Reducing Mitigation costs of Biogas Fuelled Solid Oxide Fuel Cells: An impact of new business models

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ABSTRACT

The high cost of the SOFC makes it difficult to achieve win-win between emission reduction and economic benefits. Most studies neglect the CO_2 abatement costs associated with cleaner technologies, and studies on abatement costs focus on a global perspective, neglecting technology-specific abatement costs. The SOFC abatement cost can be reduced with innovations in business models. In this work a novel enviro-economic framework whose basis is a detailed optimisation of a plant is developed and applied to quantify 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 CO_2 abatement cost of biogas fuelled SOFC systems. Case studies show the new business models reduces the abatement cost from 122 to 56 € per ton in Bulgaria, 160 to 92 € per ton in Czech Republic, and 150 to -90 € per ton in the UK.

KEYWORDS

Carbon dioxide abatement cost, business model, sewage biogas, Solid Oxide Fuel Cell, wastewater treatment plants, enviro-economic assessment.

INTRODUCTION

Background

Biogas generated through anaerobic digestion (AD) of sewage sludge addresses environmental concerns together with increasing the share of green energy to mitigate greenhouse gas (GHG) emissions. Biogas fuelled technologies like high-efficient Solid Oxide Fuel Cells (SOFC) ensure heat and electricity is produced with low carbon dioxide emissions and no particulates. However, the cost of SOFC is a major barrier for further development and adoption of biogas fuelled SOFC systems in wastewater treatment plants (WWTP). Biogas production from organic waste plays an important part in both circular economy and bioeconomy [1]. Europe leads the world on biogas exploitation and within Europe, Germany is leading with regard to biogas generation [2]. The advantage of biogas from sewage is that the issue of land use with energy crops is not a disadvantage, and this supports a circular economy. The abatement cost of CO_2 when biogas is exploited depends on the technology. Research on the abatement cost of CO_2 emissions not only provides a basis for making energy saving and emission reduction policies worldwide but also provides a certain reference value for establishing a global carbon emissions trading market in the future. The average marginal abatement cost of CO_2 emissions for China's thermal power sector is 42 Euro/ton [3] and the average CO_2 marginal abatement cost of the world is 640 Euro/ton [4]. Both values are far

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higher than carbon price in the current emission trading system pilots, implying that carbon price does not inflect supply and demand of carbon allowance. Therefore, innovative schemes need to be exploited to reduce the abatement cost, to encourage uptake of clean technology. Additionally, the abatement cost of CO_2 emissions for WWTP's using biogas as fuel to provide heat and electricity in highly efficient SOFC systems is yet to be quantified. The incumbent business models in most plants supports upfront payment for a technology, resulting in an estimation of the payback and net present value to determine if the technology is economically viable [5]. Innovations in business models could accelerate technology adoption by reducing the CO_2 abatement cost. The existing subsidies for biogas exploitation are not enough to trigger cost reduction [6]; therefore, new business models are required. Successful market penetration may not only rely on the characteristics of the technology but also on the business models available on the market [7]. The impact of new business models on reducing the abatement cost of biogas fuelled SOFC is yet to be quantified. The paper shows how to achieve win-win between economic benefits and emission reduction by exploiting new business models. This paper also assesses the economic suitability of biogas fuelled SOFC for reducing emissions in the WWTP sector.

Literature Review

Previous studies on sewage biogas exploitation focus on increasing the performance of the anaerobic digestion process [8], identification of optimal process conditions to improve the operation of fluidized bed bioreactors [9], developing numerical models to improve performance assessment of SOFC systems [10], thermodynamic performance investigation of fuel cells [11], and development of a thermodynamic simulation model for performance of biogas fuelled combined heat and power (CHP) engines [12]. Whilst research has been conducted to determine the energy, environmental, and economic impacts of integration of biogas fuelled CHP systems and solar energy to increase a plant's self-sufficiency [13], the CO_2 abatement cost associated with biogas fuelled CHP technologies is yet to be quantified, and strategies to reduce the abatement cost is yet to be evaluated.

