

**UCC Library and UCC researchers have made this item openly available.
Please [let us know](#) how this has helped you. Thanks!**

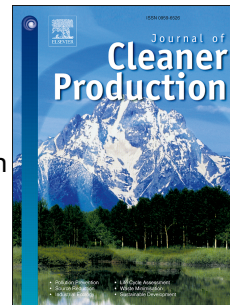
Title	The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: a case study for biomethane
Author(s)	Rajendran, Karthik; Ó Gallachóir, Brian P.; Murphy, Jerry D.
Publication date	2019-02-10
Original citation	Rajendran, K., O'Gallachoir, B. and Murphy, J. D. (2019) 'The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: A case study for biomethane', Journal of Cleaner Production, 219, pp. 278-290. doi: 10.1016/j.jclepro.2019.01.298
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://www.sciencedirect.com/science/article/pii/S0959652619303257 http://dx.doi.org/10.1016/j.jclepro.2019.01.298 Access to the full text of the published version may require a subscription.
Rights	© 2019 Elsevier Ltd. All rights reserved. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/
Embargo information	Access to this article is restricted until 24 months after publication by request of the publisher
Embargo lift date	2021-02-10
Item downloaded from	http://hdl.handle.net/10468/7636

Downloaded on 2021-11-27T07:20:40Z

Accepted Manuscript

The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: A case study for biomethane

Karthik Rajendran, Brian O'Gallachoir, Jerry D. Murphy



PII: S0959-6526(19)30325-7

DOI: <https://doi.org/10.1016/j.jclepro.2019.01.298>

Reference: JCLP 15685

To appear in: *Journal of Cleaner Production*

Received Date: 25 May 2018

Revised Date: 29 November 2018

Accepted Date: 28 January 2019

Please cite this article as: Rajendran K, O'Gallachoir B, Murphy JD, The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: A case study for biomethane, *Journal of Cleaner Production* (2019), doi: <https://doi.org/10.1016/j.jclepro.2019.01.298>.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

**The combined role of policy and incentives in promoting cost efficient
decarbonisation of energy: a case study for biomethane**

Karthik Rajendran ^{a, b, *}, Brian O’Gallachoir ^{b, c}, Jerry D Murphy ^{a, b}

^a Environmental Research Institute, MaREI Centre, University College Cork, Cork, Ireland

^b School of Engineering, University College Cork, Cork, Ireland

^c Energy Policy and Modelling Group, MaREI Centre, Environmental Research Institute,
University College Cork, Ireland

E-mails: k.rajendran@ucc.ie; b.ogallachoir@ucc.ie; jerry.murphy@ucc.ie

*Corresponding author at: Environmental Research Institute, MaREI Centre, University
College Cork, Cork, Ireland

Abstract

The levelized cost of energy of biomethane from food waste was assessed at 87 €/MWh, (87 c/L diesel_{equiv}). Allowing for gate fees the incentive required for financial viability was 0.13 €/m³ (13 €/MWh). For context, various successful renewable energy policies were analysed across the EU including photovoltaics and biogas in Germany and electric vehicles in Norway. The schemes were compared with an incentive applied (or required) per tCO₂ avoided. For Ireland, this study predicts that biomethane needs a financial subsidy of less than 180 €/tCO₂ avoided, while most successful EU systems offer incentivisation levels less than 260 €/tCO₂ avoided.

In terms of incentives per tCO₂ avoided Electric Vehicles (EV) stand out. When including all incentives such as grants and avoided parking costs, EVs can receive a sixteen-fold higher incentive as compared to biomethane based on tCO₂ emissions avoided. The rationale for this high incentive and supporting policy is based on the requirement to initiate a new infrastructure that would not otherwise happen without intervention of a government incentivising decarbonised transport and clean air.

Biomethane as a transport fuel requires a very significant change in infrastructure, including the provision of compressed natural gas service stations and natural gas vehicles. Initially (as for other successful renewable energy systems) larger incentives would be required to allow initiation of the industry, but these subsidies can be reduced over time. Biomethane as a transport fuel offers similar rewards as for electric vehicles, decarbonised transport and clean air along with energy security, renewable energy, indigenous jobs and supporting greening of agriculture.

Keywords: energy policy; renewable heat incentive; bioenergy; biomethane; CO₂ emissions.

1 Introduction

Between 1990 and 2017 primary energy supply in Ireland increased by 37 %. As of 2017, primary energy supply in Ireland was 13 Mtoe, with oil imports contributing 46 % (SEAI, 2017a). Current final energy usage is divided approximately 40 % for transport, 40 % for electricity, and 20 % for heat. A transition from energy dependence to self-sufficient decarbonised supply can lead to energy security and inclusive equitable growth across the energy sector. As of 2017, the share of fossil energy was 89 %, while renewables provided 11 % of energy (SEAI, 2017a). Obviously, usage of fossil fuels results in climate change, deleterious air quality and other environmental hazards (SEAI, 2017a).

The EU 2020 renewable targets for Ireland include 16 % final energy share from all renewables with a specified sectoral target of 10 % renewable energy supply in transport (RES-T). Ireland has national targets of 40 % renewable energy supply in electricity (RES-E) and 12 % in heat (RES-H) (Scheer et al., 2016). As of now, meeting the target for renewable electricity is the most promising (27.3 % as of 2015) (SEAI, 2016c). The share of renewable energy in the transportation section is 5.2 % (just over 50 % of the 2020 target achieved) and potential to meet the renewable heat target is quite uncertain. As we move beyond 2020 EU member countries have an ambitious target of reducing greenhouse gas (GHG) emissions between 80 % and 95 % by 2050 (SEAI, 2016b).

