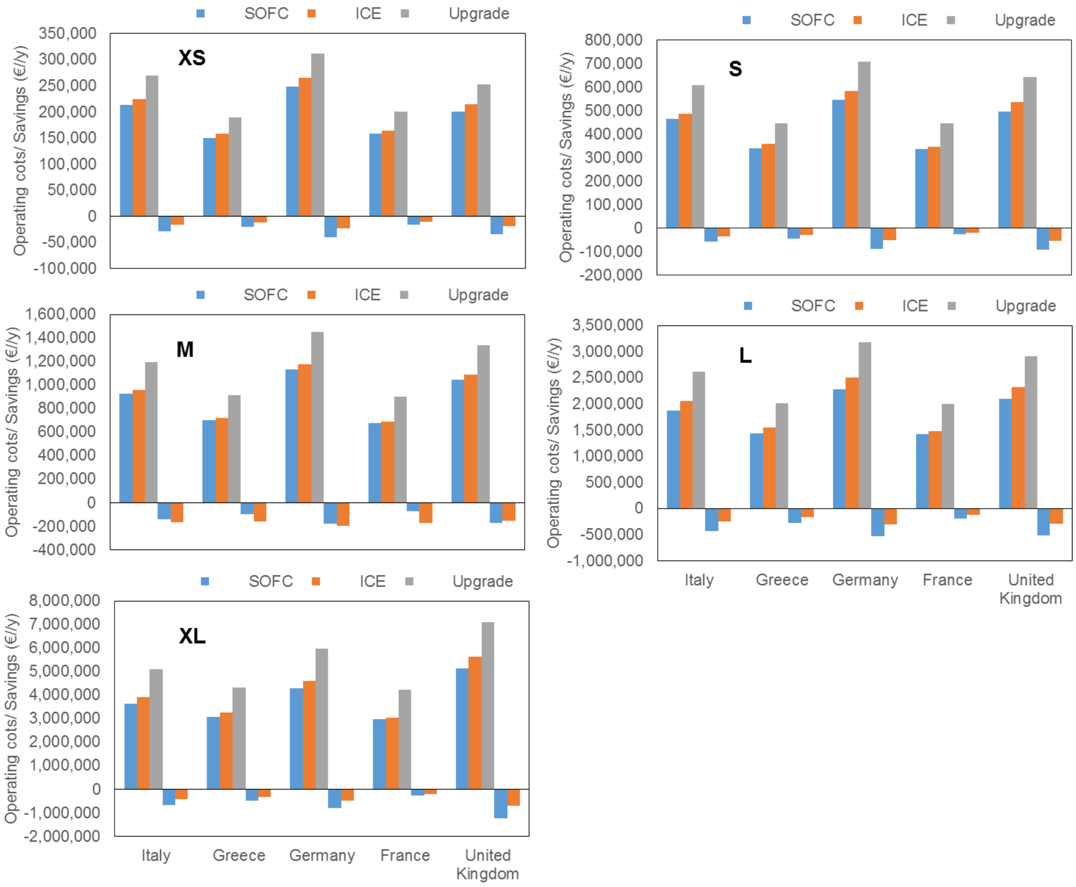


Figure 16 Operating costs and savings (negative axis) for all WWTP's archetypes and countries considered.

A sensitivity analysis to energy prices and other market conditions was conducted to determine the best pathway for biogas in all countries, archetypes, and scenarios (including the conventional/ business as usual/ base scenario. There are 5 other scenarios in addition to the Base scenario are: (1) a higher electricity price, (2) a lower electricity price, (3) lower SOFC capital, (4) combination of (1) and (3), and (5) Biogas injection price. The electricity and natural gas were varied between 0.8 and 1.2 times the base prices.

All archetypes in Italy, Greece, Germany, France and the United Kingdom are shown in Figure 17 – 21 respectively. Combusting biogas in an ICE to generate heat and electricity has the lowest overall EAC in the business as usual scenario in all WWTP and in all countries. A higher electricity price in scenario 1, makes the SOFC economically viable in the S archetypes in Italy, Greece, Germany and the UK, M archetype in Italy and Germany. In countries with a high spark spread a lower SOFC capital in scenario improves its economic viability and makes biogas fueled SOFC for generation of heat and electricity the best choice. For example XS, S, and L plants in Germany and the UK. For all WWTP archetypes, a combination of lower SOFC capital and higher electricity price gives the SOFC the lowest EAC. The EAC for biogas upgrade is lowest in scenario 5 (with biogas injection tariff) especially for the L and XL plants in Italy where the biomethane produced is highest. This is also observed for all plants in Greece (with low fuel and electricity prices). Exploiting biogas using the ICE (an established technology) is attractive due to its low capital investment. However, it is expected that the SOFC will be competitive from 2020. A base scenario uses the existing market conditions.