A lot of focus on abatement cost reduction has been for the power sector [3]. Several studies focus on determining the abatement cost of CO_2 neglecting options to reduce the abatement cost for the same technology. For example, Oliveira et al. [14] compares different top-down econometric models that estimate the amount of carbon abated due to renewable energy. Their focus was on the electricity grids in Britain, French and Spain. Wang et al. [15] applies the directional distance function to measure the abatement cost on a regional basis. Liu and Feng, [4] adopt a gravity model to obtain an overview of the global flows of CO_2 emissions and energy consumption since the beginning of the 21st century. They sampled the data of 41 regions (including 165 countries) from 2000 to 2014. Gillingham and Stock [16] reviewed the cost of various interventions that reduce greenhouse gas emissions, neglecting interventions within the process industry. Van den Bergh and Delarue [17] presents a bottom-up technology focused methodology to deepen the insight in the relation between a CO_2 cost and CO_2 abatement. Again, the focus is the power sector. The range of costs of these interventions in the power sector is extremely wide, from less than $10 per ton to over $1000 per ton. There is a lack of technology specific abatement cost analysis for biogas exploitation in WWTP in the literature.

Patteeuw et al. [18] determined the CO_2 abatement cost of residential heat pumps considering the effects on the electricity-generation system. A detailed integrated model of buildings, heating systems and the electricity-generation system is employed. Their results show that the abatement cost is sensitive to assumptions on economical parameters, as illustrated by the

difference in results due to a different discount rate. In Rehl and Muller [19] the most economical use of biogas using anaerobic digestion was identified by analysing different energy conversion technology to identify the most cost-efficient way of reducing GHG emissions based on the abatement costs. A system based on combined heat and power station was found to be the most cost-efficient biogas technology for reducing GHG emissions. However, there is no specificity as to the type of CHP system, and pathways were not explored to reduce the abatement cost of a technology. Accurately estimating CO_2 abatement costs would require data from a detailed optimisation of a plant. The method in this paper applies the multi-period Mixed Integer Linear Program (MILP) model for dispatch and operation of the SOFC in WWTP developed on Oluleye et al. [20]. The optimal energy flows are determined using [20] and applied as input into the novel enviro-economic model proposed to estimate the abatement cost. Effectively identifying the factors impacting those costs, can improve the applicability and effectiveness of policy implementation. The work presented in this paper would show how innovations in business models can minimize the cost of mitigation today, the actions taken today can influence future costs.

Contributions of this work

A novel enviro-economic framework is proposed to determine the mitigation cost of biogas fuelled SOFC and quantify the impact of a new business model on reducing the mitigation cost. The new business model will exploit the operational benefits of a more efficient clean technology. An added value of this work is that the novel framework builds on a detailed optimisation of the plant and uses real data from a demonstration of the SOFC in WWTP [21]. The novel framework is the first of its kind to quantify the impact of business models on reducing the mitigation cost of biogas fuelled SOFC. The abatement cost of new technologies is very high [4]; however, this changes per country depending on the market factors i.e. gas and electricity prices, and changes depending on the size of the WWTP. In this work, the novel framework is applied to WWTP with population equivalent (P.E.) between 60,000 and 350,000 in twelve European countries. The focus is on actual abatement costs (euros per ton of carbon dioxide avoided/reduced).

METHODS

A description of the system under consideration is provided below, and a schematic in Fig. 1. The CO_2 abatement cost is the sum of the difference in annual operating costs of the system and the annuity of the additional investment divided by the annual CO_2 emission reduction, also provided below.

System Description and Design

The system being considered is a biogas fuelled SOFC system using biogas from anaerobic digestion of sewage (Fig. 1). The production of biogas is not within the scope of this work, the focus is on the use of biogas to generate heat and electricity for the plant. The business as usual system (BAU) consists of a biogas boiler for heating provision and electricity import from the grid (Fig. 1). A natural gas boiler is available as a back-up system when biogas production is low. The multi-period mixed integer linear optimisation framework in [20] is applied to determine the optimum operating conditions of the system.