The recast Renewable Energy Directive (RED) has set the fossil fuel comparator (FFC) for heat at 80 gCO₂/MJ; for transportation fuel at 94 gCO₂/MJ; and for electricity consumption at 183 gCO₂/MJ (European Commission, 2017). For a renewable energy system to be considered sustainable, it needs to ensure a 70 % savings on the GHG emissions from these FFC values. For renewable heat, this level of savings is due to rise to 85 % in 2026 (European

Commission, 2017). As such the sustainability criteria for renewable heat is the most arduous to meet. There is a perspective (IEA, 2017) that bioenergy systems should be employed in the least decarbonised sector, which would suggest that electricity is not the prime target for bioenergy. There is another perspective that biomethane should be used in transport (which has a target of just 3.6 % advanced biofuel by 2030 in the recast RED) rather than heat which is a less complex energy vector. For example, wood chips may be simply combusted to produce heat but need to undergo an energy intensive Fischer Tropsch process to be converted to a liquid transport biofuel system.

Biogas as a renewable energy source can help Ireland meet the 2020 targets in transport and in heat. The Sustainable Energy Authority of Ireland (SEAI) calculated the biogas potential of Ireland at 0.95 Mtoe; currently, less than 2 % of this resource potential is produced (SEAI, 2016a). This is due to the high investment cost without supporting subsidies of sufficient scale and lack of detailed policy support. More than 90 % of agricultural land is covered by perennial ryegrass (a source of advanced transport biofuel), which ensures an abundance of potential feedstock supply (O'Shea et al., 2017).

A major issue with renewable energy technologies is that they must compete in the short term with established fossil sources. This is not a fair competition. The fossil source is abundant, the process has been optimised over generations, fossils release CO₂ leading to climate change, diesel is a major source of air quality deterioration and many states or cities will ban diesel-fuelled vehicles over the next decades (EPA Ireland, 2015). Ireland has stated that internal combustion cars (petrol and diesel) will not be available for sale as of 2030 (DTTAS, 2018a). This is expected to drive the sale of EVs. This governmental communication further states that public transport – where feasible – will be met by greener public

transport (DTTAS, 2018a). This should encourage the use of biomethane in natural gas buses. EVs and biomethane-fuelled buses are relatively recent developments; the technologies and integration of systems need time to mature. Detailed policy support is necessary to ensure an industry, which can meet renewable energy targets and optimise the cost of decarbonising the energy sector. Incentivization is necessary to lessen the cost of the introduction of these new renewable energy systems (Bloomberg et al., 2013).

Effective policies and incentives have helped renewable energy systems to overcome the barrier of technological advancement and market sustainability (KPMG International, 2015). A good example is the photovoltaics (PV) industry in Germany. The initial high levels of incentivization (43 c/kWh in 2005) assisted the growth in the market, accelerated innovation in technology and ultimately led to a reduced electrical cost of PV of approximately 8.7 c/kWh in 2015 (IEA 2017c); PV can now challenge fossil fuel powered electricity systems across the world with a minimum subsidy.

Green gas systems include for the production of renewable gas and injection to the gas grid for use elsewhere as a substitute for natural gas (Cucchiella et al., 2018; Hoo et al., 2018; Wall et al., 2018). The sources of green gas include for anaerobic digestion of wet organic material, gasification of woody material and power to gas systems (Wall et al., 2018). This paper is concerned with biogas facilities, which are a mature technology. For example, Germany has approximately 10,000 biogas facilities, the UK 1000 and France close to 600 (IEA Bioenergy, 2018). In 2017, the 17 member countries of IEA Bioenergy Task 37 had 532 facilities which upgraded biogas to biomethane (suitable for gas grid injection); this is an increase from 480 in 2016 (IEA Bioenergy, 2018). Six EU gas grids have committed to 100% green gas on the gas grid by 2050 (Wall et al., 2018). Energy from waste, especially biogas

from food waste and agricultural, plays a key role in achieving goal 7 (affordable and clean energy) of the UN sustainable development goal. When the organic fraction of municipal solid waste is used to produce biomethane, GHG savings as compared to the fossil fuel displaced of 79 % are possible (Ardolino et. al., 2018).

The first gas to grid system will be constructed in Ireland in 2018. The gas may be used in transport or heat (Gas Networks Ireland, 2018). Ireland introduced a renewable heat support scheme to incentivise biomethane and biomass for renewable heating systems (SEAI, 2017b). This system will be assessed in this paper. The gap in the state of the art is that the authors are unaware of any previous study, which evaluates supports and incentives of renewable biomethane in terms of CO₂ savings and compares these values with other successful renewable energy support systems on the basis of a monetary value per tCO₂ avoided. The innovation in this work is the employment of an integrated approach to calculate the excess cost needed (the difference between the cost of renewable energy and the displaced fossil energy) to avoid one tonne of CO₂. This approach was applied to successful renewable energy schemes to allow comparison with biomethane systems. The methodology included for assessment of carbon tax credits. The objectives of this paper are as follows:

1. Assess the effect of a carbon tax at various prices as a credit mechanism for a range of biomethane systems.
2. Calculate the excess cost to avoid a tonne of CO₂ for biomethane systems.
3. Calculate the excess cost to avoid a tonne of CO₂ for successful renewable energy schemes and compare with biomethane.