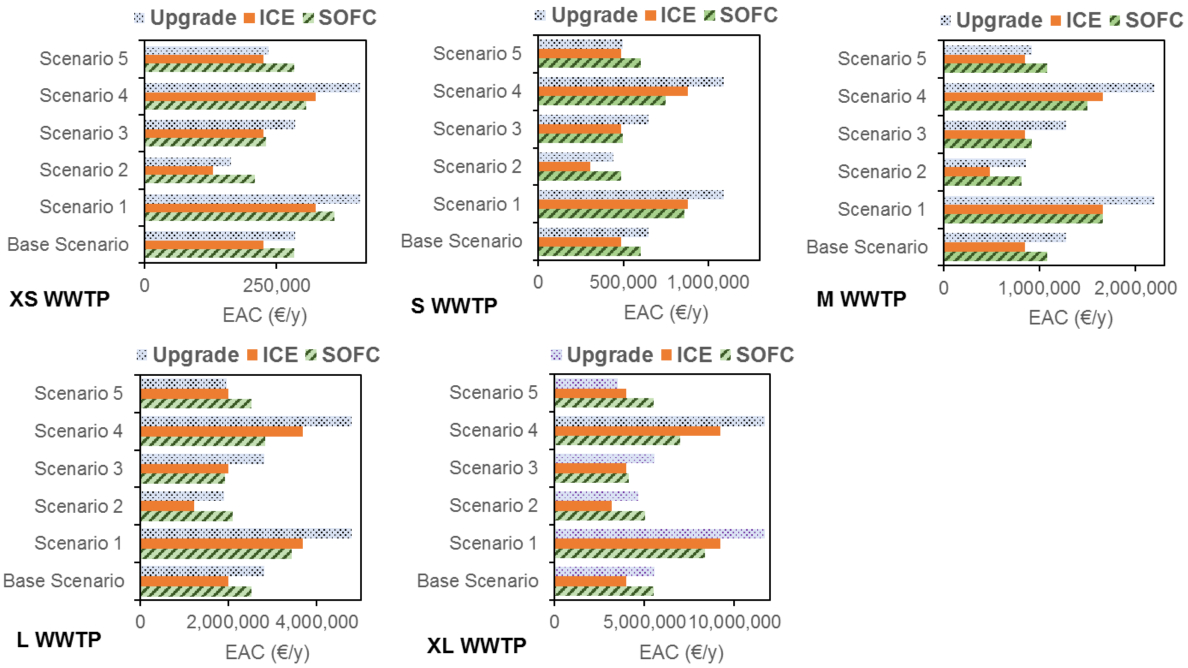


Figure 17 Economic assessment for all WWTP archetypes in Italy

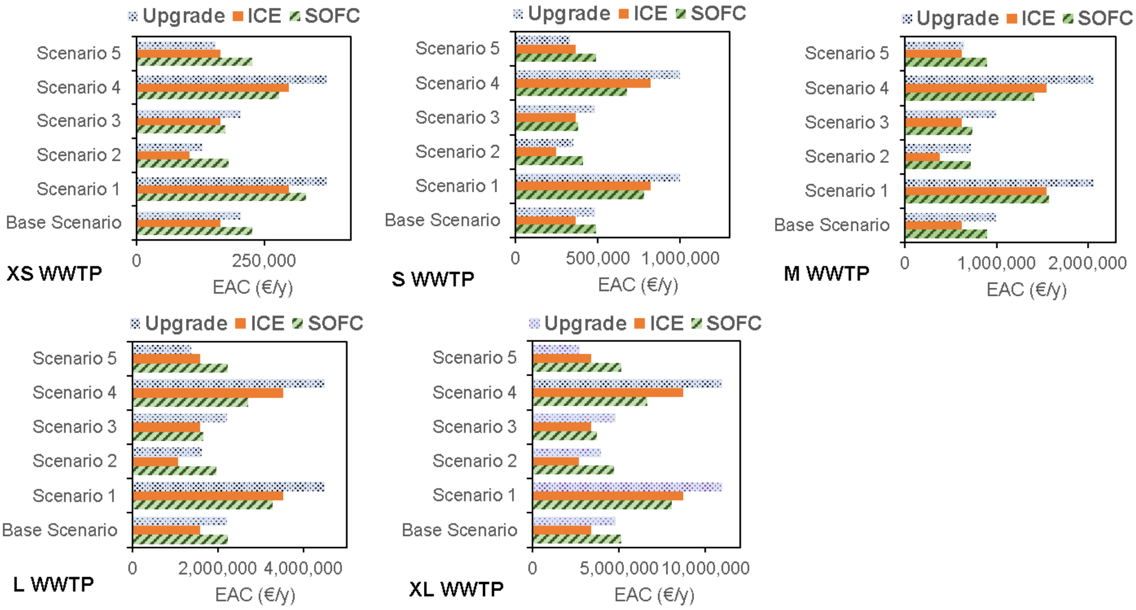


Figure 18 Economic assessment for all WWTP archetypes in Greece

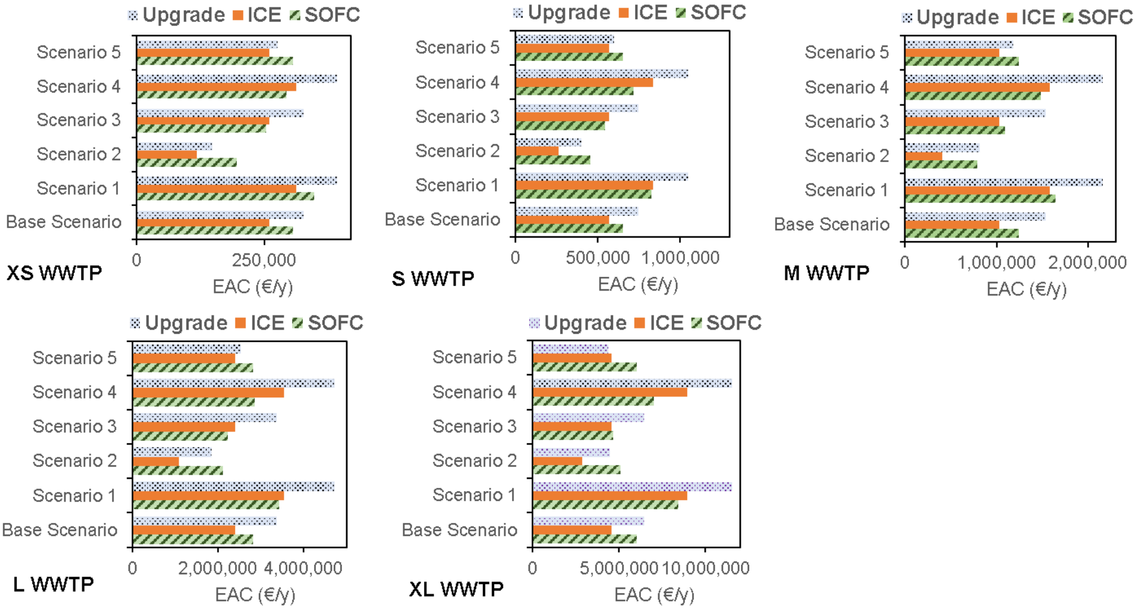


Figure 19 Economic assessment for all WWTP archetypes in Germany

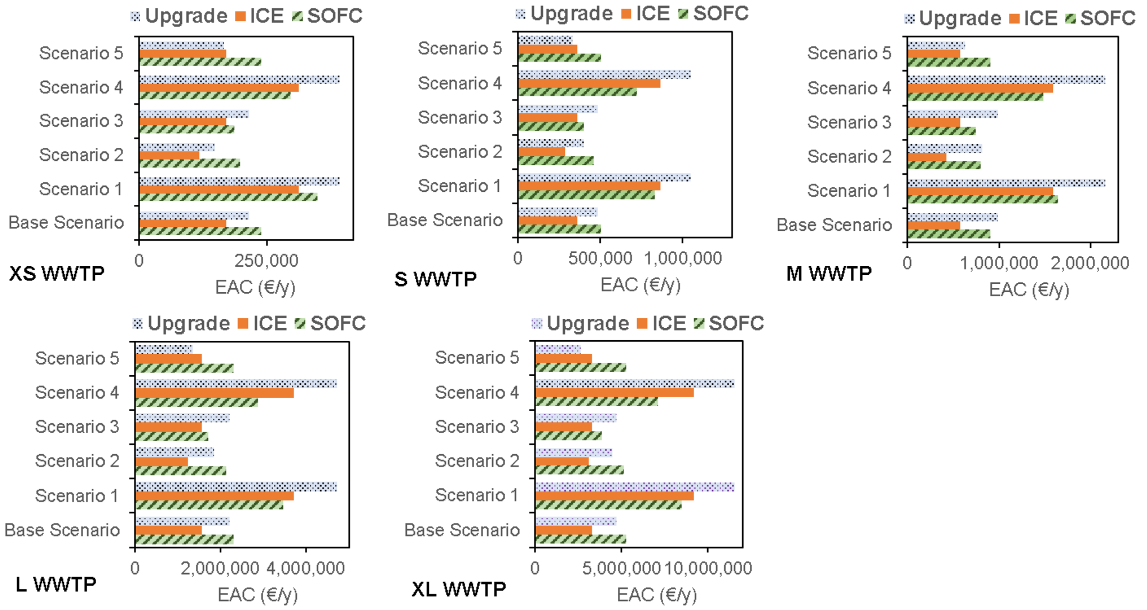


Figure 20 Economic assessment for all WWTP archetypes in France

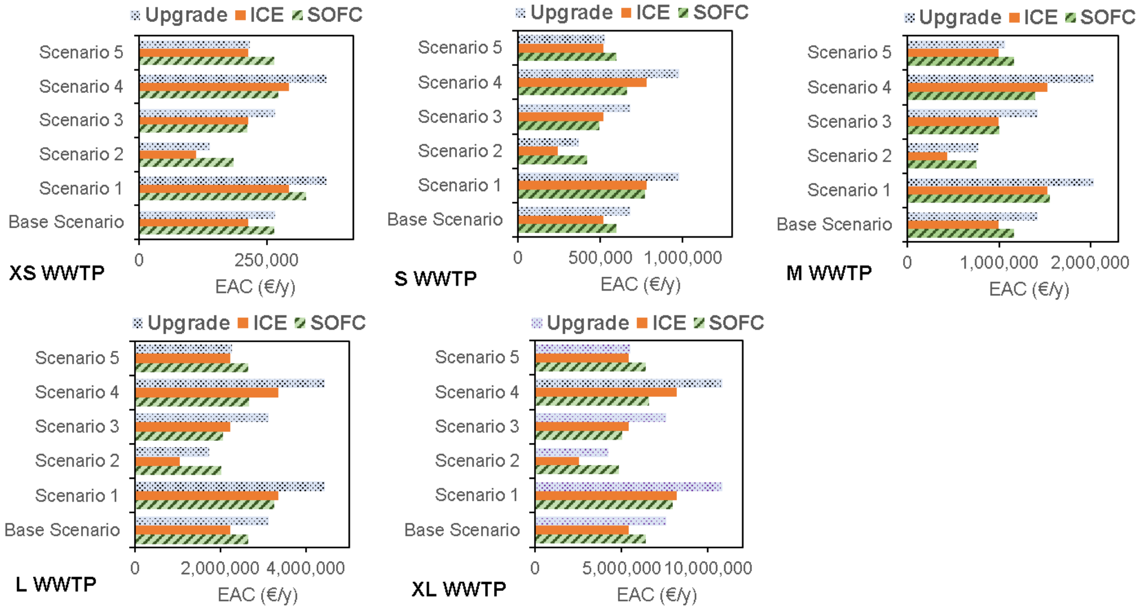


Figure 21 Economic assessment for all WWTP archetypes in United Kingdom

The MPA results for all countries showing the market share of biogas-SOFC under all sensitivities is provided in Figure 22. A market output is provided from optimized results for each WWTP: the market outlook measures the market share of each exploitation pathway in the countries studied. The market share depends on which of the pathways are economic in each WWTP archetype. An analysis of the market share under market conditions has never been done before. A technology will dominate the market if its EAC is the lowest. Based on this, the ICE dominates the market in most scenarios except for a future SOFC target CAPEX and a higher electricity price i.e. Scenario 4.