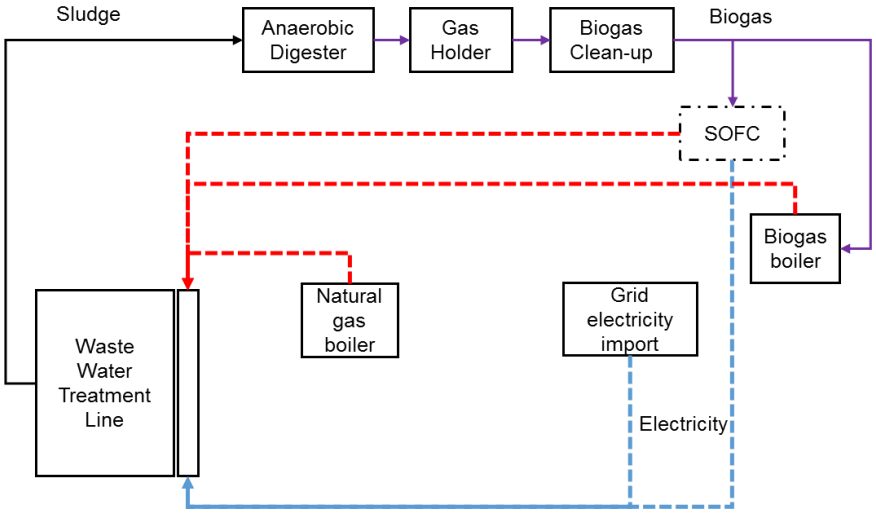


Figure 1. Energy system schematic showing the business as usual (BAU) system, and the SOFC. Red broken lines represent the flow of heat, blue broken lines the flow of electricity, and purple lines flow of biogas.

Enviro-Economic Framework

The enviro-economic framework uses the abatement cost to assess integration of biogas fuelled SOFC in WWTP's and quantifies the impact of a new business model in reducing the abatement cost. The Abatement cost is calculated by considering the costs of the new energy system with the SOFC to be established in Euro (€) and the associated CO_2 emissions in tonne (t) to a business as usual scenario (Eq. 1).

$$CA_{CO_2} = \frac{TAC_{SOFC} - TAC_{BAU}}{E_{BAU} - E_{SOFC}} \quad (1)$$

A negative abatement cost CA_{CO2} implies the total annualised cost of the business as usual system (TAC_{BAU}) is greater than the total annualised cost of the system when the SOFC is integrated (TAC_{SOFC}). A negative abatement cost is often desired. A positive abatement cost implies CO_2 emission reduction comes at an added cost to the plant. In most cases, the adoption of options with a positive abatement cost is zero [12]. The TAC_{SOFC} is dominated by the capital and operating cost (Eq. (2)). the capital cost of the SOFC, CC_{SOFC} is calculated in Eq. (3) – considering a factor for balance of plant, F^{BOP}, gas clean-up cost and stack replacement cost are also included. The optimum number of units N^{Units}_{SOFC} is determined using the optimisation framework in Oluleye et al. [20]. The annualisation factor is presented in Eq. (4).

$$TAC_{SOFC} = (CC_{SOFC} \times AF) + (OC_{SOFC}) \quad (2)$$

$$CC_{SOFC} = \left[\left(IC_{SOFC} \times F^{BOP}\right) + \left(C_{gas\ clean-up}\right) + \left(C_{stack\ replacement}\right)\right] \times Size_{SOFC} \times N_{SOFC}^{units} \quad (3)$$

$$AF = \frac{DR \times (1+DR)^n}{(1+DR)^n - 1} \quad (4)$$

The operating cost for an SOFC based system, OC_{SOFC} is dominated by the residual electricity imported from the grid, and residual heat satisfied by a natural gas boiler when the heat and electricity produced from the biogas fuelled SOFC is not enough to satisfy the plant's energy demand.