4. Compare incentives applied to successful renewable energy schemes per tonne CO₂ avoided and compare with required supports for biomethane.

2 Methodology

2.1 Levelised cost of energy of biomethane scenarios

This work draws on the results of a techno-economic analysis by Rajendran et al. (2019) of biomethane systems using feedstocks from urban(U), rural (R), and coastal (C) settings (Figure 1). The urban feedstock utilises source segregated food waste, while the rural system employs grass silage and slurry; data on this was based on previous works by Wall et al., 2014 who utilised an 80:20 Volatile Solid (VS) mix. The coastal scenario included a mix of source segregated food waste, grass silage, slurry, and seaweed as feedstocks. The annual processing capacity in the urban scenario was 100,000 t/a; this is an optimal scale for cities such as Dublin, Ireland with populations of about 1,000,000 people. For rural and coastal settings quantities of 140,000 and 102,000 t/a respectively were modelled. Biogas was upgraded by water scrubbing (WS), which is a well-established method for biogas upgrading (IEA Bioenergy Task 37, 2017). The feedstocks were coded as U-Urban, R-Rural, and C-Coastal. Thus for example, Urban Water Scrubbing was coded as UWS. In this earlier study, the levelised cost of energy (LCOE) and the incentives needed for these three scenarios were assessed (Rajendran et al., 2019). For the purpose of this paper the relevant data is as follows. The LCOE of UWS is 87 €/MWh; the LCOE of RWS is 121 €/MWh and the LCOE of CWS is 131 €/MWh.

2.2 Comparison of renewable energy systems on the basis of a cost per t CO₂ avoided

This paper is concerned with analysis of the different approaches that may be employed to support and incentivise an industry with a known LCOE (Figure 2). The methodologies used include: 1) Assessment of the excess cost incurred, over the fossil fuel displaced, to avoid a tonne of CO₂ on the assumption that the renewable energy is CO₂ neutral. The excess cost per tonne of CO₂ avoided for biogas from this work was compared with the excess cost for other renewable energy technologies per tonne CO₂. 2) Assessment of the effect of specific carbon taxes on the economic viability of Anaerobic Digestion (AD) systems. 3) A comparative evaluation of supports and incentives for a range of successful renewable energy systems was undertaken. 4) The incentives available or required for the different renewable energy schemes were assessed on the basis of a tCO₂ avoided and compared with biomethane. The biomethane technologies (and other renewable energy technologies) were considered CO₂ neutral if they meet sustainable criteria. This is the process employed in assessing the greenhouse gas inventory for a country. The CO₂ savings are based on the Fossil Fuel Comparator (FFC).

2.3 Excess costs of renewable energy over fossil fuel to avoid CO₂

The excess cost needed to avoid a tonne of CO₂ from fossil fuel sources using a number of scenarios was assessed. The FFC for heat was 80 gCO₂/MJ and 94 gCO₂/MJ for transport (European Commission, 2017). The excess cost was calculated by differentiating between the costs of the fossil fuel comparator and biomethane technologies.

2.4 Carbon tax calculations

Carbon tax is imposed on fossil fuels. The carbon tax in Ireland is applied to fossil fuels at the rate of 20 €/tCO₂ (EPA Ireland, 2015). However, this tax is expected to increase exponentially over the next decades. The imposed carbon tax is an economic credit to the AD system; it adds to the economic viability of the system (Glynn et. al., 2018). The scenarios investigated (Figure 1) need incentives to reach a break-even point with the fossil fuel displaced. The existing carbon tax credit of itself is presently insufficient; however, this credit will reduce the amount of incentive required. Based on the different levels of the carbon tax, revised incentives were calculated. The carbon tax rates were assessed between 0 and 350 €/tCO₂. The carbon tax calculations included only the net emissions; the emissions avoided by using biomethane technologies instead of the FFC.

2.5 Policy evaluation with successful renewable energy schemes

The third approach was to compare successful renewable energy policies for a range of renewable energy systems with biomethane. This enabled a feedback mechanism to assess current policy and potential improvements in policy. For comparison, five technologies were considered. Norway is the leading country in terms of per capita usage of electric vehicles (EV) (IEA, 2018). The policy in Norway was assessed over a decade. Similarly, Germany has pioneered photovoltaic (PV) technology and biogas technology and is world leading in these technologies (IEA, 2018). The support mechanism was assessed. As this work includes the assessment of biomethane in renewable heat, relevant heat incentives in the UK were also assessed.

2.6 Comparison of incentives per tonne CO₂ avoided of biomethane with renewable energy schemes

The goal behind any incentivization scheme is to avoid CO₂ emissions. Green gas can be used for heat or transport; these sectors are least decarbonised in an Irish context. Gas to grid systems inject biomethane to the natural gas grid and as such end use may be for heat or transport. Therefore, the incentives supporting EV in Ireland were compared with those for natural gas vehicles (NGV) operating on biomethane. The incentives from different policies were compared based on a tonne of CO₂ avoided (€/tCO₂ avoided).

3 Results and Discussion

3.1 Technical evaluation of costs of avoiding CO₂ emissions

3.1.1 Levelised cost of energy of biomethane scenarios

The levelised cost of energy (LCOE) was previously calculated (Rajendran et al., 2019) for the three scenarios detailed in Figure 1. LCOE was calculated through assessment of the total cost (CAPEX and OPEX) incurred over the lifetime of an energy system expressed per unit of energy produced in its lifetime. Digestion of food waste in the urban feedstock scenario with conventional water scrubbing (UWS) was the cheapest scenario with an LCOE of 87 €/MWh. Figure 3a shows the LCOE of the three scenarios graphed against the capacity of the facility. The urban feedstocks received a major share of revenue through the gate fee of 50 €/t for food waste, which reduced the incentives needed to reach a break-even point. The incentive needed was lowest for urban feedstock with conventional water scrubbing (UWS) at 13 €/MWh (Figure 3b).