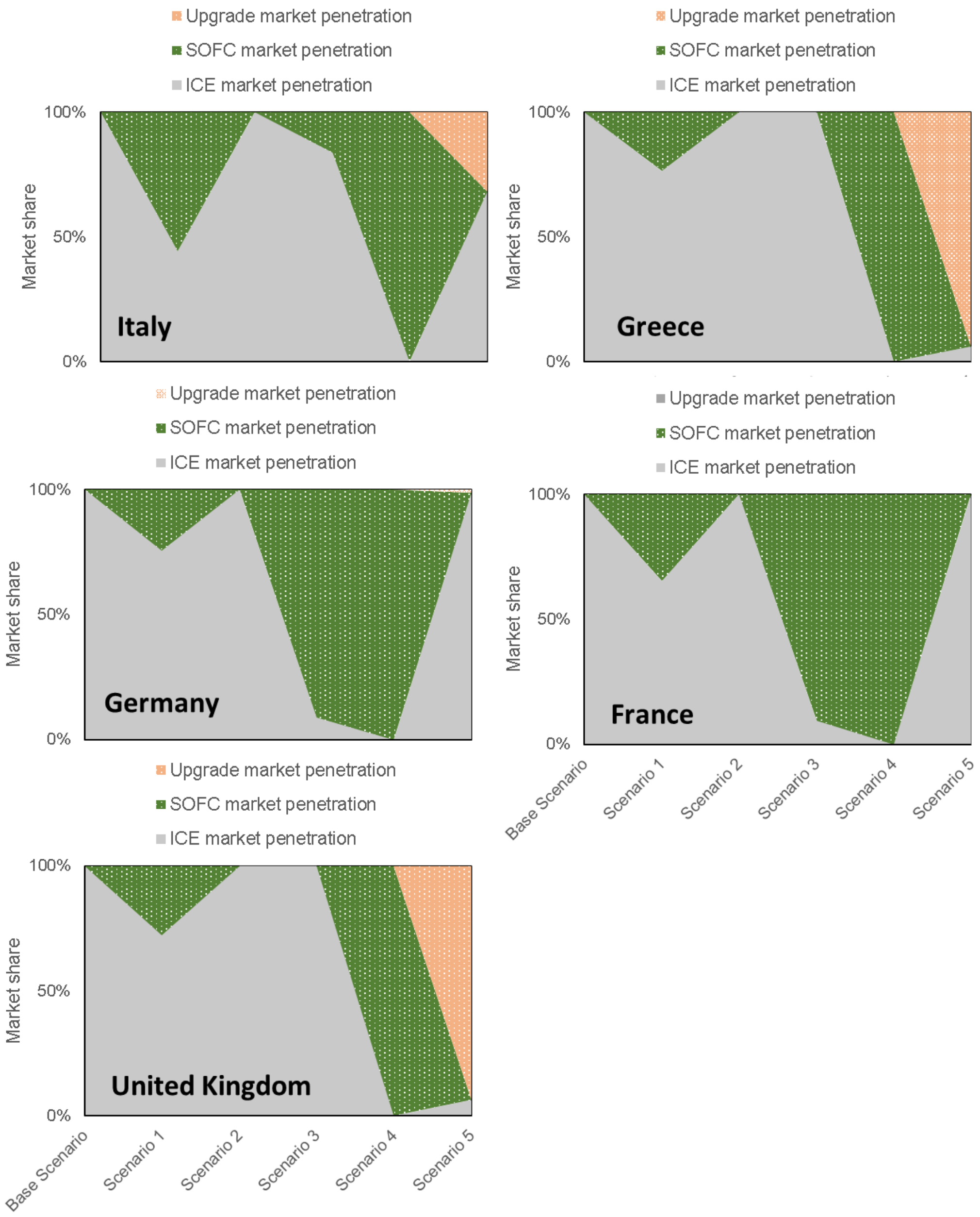


Figure 22 Country-level market size using all WWTP's with P.E. > 20,000

The SOFC in scenario 1 occupies from 25 – 50% of the market, hence a higher electricity price or countries with high spark spreads could be early adopters of the SOFC. The SOFC occupies 28% of the market in scenario 1 in Italy. With biomethane injection price, the upgrade occupies the L and XL WWTP archetypes market and occupies 32% of the market overall in Italy, 94% of the market in Greece, 1.2% in Germany, 98% in UK. These are markets with high electricity and gas prices hence it's rather expensive to satisfy the energy demands of the site if the biogas is upgraded to biomethane and injected into the grid. Market outlook analysis is necessary to inform policy and manufacturers on conditions required to increase biogas use in WWTP. Conversion of biogas to biomethane is already a strategic target in many countries (Angelidaki et al., 2018), hence more incentives may become available.

4.3. Incentivised results

In this section, the market share results is discussed for all countries using existing policy instruments in the EU (Table 9). The income from price incentives is subtracted from the Total annualised cost. Both the value and duration of incentives is accounted for. Under today's CAPEX for the SOFC, the market share is zero, even with incentives offered in over 12 countries. The ICE dominates the market. Unfortunately, existing incentives are not technology-specific; hence, a less efficient mature technology might still be incentivised.

The potential of new incentives was also explored in WP6 (Task 1). For example the impact of capital subsidy (from 5 – 30%), and assuming the ICE is not incentivised due to its maturity. With capital subsidy, the SOFC begins to dominate the market under low cost projections. Stopping incentives for the ICE creates a market for the SOFC under today's very high CAPEX assumptions.

A new incentive also explored in WP6 (Task 1) is a coordinated policy. A hypothetical situation is analysed where the same price instruments are applied to the whole of Europe for one year. For the coordinated policy, a scenario is designed where the FiT is offered in all European countries. The minimum FiT is 4.2 euro cents/ kWh offered in Hungary and the maximum is 19.1 euro cents/kWh offered in Luxembourg. The coordinated policy only applies to the SOFC, here the ICE is not incentivised, and incentives for upgrade still remain. In the scenario, FiT was varied from 2 euro cents/kWh to 20 euro cents/kWh based on the lowest and highest incentive available in individual countries. The total income from incentives currently in all countries, where only 13 countries have incentives, is the same as applying 4p/kWh to all 27 countries with WWTP. At low values of the premium i.e. below 12 p/kWh, the impact is felt when the capital costs reductions are in the low range. In this case, an incentive as low as 2 p/kWh increases the market share to 14%, if it is offered for 10 years. At 4p/kWh (which gives same income as the existing incentives), the market share when offered for 7 years, is 30% i.e. twice the existing market share. For the coordinated policy case, countries that have a suitable market are Denmark, Italy, Sweden, UK, Germany, and Cyprus. Whilst for the conventional case Belgium, Denmark, Italy, Hungary. The coordinated policy scenario only has an impact under medium capital cost assumptions when the value increases to 12p/kWh. Under this – the market share is 32 % if the incentives runs for 20 years. Countries that have favourable market are Belgium, Denmark, Germany, Spain, Italy, Cyprus, Portugal, Slovakia, Sweden, and UK. Under the existing policy, the market share is 1.1% and only in Hungary. In the 12p/kWh case the income from incentives is 3 times the amount. Therefore, tripling the income from incentives, increases the market share by a factor of 28. Under high capital cost assumptions, only when the premium increases to 18 p/kWh. In this case the market share is 1.6% in Denmark and Italy. Under the existing incentive scheme, at high capital cost, the market share is 0.6% in Hungary.