$$OC_{SOFC} = \left(\Delta W_{SOFC}^{grid} \times GEP\right) + \left(\Delta Q_{SOFC}^{NG} \times NGP\right) + MC_{SOFC} \quad (5)$$

The total annualised cost of the business as usual system (TAC_{BAU}) in Eq. (6) is dominated by the operating cost since the BAU system already exists i.e. capital already incurred. In the BAU system, all the plant's demand for electricity is provided from the grid.

$$TAC_{BAU} = \left(W_{BAU}^{grid} \times GEP\right) + \left(\Delta Q_{BAU}^{NG} \times NGP\right) \quad (6)$$

CO_2 emissions from the BAU system and the SOFC is presented in Eq. (7) and (8) respectively. The emissions from biogas fuelled SOFC system is the sum of emissions from residual electricity imported from the grid, and residual heat from the natural gas boiler when the heat and electricity produced from the SOFC is insufficient to meet the plant's energy demands.

$$E_{BAU} = \left(W_{BAU}^{grid} \times GEF\right) + \left(\Delta Q_{BAU}^{NG} \times NGEF\right) \quad (7)$$

$$E_{SOFC} = \left(\Delta W_{SOFC}^{grid} \times GEF\right) + \left(\Delta Q_{SOFC}^{NG} \times NGEF\right) \quad (8)$$

Using a biogas fuelled SOFC system reduces the residual heat and electricity compared to the BAU system. The efficiency of the SOFC is also higher than the BAU system [20, 21]. Quantifying the impact of a new business model in reducing the CO_2 abatement cost (Eq. (1)) is presented below.

Impact of business models

The benefits of a more efficient technology are the reduction in operating costs since more units of heat and electricity are produced, thereby reducing reliance on the back-up systems. The incumbent business model in most plants supports product sale and service without finance i.e. upfront payment for a technology. Most technologies that can deliver steep reduction in CO_2 emissions have a high abatement cost, hence the incumbent business model may delay uptake of new cleaner technologies. The hypothesis in this paper is a new business model could increase uptake of new technologies by reducing the CO_2 abatement cost. The new business model explored supports product sale and service with finance, specifically allowing the savings in operating cost when a more efficient technology is integrated to be ploughed back to offset the capital investment. Implementing it means, the end-user ploughs back the savings in order to offset some of the capital investment. The difference in operating cost from a highly efficient system is shown in Eq. (9) and the impact on the CO_2 abatement cost in Eq. (10).

$$\Delta OC = (OC_{SOFC}) - (OC_{BAU}) \quad (9)$$

$$CA^{BM}{}_{CO_2} = \frac{TAC_{SOFC} - \Delta OC - TAC_{BAU}}{E_{BAU} - E_{SOFC}} \quad (10)$$

The condition to implement the new business model is that ΔOC is greater than 0. The technology manufacturer can offer this new business model to end-users. The impact is assessed using a case study approach.

CASE STUDY

The case study considers WWTP's with Population Equivalent between 60,000 to 350,000 in twelve European countries. Design inputs and results are presented below.

Design Inputs

The annual biogas produced and energy demand from the plants considered are shown in Table 1. A plant whose P.E. is between 60,000 and 150,000 is categorised as a Small (S)

archetype, and a plant whose P.E. is between 150,000 and 350,00 categorised as a Medium (M) archetype (Table 1). The economic characteristic of the SOFC system is presented in Table 2.

Table 1. WWTP archetype, P.E., number of plants, biogas produced, energy demand and CHP units installed.