3.1.2 Excess costs per tonne of CO₂ avoided for biomethane

Excess costs are defined here as the cost incurred when fossil technologies are replaced with renewables. Obviously, the cheaper fossil fuels produce climate-damaging GHG emissions and air pollution (EPA, 2015). Thus, the excess costs are associated with climate change mitigation and improved air quality (EPA, 2015). The excess cost to avoid a tonne of CO₂ for different technologies was calculated. These costs were assessed for other renewables to evaluate biomethane systems in this study.

Box 1 (Appendix) shows the calculation methodology to evaluate these excess costs to avoid a tonne of CO₂. Firstly, the GHG emissions from the FFC were reported; as the renewable scheme is deemed carbon neutral this is the CO₂ avoided through use of renewable energy. Secondly, the difference in LCOE between renewables and the FFC was assessed. This difference is the excess cost incurred. Finally, the excess cost is divided by the tonnes of CO₂ avoided. Figure 4 shows the excess costs incurred to avoid a tonne of CO₂ produced for various scenarios from this study and from other renewable systems. The excess costs to avoid a tonne of fossil CO₂ for UWS for use as a source of thermal energy was 215 €/t CO₂ avoided (Appendix, Box 1). For, rural water scrubber (RWS) and (coastal water scrubber) CWS it was assessed as 330 and 368 €/tCO₂ avoided respectively. Changing the energy vector to renewable transport reduces the cost; a similar calculation for UWS yields a value of €115/tCO₂ avoided for biomethane as a transport fuel displacing diesel.

3.1.3 Excess costs per tonne of CO₂ avoided for renewable energy schemes

To put these values in context they were compared with renewable electricity from PV and Wind. For PV, large-scale solar plant of 10 MW and roof-top PV of 5 kW were used in the

comparative assessment. The LCOE of large-scale PV used was 121 €/MWh, while for roof-top PV it was 221 €/MWh (Cambridge Economic Policy Associates Ltd, 2017). The excess cost to avoid a tonne of CO₂ (based on the FFC of 183 gCO₂/MJ or 656 kg CO₂/MWh) for PV varied between 123 (solar park) and 276 (roof-top) €/t CO₂ avoided. This shows the effect of scale in reducing the cost of decarbonisation of energy.

Similarly, onshore, and offshore wind, were used as other renewable energy comparators. The LCOE for wind energy was 89 (onshore) and 129 (offshore) €/MWh (Cambridge Economic Policy Associates Ltd, 2017). Thus, the excess cost to avoid a tonne of CO₂ for wind energy was 75 (onshore) and 136 (offshore) €/t CO₂ avoided. This shows how increasing technology readiness levels (TRL) reduce the cost of decarbonisation of energy.

It is difficult to compare biomethane from an UWS for use as thermal energy (215 €/t CO₂) and for transport fuel (115 €/tCO₂) to for example onshore wind energy. Obviously, here we are not directly comparing like with like; there is a hierarchy in energy vectors. A wood chip can provide heat but cannot propel a car unless it is transformed to a liquid transport fuel via a biomass to liquid (BtL) system with all the energy and cost input this entails. This is exemplified in figure 4 where Fischer Tropsch (FT) diesel (an advanced biofuel) is shown to have an excess cost of € 413 to avoid a tonne of CO₂; this is therefore comparable with the excess costs of biomethane as a transport biofuel of 115 €/t CO₂ avoided. This again highlights the available technology of gas to grid systems (high TRL) as compared to undeveloped technologies such as Fischer Tropsch diesel (low TRL).

The recast RED (EU, 2017) has set a target of 3.6 % advanced biofuels for 2030 highlighting the overall low level of commercial maturity in this market. Biomethane has a significant advantage here. As such though the cost of avoiding carbon using biomethane as a source

of thermal energy is higher than for advanced technology (high TRL) ready sources of electricity (such as PV and wind) the cost of decarbonisation is lower when using biomethane for advanced biofuels as compared to Fischer Tropsch diesel.

Even comparing intermittent renewable electricity (such as from wind turbines) it is advisable to include for the LCOE of energy storage systems to allow a direct comparison with dispatchable fossil fuel power plants (such as a combined cycle gas turbine). When comparing wind, PV, and AD, it is worth noting that only AD can store the produced energy; AD is dispatchable and can be used for renewable electricity, heat and/or transport fuel (Wall et al., 2018).

3.1.4 Effect of the carbon tax as an incentive for renewable energy schemes

The next approach was to check the effect of carbon tax on the incentives needed. At present, there is a carbon tax in Ireland applied to the use of fossil fuel. The carbon tax as of 2017 is € 20 for every tonne of CO₂ released (EPA Ireland, 2015). Biogenic CO₂, on the other hand, is a part of the carbon cycle, which does not incur carbon tax (IEA Bioenergy, 2018). Thus the carbon tax imposed on the fossil fuel is a tax credit to renewable technologies such as a biogas facility.