4.4. The Impact of Business Models

Innovations in business model have the potential to accelerate adoption of technologies. The incumbent business model is one in which the end-user pays upfront for the technology, with this, the market share of the biogas-SOFC is zero (Figure 23 and 24). A new business model is investigated and quantified in WP6. In the new business model, we explore the potential in ploughing back operational savings from integrating a more-efficient SOFC. The operational savings is the difference between the energy costs when the SOFC is integrated and the energy costs without the SOFC. The energy costs id dominated by the residual heat and electricity demand not met by the SOFC – this includes any residual electricity from the grid, and any residual heat from a natural gas boiler. In some plants, depending on the biogas availability, this difference is positive. Due to a higher efficiency of the SOFC, the energy cost associated with integrating it are also lower than the ICE. When a plant decides to plough back operational savings from using a more efficient technology, it has potential to reduce the capital investment in the technology. Ploughing back operational savings reduces the capital investment and this in turn has potential to reduce the CO2 abatement cost (methodology explained in section 2.5). this can be illustrated as: if the energy costs associated with a BAU system is 4,000 Euro/y, and the energy costs associated with integration SOFC is 2,300 Euro/y, the savings is 1,700 Euro/y. A new business model can be created to support ploughing back this savings to offset the capital investment. If end-users agree to plough back the savings, a technology manufacturer can decide to reduce the capital cost with the ploughed back operational savings. The impact is quantified using the CO2 mitigation cost. The method to estimate the CO2 mitigation cost is presented in Section 2.5. if a new business model is implemented, the ploughed back operational savings is subtracted from the numerator (as explained in Section 2.5).

The CO2 mitigation cost based on the incumbent business model is presented in Figure 28 (Left hand side). By ploughing back operational savings from using a more efficient SOFC, the cost associated with CO2 reduction reduces as shown in Figure 23 (left hand side).

Ploughing back operational savings from integration a more efficient biogas-SOFC reduces the abatement cost for the S and M archetype (Figure 23).

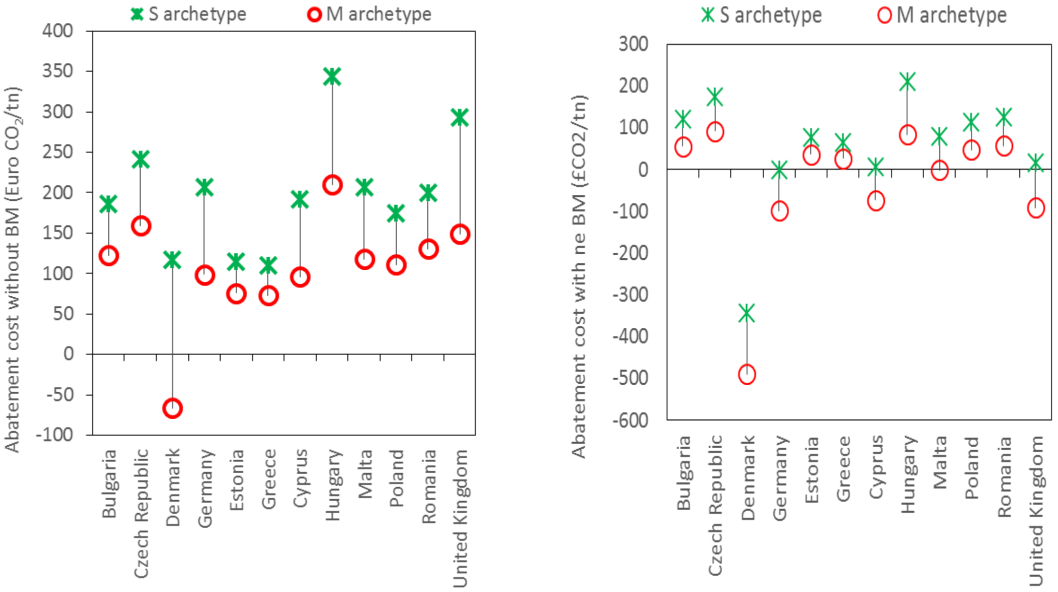


Figure 23 Business as usual abatement cost and abatement cost with new business model implemented

5. Conclusions and Future Work

Biogas exploitation reduces the need for carbon laden energy sources like NG and grid electricity in WWTP. Most importantly by producing biogas from sludge, more value is added to liquid waste. The challenge is deciding the right combination of technology and systems to exploit the biogas. The quantified market share is relevant for assessing cost reduction based on manufacturing volumes. The financial viability of biogas projects can be improved if policy frameworks are amended to increase the market share of exploitation paths as part of the renewable programme. The method developed in WP6 (Task 1) can aid policy makers in the decision process for biogas use.

Key insights from this work are presented below:

- Price instruments should be technology-specific whilst quantity instruments can be technology-agnostic
- An attractive legal framework is needed to support the biogas sector and the policy chosen by each country is decisive for the growth of the sector.
- Simultaneous innovation in policy and business models is required to increase the market share of SOFC
- SOFC is economically viable when costs are less than 4,560 €/kWh
- Attractive markets do not require significant cost reductions
- Transitions to a low-carbon future can be driven by market forces.