Population Equivalent (P.E.)	WWTP category	Total biogas (GWh/y)	Total heat demand (GWh/y)	Total electricity demand (GWh/y)	Number of units (CHP size is 58kW)
60,000-150,000	Small	0.205	0.055	0.109	2
150,000-350,000	Medium	0.430	0.088	0.173	3

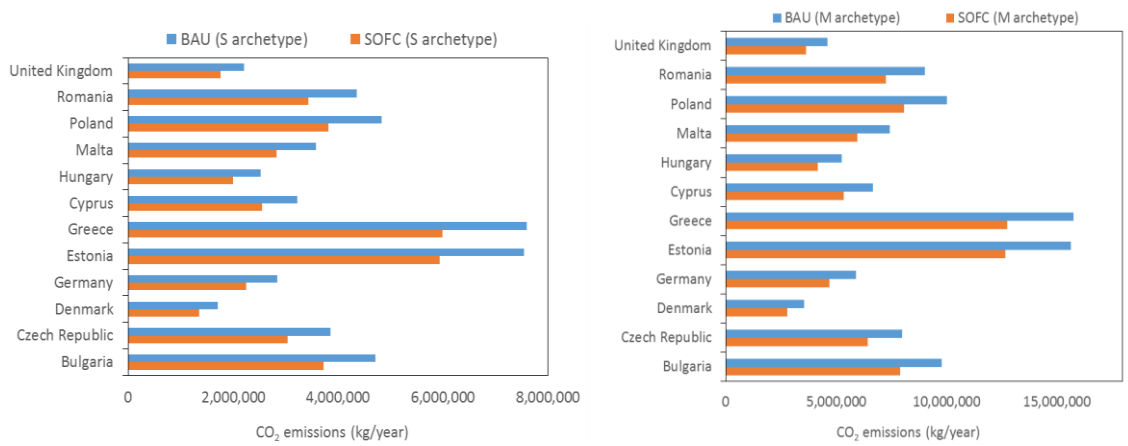
Table 2. Economic characteristics of the SOFC [20–22]

SOFC	Unit	Low – Very high
Stack lifetime	year	3-3-4-4
Module CAPEX	€/kW	15,700
Stack replacement	€/kW	1,223
Maintenance	€/kW-year	72
Gas clean-up CAPEX	€/kW	917
Gas clean-up OPEX	€/kW-year	76

The factor for the balance of plant is 1.5 [20]. The market conditions i.e. natural gas and electricity price for the twelve countries considered are obtained from [23] and [24] respectively. The natural gas and grid emissions factors for all twelve countries are obtained from [25]. The energy prices depend on the size of the plant, and energy demands, and the data was extracted for 2018/2019.

Results and discussion

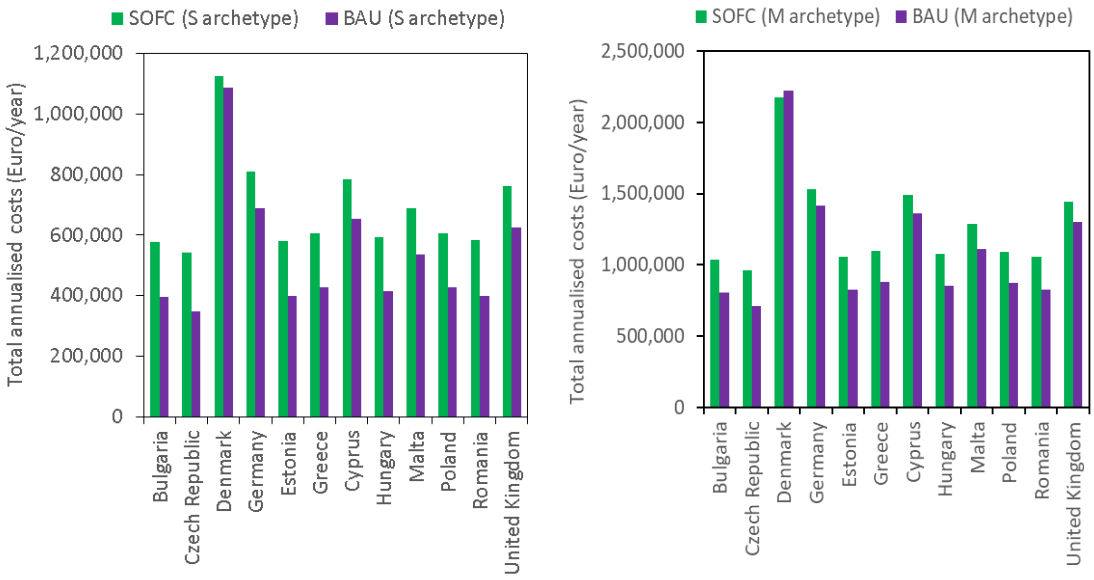
The CO_2 emissions calculated using Eqs (7) and (8) for the Small (S) and medium (M) archetype in all 12 countries are presented in Fig. 3. Countries with a high share of renewable electricity like Germany, Denmark, the UK have a lower grid emission factor and lower CO_2 emissions (Fig. 3 (a) and (b)). In all plants and archetype, the BAU CO_2 emissions is greater than CO_2 emissions from a biogas fuelled SOFC system (Fig. 3). CO_2 emissions from the M archetype (Fig. 3b) is greater than the S archetype due to the higher energy demands (Table 1).