The carbon tax credit based on the FFC was calculated for the three scenarios. This tax credit can reduce the incentives needed to reach a break-even point. The revised incentives were calculated based on the FFC CO₂ emissions avoided at different carbon tax rates (Appendix, Box 2). The various scenarios had varied energy production capacities, which impacted the revised incentives accordingly. A general trend of increasing carbon tax decreased the incentives needed. The most profitable scenario for renewable heat was

biomethane from UWS, which needed 13 €/MWh as an incentive. With the current rate of a carbon tax at 20 €/tCO₂, the revised incentive needed was 5.76 €/MWh. If and when the carbon tax increases to 50 €/t CO₂, biomethane from UWS for use in renewable heat would not need any incentive (Figure 5). If the support for renewable energy is totally in the form of a carbon tax, the scenarios including RWS and CWS need a carbon tax of at least 350 €/tCO₂.

3.1.5 Resource analysis and avoided emissions

Based on the above analysis, the potential CO₂ emission savings and energy production in an Irish context were calculated. This study used 100,000 t/a in the UWS scenario; national food waste estimates 6.4 Mt per annum (Table 1) (O'Shea et al., 2016). For every tonne of food waste that is processed to produce renewable methane, 0.34 t of CO₂ emissions can be avoided. When extrapolated to national food waste estimates in Ireland, the avoided emissions correspond to 2.19 Mt CO₂/a. Using the urban food waste from Ireland for AD results in renewable methane production of 7605 GWh/a. Similarly, the national estimates for excess grass silage and slurry amount to 31.3 and 28.5 Mt/a respectively. If the resource of grass silage and slurry are co-digested, the energy generated is equivalent to 36,176 GWh/a. The CO₂ emissions avoided using this theoretical resource in Ireland amounts to 10.42 Mt CO₂/a. For every tonne of silage and slurry (on an 80:20 VS basis), 0.17 tCO₂ emissions are avoided, while the energy generated amounts to 0.6 MWh/t of feedstock (Table 1).

3.2 Policy evaluation with successful renewable energy schemes

3.2.1 Electric vehicles in Norway

Electric vehicle (EV) sales in the EU increased 21 fold over six-years between 2010 and 2015 (Statista, 2015) (Figure 6a). Norway leads the use of EVs in the EU and around the world in terms of per capita usage. Nearly, one out of three cars in Norway, as of 2016, is an EV and this number is increasing (EAFO, 2017). The use of EVs has increased significantly worldwide since 2010. However, Norway had removed import taxes on EVs before 2005 (EV Norway, 2017). The promotion of EV in this Scandinavian country is primarily due to three main reasons: 1) The country generates 95 % of electricity from hydro power (a clean source of energy) (Statistics Norway, 2011), which rules out ambiguity around power source and net emissions associated with the EV; 2) Due to its high per capita GDP (greater than € 65,250) (IMF, 2018) the government and public can afford the costs associated with the technology; 3) Norway recognised the race against time and the responsive action that needs to be taken to mitigate climate change (Norden, 2018).

Technologies may be promoted in a number of ways including: 1) Policy support provided at a governmental level to promote adoption of the technology and 2) Technological advancement over time with increasing technology readiness levels, and associated reduced costs. EVs have gained support in Norway using both these means. In terms of technology, the battery cost decreased by 71 % in 8 years (IEA, 2017a). Over the same period, the energy storage density increased three-fold (Figure 6b). As a technology, development over time self-supports market sustainability. Adding policy support to the technical developments helps in the maturity of a technology.

Until 2012, the market share of EV in Norway was 3.27 %. Between 2007 and 2012, 7140 new EVs were registered (IEA, 2017a) (Figure 6c). In 2012, the Norwegian government announced financial incentives for 50,000 EVs up to the year 2018. This announcement doubled the amount of new EVs registered between 2012 and 2013 increasing the market share of EV to 6 %. These policy supports built upon earlier supports in the form of access to bus lanes, infrastructure development program, and free access to ferries (Figure 6d). However, the financial incentives announcement in 2012 helped to kick-start adoption of this technology. Later in 2015, the 25 % VAT level was exempted for EV purchase (EV Norway, 2017). This policy change increased the number of new EV registrations by 41 % in 2016. The promotion and uptake of EVs in Norway is a combination of technology advancement reducing the costs and policy support incentivizing it. Norway is not driving the technical advancements, while it is reaping the benefits due to the global technology advancement.

3.2.2 Photovoltaics in Germany

Germany is a pioneer in terms of energy production from PV. In 2005, the share of electricity from PV was 0.25 %; by 2016, this share increased to 7.4 % (Figure 7a) (Wirth, 2018). Between 2005 and 2016, the projected installed capacity of photovoltaics is expected to increase 20 fold reaching 41 GW of peak capacity (EPIA, 2014).

The cost of PV as a technology has reduced 70 % since 2010 (Mayer et al., 2015; Wirth, 2018). This allowed manufacturers and operators to optimise profit through a sale price that was affordable for end users with an increased share of the market and returns to the manufacturer. The Feed-in Tariff (FiT) in 2005 for PV was 43 ¢/kWh; in 2014 through technology advancement, it reduced to 8.7 ¢/kWh (Figure 7b) (Mayer et al., 2015). During

the same period, the domestic tariff for electricity increased from 18 to 29 ¢/kWh (Löschel, 2016; Statista, 2017). This achievement was made through a series of policies implemented over the last two decades.