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7. Appendix

The optimisation model applied is presented in Section 7.1. A detailed description is available in Giarola et al., 2018. An output from this analysis is a narrative for the SOFC for three stakeholder – policy makers in Section 7.2, technology manufacturers in Section 7.2 and end-users in Section 7.4.

7.1. Optimisation Model

A more specific definition of the design problem is:

- Given:
    - The heat and electricity demands of the WWTP archetypes (XS '20,000-60,000 P.E.', S '60,001-150,000 P.E.', M '150,001-350,000 P.E.', L '350,001-750,000 P.E.', XL '750,000-1,100,000 P.E.').
    - The energy demands are provided in 1 hour time slices for all the days in a year.
    - The biogas produced from all WWTP archetypes.
    - Energy prices (electricity and fuel) for all archetypes, electricity tariff structure, technology capital costs for the SOFC, ICE and upgrade option.
    - The number of WWTPs in the countries considered. This is used to determine the market size.
- Determine:
    - Optimal base case energy system design of a biogas boiler satisfying the heat demand, backed-up by a natural gas boiler, with electricity import from the grid. The base case energy system is determined for all archetypes, taking into account their locations.
    - Optimal energy system design for other options integrated to exploit biogas produced.
    - Energy system dispatch strategy and biogas contribution to the plant's energy demands.
    - The economically viable biogas exploitation option for each WWTPs in each country from a model based techno-economic assessment of individual plants, and analysis of plants in a market (where the market is defined in a country-context).
- Subject to:
    - Energy (both heat and electricity) balances
    - Technology capacity constraints
    - Biogas availability
- In order to:
    - Minimise the equivalent annual cost of meeting a WWTPs energy demand

  - Determine the market uptake of technologies to exploit biogas under different scenarios

The optimisation framework is necessary to select the best technology and system to exploit biogas. Hence it is formulated as a multi-period MILP problem in GAMS. The optimisation forms the basis for the economic assessment which involves the techno-economic assessment for a plant, and assessment for all plants in a country. The objective in Eq(1) is formulated to minimise the Equivalent Annual Cost (EAC) defined as the sum of the Annualised Capital Cost (ACC), the fuel costs (FC) and maintenance costs (MC) and the cost associated with grid electricity import (CW^{Grid}).

$$Min: [ACC + FC + MC + CW^{GRID}] \tag{1}$$

The ACC is defined in Eq(2). Where Size is the technology size, Z is binary variable for technology selection, and IC is the installed capital, and *i* represents the set of all technologies.

$$ACC = AF \times \sum_{i} \left(\left(Size_i \times Z^i\right) + (IC_i)\right) \tag{2}$$

Constraints include the balance around biogas flow (B) in Eq(3), heat (Q) in Eq(4) and electricity (W) in Eq(5). The biogas can be kept in a holder. Where BD and BS are biogas wasted due to shut down and start-up events respectively, BOI is boiler, and *t* represents the time period. BBOI and NGBOI are biogas and NG boilers, PSD and PSU are power absorbed during shut down and start-up events.

$$\text{GasHolder}_{t+1} - GasHolder_t + Bflare_t + BGD_t + BGS_t + B_t^{SOFC} + B_t^{ICE} + B_t^{Upgrade} + B_t^{BOI} = 0 \tag{3}$$

$$Q_t^{SOFC} + Q_t^{ICE} + Q_t^{BBOI} + Q_t^{NGBOI} - Q_t^{DEMAND} = 0 \qquad \forall\, \mathrm{t} \in \mathrm{T} \tag{4}$$

$$W_t^{SOFC} + W_t^{ICE} + W_t^{GRID} + PSD_t + PSU_t - W_t^{DEMAND} = 0 \qquad \forall\, \mathrm{t} \in \mathrm{T} \tag{5}$$

Ramping constraints, and biogas and electricity consumption for start-up and shut-down events are provided below: r_{up} is the ramp rate of the CHP technologies. Where Y is the binary variable for operation, and τ the maximum number of hours in any time period *t*

$$W_t^i + W_{t-1}^i \le r_{up}^i \times \tau \tag{6}$$

$$PSD_t^i \ge PSD_{abs}^i \times \tau \times Y_t^i \tag{7}$$

$$PSU_t^i \ge PSU_{abs}^i \times \tau \times Y_t^i \tag{8}$$

$$BD_t^i \ge BD_{abs}^i \times \tau \times Y_t^i \tag{9}$$

$$BS_t^i \ge BS_{abs}^i \times \tau \times Y_t^i \tag{10}$$

Eq(11) is formulated to choose the technology and determine the electricity produced. Eq(12) states that technology can be selected but may not operate in a time period.

$$W_t^i - size_i \times Y_t^i \leq 0 \tag{11}$$

$$Z^i - Y_t^i \geq 0 \tag{12}$$

The optimisation framework is applied to every WWTP archetype in the five countries selected. The computational time is 1.2 s using Cplex solver in GAMS on an Intel(R) core(TM) i7-6700 CPU.

7.2. Narrative for policy makers

Are today's price instruments sufficient to commercialise biogas fuelled Solid Oxide Fuel Cells?

Solid oxide fuel cells keep at zero the environmental impact (NOx, SOx and particulates emissions) of on-site power generation from biogas – as measured as part of the DEMOSOFC plant in Collegno (Italy) [6]. If biogas produced from anaerobic digestion of sludge from wastewater treatment is supplied as fuel to solid oxide fuel cell, the electricity generated can displace two times more carbon dioxide than competitive technology like internal combustion engines. Solid oxide fuel cells can also produce more electric energy from one unit of input energy than conventional technologies such as internal combustion engines and micro-turbines, because of their higher electrical efficiency (50-60% vs. 30-40%). Therefore, installing the solid oxide fuel cells results in higher savings in energy costs for the plant owner. From the DEMOSOFC project case study, the installation of the full power solid oxide fuel cell system led to an annual saving of around 250'000 € in the electricity bill (with an average electricity price of 16 €cent/kWh[7]).