(a) (b)

Figure 3. Emissions from the WWTP's in all countries considered. (a) emissions from the small (S) archetype, (b) emissions from the medium (M) archetype

Results of the total annualised cost using Eqs. (2) and (6) are presented in Figs. 4(a) and (b) for the WWTP's archetype in all 12 countries. For similar energy demand based on the archetype there is a wide disparity in cost in all countries due to the different market factors i.e. gas end electricity prices. The cost associated with the BAU system for the S archetype in all countries is less than the SOFC cost (Fig. 4a) resulting in a positive CO_2 abatement cost (Fig. 5). The cost of the BAU system for the medium archetype is lower than the SOFC based system except in Denmark (Fig. 4(b)), hence all countries have a positive CO_2 abatement cost except Denmark. Denmark has a large spark spread i.e. difference between the electricity and gas price, thereby favouring combined heat and power generation. Therefore, today the market condition in Denmark favour biogas fuelled SOFC systems.



(a) (b)

Figure 4. Output from economic assessment of all plants on a country basis. (a) assessment results for the small (S) archetype, (b) assessment results for the medium (M) archetype

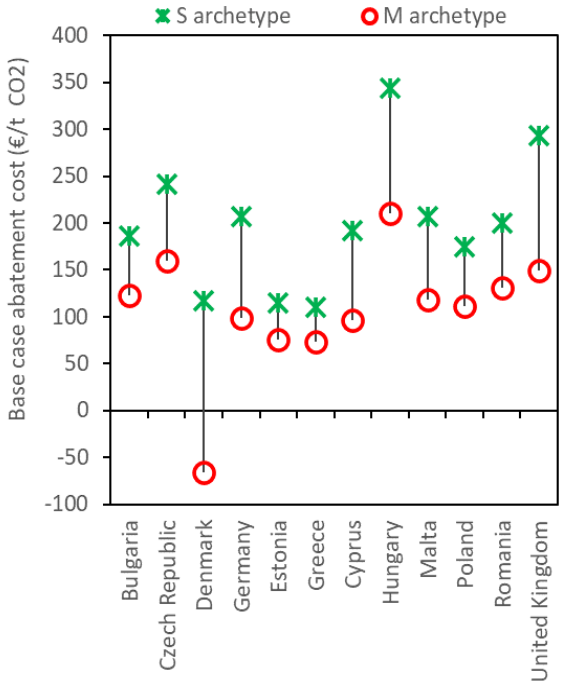
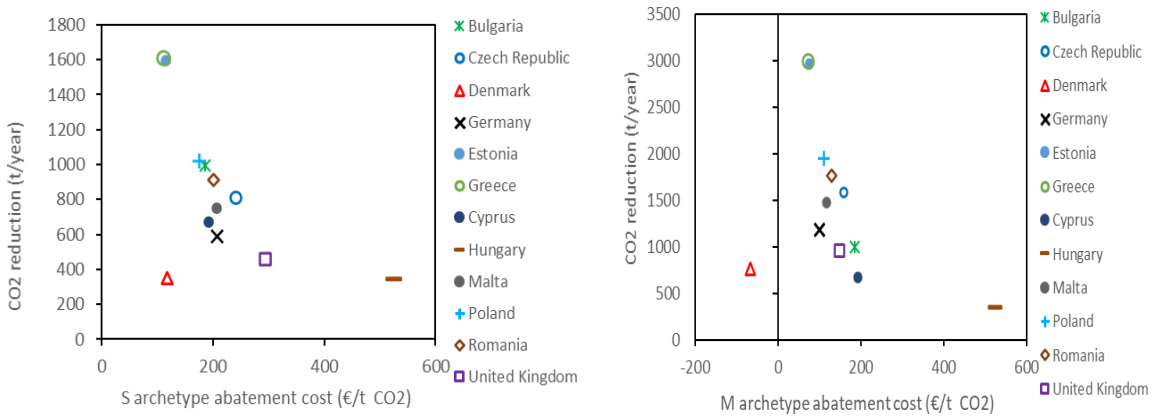