The historical developments on the policies implemented to incentivize PV in Germany are identified below and indicated in Figure 7c. The renewable energy sources act (RESA) initiated supports for a range of renewable energies in the year 2000 (IEA, 2017b). Since its launch and up until 2014, this act was amended eight times with special interim acts for PV. In 2003, tariffs were raised for small rooftop installations (Figure 7c). The RESA act was amended in 2004 to increase the FiT across a variety of sizes to 43 ¢/kWh (Figure 7b). In 2009, the FiT was decreased to 31 ¢/kWh; between 2004 and 2009 the installed capacity increased by 421 % (IEA, 2017b). The increase in domestic electricity prices and decreases in FiT ensured adequate demand for growth was created in the market (Statista, 2017).

Thereafter, the tariffs were decreased every year through amendments. In 2013, a 30 % reduction in FiT was enacted. As of 2015, roof-top electricity sourced from PV yields 12.8 ¢/kWh, and from solar parks 8.9 ¢/kWh (IRENA, 2015; Mayer et al., 2015). Initially, the policy support gave a cover to recover investments. With the technology becoming affordable and increasing electricity prices, PV pays for itself. In addition, the government ensured competition between industries to bring down the costs. This would eventually help in removing earlier subsidies.

The PV market in Germany is not increasing exponentially as of now (EPIA, 2014) (Fig 7a). However, the decade-long policies and amendments have helped the country to generate a fair share of clean energy at an affordable price, while Germany became a technology leader and exporter of Intellectual Property (IP). The PV industry in Germany is a good example of a

policy on giving a strong subsidy at an initial phase, controlling it during maturation of the technology and industry, and removing it after the technology matures. This technology, however, is in the electricity market as opposed to the gaseous fuel market, which is of primary concern here for biomethane.

3.2.3 Biogas in Germany

Like PV, Germany is a world leader in implementation of biogas systems. Between 2001 and 2017, the number of biogas plants installed in Germany increased by a factor of seven (Fachverband Biogas, 2017). During the same time, the installed electricity capacity increased by a factor of 25 (Figure 8a). The innovative policies implemented over the last two decades have led to German dominance in biogas adoption. In addition to policy support, capital support was provided by the banks by the provision of low-interest loans (ca. 4 %) (KPMG International, 2015). It is essential for industry growth that banks recognize the new revenue sources associated with sustainable technologies and the business model driven by policy support and incentives. Bankability of a development is essential to finance the development.

Policy support and incentives enacted together initiate the adoption of a nascent technology. Ideally, these supports have a level of complexity that promotes and reward innovation and optimisation of technologies. The German system staggered incentives based on the size of the plant, the feedstock used, and type of technology employed and modifications to minimise water use and emissions (Capodaglio et al., 2016). It is crucial to note that additional incentives were given on top of basic incentives when the biogas facility was optimised. These additional incentives led to technological advancements in biogas systems (Engdahl, 2013).

Excessive food production from agriculture in the late 1990's led to lower costs and lower demand for the food crops. This forced farmers to look for alternatives including the transition of using agricultural land for energy crops. Energy crops generated a new source of income and a transition of reliance on demand for food revenues. The incentives for biogas started through the RESA act in the year 2000 through a basic feed-in-tariff (FiT) (IEA, 2000). Assured FiT for 20 years led to bankability and resulted in the construction of ca. 250 new biogas plants every year from 2001 to 2004 (Figure 8).

The RESA act was amended in 2004 by giving a staggered FiT for various sizes of the plant. Four different sizes were considered based on the electricity generation capacity up to: 150 kW; 500 kW; 5000 kW; and 20,000 kW. From the basic incentive, added incentives were provided for using energy crops and obtaining a heat market for the facility. This resulted in the construction of 450 new plants every year from 2004 to 2009. The basic tariff was varied between 8.37 and 11.50 ¢/kWh depending on the size of the plant (Figure 8b) (IEA, 2004).

The FiT was revised regularly thereafter promoting the construction of new plants. For smaller plants (less than 150 kW), the FiT was increased in 2009 and 2012 to help farmers adopt farm scale technology (IEA, 2009; IEA, 2012). However, capacities larger than 20,000 kW had a decrease in FiT from 2004 until 2017 between 8.37 and 5.71 ¢/kWh (IEA, 2009, 2012, 2014, 2017c). Since 2017, large-scale plants do not receive any FiT (Figure 8c). This ensured the promotion of technology as well as adequate competition between facilities to promote innovation and reduce costs.

Besides FiT, additional incentives were given for different purposes. This includes the use of energy crops, technology bonus, use of manure, formaldehyde bonus, and installing combined heat and power (CHP) facilities. This bonus in FiT was mostly applicable to plant

sizes less than 20,000 kW that ensure decentralization and adequate facilities being built.

Besides FiT of 9.18 ¢/kWh, a 500 kW plant installed in 2009 received an additional 7 ¢/kWh for using energy crops, 3 ¢/kWh for CHP, up to 2 ¢/kWh for technology innovation, and 1 ¢/kWh for using manure. This helped the industry to build 1000 new plants every year from 2009 to 2012 (Figure 8c) (Fachverband Biogas, 2017). Though FiT was in place, 1 % reduction every year on FiT was enforced to ensure the market and technology sustain its self with innovative approaches and new revenue generating mechanisms.

Since 2015, additional incentives such as for upgrading biogas were removed for large plants. This has led to a reduction in the number of new plants that are being built.

However, over the decade with technology maturity and demand in place, the market can survive on its own. Germany biogas policy is a good example of proposing an incentive, forcing the market to adapt, and removing or reducing the incentive once a self-sustaining market is in place.