The cost of solid oxide fuel cells, in the present situation of European manufacturers, seems a major barrier for further development of biogas fuelled SOFC systems: with today's cost of the technology, the market share of the solid oxide fuel cell is zero i.e. not competitive. Today, 71% cost reduction is required for a 58 kW solid oxide fuel cell to be economically viable. Nevertheless, the reduction in environmental impact of plants and the higher energy efficiency form strong evidence to support policies for integrating biogas fuelled solid oxide fuel cells, in order to pave the way for a larger deployment of the technology and a consequent reduction of their costs. The support policy adopted in South Korea (FCs considered in the same support segment of renewable sources) has determined a huge increase of installations of plant in the Country, and a consequent reduction of their cost.

Existing policies that can be exploited to increase the market share of solid oxide fuel cells are the Feed in Tariff offered in Austria, Croatia, France, Hungary, Italy, Luxembourg, Poland, Portugal, Slovakia and the United Kingdom, quota system in Belgium, Romania and United Kingdom, and Feed in Premium in Denmark, Estonia, Finland, France, Hungary, Lithuania, Netherlands, Poland, and United Kingdom.

The analysis of the impact of policies on today's market share of the solid oxide fuel cell shows that only the income from the Feed in Tariff offered in Hungary, 4.2 – 11.52 €c/kWh (currently runs for 25 years) is able to offset the total cost in a plant by 9 – 13%. The resulting demand for the fuel cells and associated manufacturing volumes can reduce capital cost by 13 – 38%. However, even with this, the technology is still not economically viable. Therefore, new policy instruments are required.

A higher cost reduction (about 30 – 53%) is possible if the value of the price instruments increases by 1.5 times for a shorter duration. Today's policies are not enough to trigger the market.

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[6] http://www.demosofc.eu/wp-content/uploads/2017/10/D4.3.pdf

[7] http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

7.3. Narrative for technology manufacturers

The incumbent business model is not enough to accelerate adoption of SOFC

Solid oxide fuel cells keep at zero the environmental impact (NOx, SOx and particulates emissions) of on-site power generation – as measured as part of the DEMOSOFC plant in Collegno . If biogas produced from anaerobic digestion of sludge from wastewater treatment is supplied as fuel to solid oxide fuel cells, the electricity generated can displace two times more carbon dioxide than competitive technology like internal combustion engines. Solid oxide fuel cells can also produce more electric energy from one unit of input energy than conventional technologies such as internal combustion engines and micro-turbines. Therefore, installing the solid oxide fuel cells results in higher savings in energy costs. From the DEMOSOFC project case study, the installation of the full power solid oxide fuel cell system led to an annual saving of around 250’000 € in the electricity bill (with an average electricity price of 16 €cent/kWh).

The cost of solid oxide fuel cells seems a major barrier for further development of biogas fuelled systems, with today’s cost, the market share of the solid oxide fuel cell is zero i.e. not competitive. Today, 71% cost reduction is required for a 58 kW solid oxide fuel cell to be economically viable and be competitive enough to occupy a share of the WWTP market. With the incumbent business model i.e. pay upfront for the technology, the market share of biogas SOFC in all 6,181 plants considered is 0. A new business model –where the end-user does not need to pay upfront for the technology, can increase the market share to 4%, implying more plants become economically viable. Cost reduction of 47% is possible with the associated demand for the SOFC. Countries with suitable markets for the new business model are Denmark and Italy. A further cost reduction is possible as with the new CAPEX, the impact of the business model makes plants located in Denmark, Germany, Italy, Cyprus, Sweden and the UK – the associated market share is 22.14%. This market share is sufficient to reduce the module CAPEX to 4,560 €/kW, at which point the SOFC is economically viable. A new business model that supports plant owners ploughing back savings in operational costs from using a more efficient technology also has similar potential. In recent times, considerable attention is given to business model innovations are a strategy to increase adoption of cleaner technology.

7.4. Narrative for end-users (WWTP owners)

Ploughing back operational savings from a more efficient technology could reduce its carbon dioxide mitigation cost

Solid oxide fuel cells keep at zero the environmental impact (NOx, SOx and particulates emissions) of on-site power generation – as measured as part of the DEMOSOFC plant in Collegno . If biogas produced from anaerobic digestion of sludge from wastewater treatment is supplied as fuel to solid oxide fuel cell, the electricity generated can displace two times more carbon dioxide than competitive technology like internal combustion engines. Solid oxide fuel cells can also produce more electric energy from one unit of input energy than conventional technologies such as internal combustion engines and micro-turbines. Therefore, installing solid oxide fuel cells results in higher savings in energy costs. From the DEMOSOFC project case study, the installation of the full power solid oxide fuel cell system led to an annual saving of around 250’000 € in the electricity bill (with an average electricity price of 16 €cent/kWh).

The cost of solid oxide fuel cells seems a major barrier for further development of biogas fuelled systems, with today’s cost, the market share of the solid oxide fuel cell is zero i.e. not competitive. The abatement cost for the SOFC ranges from -66 to 580 € per ton CO2 depending on market conditions. An effective way to reduce cost is to plough back operational savings from using a more efficient SOFC. The percentage of the operating cost that can be saved on average for the SOFC in the 1685 plants in Italy is 17%, 97 plants in Greece if 15%, 1415 plants in Germany is 18%, 756 plants on France is 10.21%, and 611 plants in the UK is 20.2%. The savings reflect the market conditions in each country i.e. natural gas and electricity prices. Ploughing back operational savings to offset capital investment in the SOFC reduces the abatement cost to -300 to 406 € per ton CO2 and could make the SOFC competitive with the combustion engines.