Figure 5. Country-specific abatement costs from integrating the SOFC using the incumbent business model

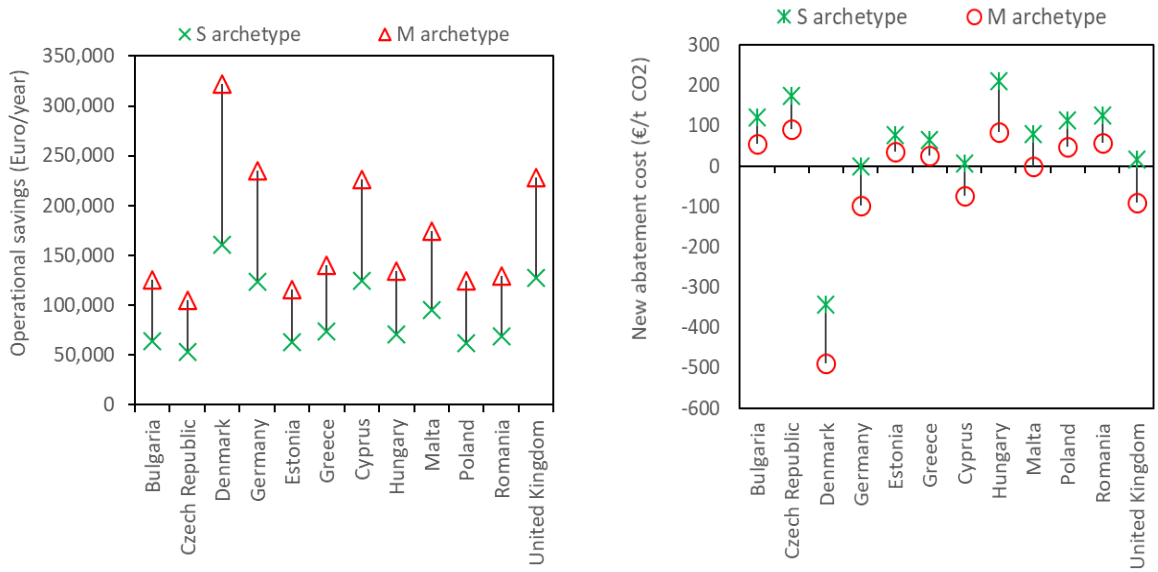
The difference between the CO_2 of the SOFC based system and the BAU is presented in Figs. 6 (a) and (b). The CO_2 abatement cost for the S archetype in most countries ranges from 200 to 300 Euro/t CO_2 except in Hungary, Denmark, and Greece (Fig. 6(a)). The same is observed for the medium archetype in Fig. 6(b).