These policies have allowed the German biogas industry generate revenues through technology transfer and consultancy services to other countries. Though the biogas technology matured in Germany, it created another source of revenue through innovation, patents, and production of intellectual property.

3.2.4 Gas to Grid in the UK

It is important to compare a policy mechanism for the same energy vector, be it electricity, heat or transport fuel. Thus the policy for biomethane in the UK is very relevant for biomethane in Ireland. The UK and Ireland have similar socio-cultural conditions, and levels of economic prosperity, which help in assessing the incentives provided. All the incentives were converted from sterling to Euro. The conversion rate used was 1.12 € to 1£. To initiate

the UK gas to grid industry in 2013, the incentives for all biomethane injection capacities were 9.21 ¢/kWh. This support has evolved. The incentives can be divided in two; biogas for heat and gas to grid. Figure 9 shows the present renewable heat mechanism in the UK for biogas heat and grid injection. Injecting biomethane to the grid receives higher incentives than direct heat. The incentive for biogas heat is provided up to 600 kW_{th} (maximum 3.23 ¢/kWh). Biomethane injection to the grid receives incentives from 40,000 to 85,000 MWh/a. The incentives varied between 3.58 and 2.61 ¢/kWh depending on the capacities (OGEM, 2017).

3.2.5 Support scheme renewable heat in Ireland

Ireland recently announced the Support Scheme for Renewable Heat (SSRH), which is a high-level support scheme instead of financial support. The main goal of this scheme is meet the 2020 renewable energy targets in reducing GHG emissions associated with heat. The SSRH can be divided in two parts: operational support and installation grant. The operational support is provided to technologies that will replace fossil systems or new sustainable installations. The technologies get the aid based on their heat output, which includes biomass heating systems and AD heating systems. The installation aid is provided to heat-pump technologies including air source, ground source and water source heat pumps. The installation aid for the heat-pumps is set at 30 % of the installation costs (SEAI, 2017b).

The support schemes proposed a FiT for biomass and AD based heating systems for an assured period of 15 years. The FiT varied based on the annual energy production capacity (MWh/a) and type of technology used. For example, when an AD system generates greater than 2,400 MWh/a there is no assured FiT; this approximates a 300 kW_e facility. While for biomass-based heating systems, capacities that produce energy between 10,000 and 50,000

MWh/a receives a FiT of 0.37 ¢/kWh (Figure 10). This proposed tariff will be revised every year depending on many factors. These payments will be made quarterly once the requirements are met. Sustainable Energy Authority of Ireland (SEAI) will check and control the quality of the eligibility criteria and other obligations (DCCAE, 2017).

3.3 Comparison of incentives for renewable energy schemes

3.3.1 Incentives for EVs expressed per tonne CO₂ avoided

Like Norway, Ireland has an incentivization scheme for EVs. The Irish government had a target of 10 % of passenger vehicles to be electric by 2020. EVs receive supports in capital cost, motor tax, parking, installation of fuelling points and free electricity in public fuelling points. Box 3 (Appendix) shows how the incentives are calculated for an EV in Ireland. The maximum capital incentive provided for an EV in Ireland is €5000 (SEAI, 2018). The vehicle registration tax provides a maximum of €5000 as an incentive for EVs registered until 2021 (VRT, 2018). The installation of a charging system receives a subsidy of € 600. Conservatively assuming the lifetime of an EV of 20 years, the capital incentive may be annualised to 250 €/a, registration tax to 250 €/a, and the charger incentive to 30 €/a. The average parking cost for any car in Ireland is 1.5 €/h (IPA, 2010). Calculating the free parking incentives at the rate of 150 h/month is equivalent to 2700 €/a. Recently, a toll incentive of up to 500 €/a was announced for EVs (DTTAS, 2018b). Totalling all the incentives generates a benefit to the EV of between 3924 and 4112 €/a. The base assumption is that the efficiency of an EV achieves 12.4 kWh/ 100 km. Recalculating the incentives based on the CO₂ avoided corresponds to 1851-1940 €/tCO₂ avoided. Without parking, the incentives equate to 666 €/tCO₂ avoided.

3.3.2 Incentives for biomethane as a transport fuel as compared to EVs in Ireland

As of now there are little policy support or roadmaps for NGVs in Ireland. Biomethane can be used in an NGV without modification. The fuel efficiency of an NGV (VW Golf is used for comparison with an equivalent diesel version) is 3.5 kg/100 km (CNG Europe, 2018). To drive 20,000 km annually, 700 kg fuel is needed. The highest incentive in the SSRH for biomethane was 2.95 ¢/kWh (DCCA, 2017). The assumption here is that renewable gas will get the same subsidy independent of end use; as such this is the modelled incentive for gaseous transport biofuel. Box 4 in the appendix calculates the incentives for an NGV operating on biomethane of up to 260 €/a. Recalculating the incentives based on the avoided emissions results in 123 €/tCO₂avoided for biomethane respectively. When compared with EV, this can be sixteen-fold less.