7.5. General Narrative

Diffusion of Solid Oxide Fuel Cells (SOFC) in EU Wastewater Treatment Plants (WWTP)

SOFCs are modular, low-emission, vibration free and silent devices that offer high (55–60%) electrical efficiency with reduced CO_2 emissions, near-zero pollutants emissions (NOx, SOx, VOC, PM) and high temperature residual heat, which can improve biogas production through thermal pre-treatment of the substrate for anaerobic digestion. Thanks to the highest electrical efficiency among the competitors, SOFC can produce more electric energy from one unit of input energy than conventional technologies (Internal Combustion Engines - ICE - and micro-turbines).

The DEMOSOFC project involves the integration of an SOFC system to exploit biogas from a Wastewater Treatment Plant (WWTP) treating around 180’000 Population Equivalent (P.E.), like the Collegno plant. SOFC integration into the plant leads to a coverage of around 22% of electrical load and 26% of thermal load, based on the current biogas specific productivity (10 litres biogas/P.E./day) and could be increased by optimizing the entire WWTP process. The coverage by the SOFC results in operational savings since the electricity produced would be otherwise bought from the national grid. For the DEMOSOFC case study, the installation of the full power (174 kW) SOFC system would lead to an annual saving equal to around 250’000 € in the electricity bill (with an average electricity price of 16 €cent/kWh). The SOFC plant keeps at zero the environmental impact (NOx, SOx and particulates emissions, as measured on site at the DEMOSOFC plant in Collegno).

SOFC could play a fundamental role in the transition of WWTP from high to low energy intensive systems, or even prosumers. There are 6,181 WWTPs in the EU-28, with secondary treatment in the range of Population Equivalent P.E. 20,000 – 1,100,000. The estimated total biogas produced is 9,995 GWh/y (based on 10 litres biogas/P.E./day). The electricity generated from biogas can displace 3 Million tonnes of CO2 per year, compared to the ICE that can only displace 1.4 Million tonnes of CO2 per year. These benefits make the SOFC a potential replacement for the ICE.

The cost of SOFC seems a major barrier for further development of biogas fuelled SOFC systems. Based on new manufacturing techniques, material investigations, favourable market sizes and incentives, the SOFC costs are expected to come down to some extent in the near future. Possible cost projections based on manufacturing volumes are provided in the table below. The manufacturing volumes represents the cumulative production per company. If all 6,181 WWTP’s install SOFCs, the market demand will be 13,280 units for 58 kW cells, and if all WWTP install the SOFC (i.e. 100% installation rate), the target cost projection could be reached today. The installation rate is the ratio of manufacturing volumes to the SOFC market demand. The installation rates calculated in the below table are based on an ideal market demand of 13,280 units and it changes depending on the market size.

	Very High	**High**	**Medium**	**Low**	**Short term**	**Target**
Module CAPEX projections (€/kW)	> 15,700	8,300 – 15,700	4,560 – 8,300	3,350 – 4,560	2,080 – 3,350	< 2,080
Manufacturing Volumes	1	1 - 100	100 - 780	780 - 1000	1000 - 10000	> 10000
EU wide installation rate for cost reduction	< 0.01	0.01 –0.8 %	0.8 – 6%	6 – 8%	8 – 75%	>75%

An analysis was conducted to establish pathways to increase market uptake of biogas fuelled SOFCs. Results indicate that the SOFC becomes competitive when the module CAPEX is less than 4,560 €/kW using existing energy prices in the EU. Therefore, the challenge is generating enough market interest (in terms of demand) to drive down costs to 4,560 €/kW.

A market can be created today under very high cost projections using already existing incentives in some EU member states and innovations in Business Model (BM). An innovative BM is product sale and service with finance. Specifically, the end-user ploughs back the savings in operational expenses (from installing the SOFC) on an annual basis for the lifetime of the technology. A discount rate of 9% is applied to make this BM attractive to financers. The pathways to create favourable market sizes that would drive down costs are explained below:

Pathways from Very High CAPEX projections to 8,303 €/kW: Today's incentive in Hungary – Feed in Tariff (4.2 – 11.52 €c/kW currently runs for 25 years), generates a market demand that can bring down the module CAPEX to 13,600 €/kW (based on 35% installation rate in Hungary), and 9,700 €/kW based on 100% installation rate (i.e. manufacturing volumes are the same as the market demand). The new business model offered under very high CAPEX projection makes the market in Denmark and Italy favourable. This can reduce module CAPEX to 8,300 €/kW based on 45% installation rate in both countries, and 7,650 €/kW based on 100% installation rate. Combining impact of incentives in Hungary and business models in Denmark and Italy reduces the CAPEX to 8,300 €/kW based on a lower installation rate (33%) in these countries, and 7,200 €/kW based on 100% installation rate.

Pathway from 8,303 €/kW to 4,560 €/kW module CAPEX: when cost reduce to 8,303 €/kW, the incentive in Belgium – green certificates under the quota system, creates a favourable market. The impact is a reduction in module CAPEX to 8170 €/kW at a 35% installation rate in Belgium, and 7,920 €/kW at 100% installation rate. If the remaining of the market in Hungary, Denmark and Italy also install the SOFC – the cost falls to 4,560 €/kW at 62% installation rate. Incentives in other countries only have an impact when capital costs are low.

Accelerated pathways from 8,303 €/kW to 4,560 €/kW module CAPEX: there are two ways to reduce module CAPEX at a lower installation rate: (1) Increasing the value of today's incentives by 1.5 for a shorter duration – the same total contribution is made from incentives, and (2) offering a lower discount rate to accelerate adoption of the new business model. By combining the two, higher incentives offered for 10 years in Hungary and Belgium, together with the impact of business models adopted in Denmark, Italy, Germany, Cyprus, Sweden and the UK can generate market demand to drive costs down to 4,560 €/kW based on 18% installation rate, with 100% installation rate costs reduce to 2,860 €/kW.

Overall, exploiting today's incentives without the need to create a new policy, and offering a different way to pay for the SOFC can increase market uptake. Taken together, these analysis indicates that transitions to a low-carbon future can be driven by market forces. Market forces can drive clean-energy industry going forward.