(a) (b)

Figure 6. Enviro-economic outputs showing the environmental impacts and abatement cost. (a) data for the small (S) archetype, (b) data for the medium (M) archetype

The operational savings (calculated using Eq. (9)) associated with using a highly efficient biogas fuelled SOFC system is shown in Fig. (7a). The savings from the M archetype are more than the S archetype, and savings from countries with a higher spark spread are also more. Ploughing back the savings reduced the total annualised cost and offsets the capital investment in the SOFC. The new CO_2 abatement cost is presented in Fig. (7b). Implementing the new business models reduces the CO_2 abatement cost in the UK by over 100% for the M archetype, and about 90% for the S archetype. In Romania adopting the new business model reduced the CO_2 mitigation cost from 200 Euro/t to 125 Euro/t for the S archetype and from 130 Euro/t to 57 Euro/t for the M archetype. Ploughing bac operational savings reduced the CO_2 mitigation cost in all countries with a minimum reduction of 27%. This implies a lower carbon price can be applied in this sector as a result of implementing the new business model. Therefore, with innovations in business models, adoption of highly efficient more expensive clean technology can be accelerated in industry.



(a) (b)

Figure 7. (a) Country-specific savings from a highly efficient SOFC system, (b) SOFC abatement cost from implementing the new business model

Limitations of this work

The findings of this work need to be viewed alongside the assumptions on energy demands, gas and electricity prices, technology economic characteristics and CO_2 emission factors. These assumptions even though taken from reputable sources are subject to variations. The numerical results obtained from this study on CO_2 abatement costs can only be compared to other technologies if identical assumptions on technical and economic parameters are made.

CONCLUSION

It is commonly believed that the most economically efficient way to reduce greenhouse gas emissions it to reduce emissions to the point that the economic benefits of the reduction equals the added costs. A carbon tax is usually implemented to support this belief – where the tax rate is the CO_2 abatement cost. However, in most studies, the tax rate is lower than the CO_2 mitigation costs. Hence, there is need to explore innovative strategies to reduce the CO2 abatement cost thereby increasing adoption of clean technology. A novel enviro-economic framework whose basis is a detailed optimisation of the system is developed in this work to explore the impact of business models in reducing the CO_2 abatement cost. The framework is applied to biogas fuelled SOFC integration in WWTP (P.E. between 60,000 and 350,000) in twelve European countries. The high capital cost of innovative sustainable technologies like the SOFC hinders widespread market penetration, and current business models may be inadequate to address these barriers. The benefits of a more efficient technology can result in a lower operating cost compared to the business as usual system – this is exploited in this work to create a new business model where these operational savings are ploughed back to offset capital investment. Results show the new business models reduces the abatement cost of WWTP whose P.E. is between 60,000 and 150,000 in Bulgaria from 122 to 56 € per ton, 160 to 92 € per ton in Czech Republic, 73 to 26 € per ton in Greece, 150 to -90 € per ton in the UK, 99 to -98 € per ton in Germany, 210 to 84 € per ton in Hungary, 192 to 7 € per ton in Cyprus, 76 to 37 € per ton in Estonia, 187 to 19 € per ton in Ireland, and 111 to 47 € per ton in Poland. 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. This paper is the first to assess the economic suitability of the SOFC for reducing emissions in the wastewater treatment sector, and the impact of business models on the CO_2 abatement cost. Accurately estimating CO_2 abatement costs, and effectively identifying the factors impacting those costs, can improve the applicability and effectiveness of policy implementation.

ACKNOWLEDGMENT

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NOMENCLATURE

Symbol	Description	Unit
AF	Annualisation factor	-
BAU	Business as usual	-
BM	Business Model	-
BOP	Balance of Plant	-
CA_{CO2}	CO2 abatement cost	Euro/t
CC	Capital cost	Euro/y

DR	Discount rate	%
E	CO2 emissions	t/y
GEP	Grid emission factor	kg/kWh
GEF	Grid electricity price	p/kWh
MC	Maintenance cost	Euro/y
n	System lifetime	y
N	Number of technology units	-
NG	Natural gas	-
NGEF	Natural gas emission factor	Kg/kWh
NGP	Natural gas price	p/kWh
OC	Operating costs	Euro/y
Q	Quantity of heat flow	kW
SOFC	Solid Oxide Fuel Cell	-
TAC	Total annualised cost	Euro/y
W	Quantity of electricity flow	kW
WWTP	Wastewater treatment plant	-
Δ	Change	-

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