Based on the motor tax bracket, the emissions for a Plug in Hybrid Electric Vehicle (PHEV) should be 60 gCO₂/km. Calculating based on the motor tax bracket, a PHEV should emit 1.2 tCO₂/a travelling 20,000 km/a. However, according to the Sustainable Energy Authority of Ireland (SEAI, 2018c) the actual emissions are much higher, in the range 1.58 to 2.05 tCO₂/a. These higher emissions were not considered in the incentivization mechanism. In addition, the emissions of an EV are directly proportional to how green the electricity grid is. In 2020 it is expected that the electricity grid will be ca. 40 % renewable; by 2040 it is expected to reach 75 % renewable. Thus, the electricity used in the PHEV now emits more CO₂ than the motor tax bracket allowed for. Biomethane reduces the emissions in a comparable manner to an EV, but the incentives for an EV are sixteen-fold higher. The authors suggest that incentives should be provided with cognisance of the amount of CO₂ avoided. Natural gas

vehicles can readily use biomethane from AD avoiding significant GHG emissions but the incentives for NGV are not comparable with EV.

3.3.3 Supports and incentivisation for biomethane compared to successful renewable energy schemes

This section compares the renewable heat support scheme in Ireland and the recompense for green gas with other renewable policies mentioned above. Priority is given to small-producers; this is similar to German biogas policy. However, the definition of the small-producer in Germany is less than 150 kW while in Ireland it is defined as 300 MWh/a. If we use the same metric for the grass silage and slurry scenario at 80:20 on a VS basis, a scale of 300 MWh/a equates to ca. 525 t/a. In the German case, 150 kW for the same feedstock equates to 4700 t/a. Thus, the Irish small condition is a factor of 9 times smaller than the German small condition. This will have an impact on economies of scale, which is critical in allowing financial sustainability for gas to grid schemes. The authors recommend that this small threshold be increased.

The policy exemplar of biogas in Germany supported innovations that could reduce the cost of production of renewables. This allowed more innovative companies generate more revenue, to become dominant in the market and led to a more developed market with lean innovative pioneers. The SSRH scheme, which is just initiated, at present lacks the complexity of policy enrichment that creates adequate competition between the companies. Such detailed complex support systems are not available in the SSRH scheme in Ireland at present. The authors recommend that future amendments of the SSRH should consider implementing additional incentives for technology innovation and feedstock credits.

Bankability is a huge issue for developers of renewable technologies. FiT are common to the PV and biogas sectors in Germany; it is also an element of the SSRH in Ireland. However, other supports such as subsidies for CAPEX are limited in the SSRH. The SSRH provides FiT for Biomass and AD systems; however, installation support up to 30 % is only available for heat-pumps. By contrast, the policy for EV adoption in Norway included removal of import taxes, reduced VAT, and capital incentives for the first 50,000 EVs.

It is important to incentivize the technologies based on the emissions avoided. In this work, incentives were calculated based on the GHG savings with regard to the financial incentives and policy benefits. The incentives calculated in this work for AD to heat in Ireland ranged between 123 and 171 €/tCO₂ avoided (Figure 11). In the UK, the biogas heat incentives were up to 140 €/tCO₂ avoided while the biogas grid injection received up to 156 €/tCO₂ avoided. Thus, the policy and incentive in the UK would be deemed adequate and not be deemed to be greater than needed. PV and AD for electricity in Germany receives 143 and 259 €/tCO₂ avoided respectively. This is more generous but could if applied to Ireland aid in the initial stimulation of the market in Ireland.

3.4 Rationale for use of biomethane as a transport fuel

When comparing the EV and the NGV operating on biomethane in Ireland, the EV receives up to a sixteen-fold higher incentive. This highlights the need to ensure the maximum utilisation of taxpayers' money in decarbonising energy. The level of incentive may be excessive, but it may be argued that the prize of decarbonised transport and clean air is worth this investment. To decarbonise heavy commercial vehicles and intercity buses biomethane is the most obvious choice. It should also be considered that biomethane not

only decarbonises the transport systems but also minimises particle emissions and in a circular economy system reduces emissions in agriculture (if slurry digested) or in municipal waste (if food waste digested). The use of biomethane as an advanced transport biofuel is also a big prize when it is considered that the Irish public transport company is not permitted to purchase diesel buses after 2019 (DTTAS, 2018a). Transport is a higher energy vector than heat. GHG savings from biomethane use for heat is less than that for transportation fuel as diesel has higher emissions than natural gas central heating (European Commission, 2017). However, for use as a fuel in a NGV the biogas needs to be upgraded and compressed to 200 bar (Rotunno et al., 2017). Furthermore, a separate gas filling station is necessary. Thus, biomethane for transport needs more incentives and policy support as compared to biogas for heating. Intelligent policy and incentives need to allow for the complexity of the different markets for green gas.

4 Conclusion

Incentivising renewable energies is normally based on a unit of energy. For electricity these are assessed per kW_eh , for transport fuel per L diesel equivalent. This does not allow ready comparison across renewable energy systems. In this report incentives and financial savings associated with policy are compared by assessment per tonne of $\text{CO}_{2\text{avoided}}$. The excess cost of renewable energy over the fossil fuel displaced to avoid a tonne of CO_2 is lower for mature technologies such as on-shore wind (89 €/t CO_2) while higher for advanced biofuels (413 €/t CO_2 for FT diesel). The excess cost to avoid 1 t CO_2 for biomethane from food waste is in the range 115 €/t $\text{CO}_{2\text{avoided}}$ for transport to 215 €/t $\text{CO}_{2\text{avoided}}$ for thermal energy. This translates to incentives required to effect minimum financial sustainability of between 123

and 171 €/tCO₂avoided. Transport is probably the most relevant sector for biomethane as it is the least decarbonised and requires the least incentive per tCO₂ avoided.

The incentivisation scheme needs to be intelligent and granulated supporting higher returns on investment for more innovative, competitive and sustainable systems. Incentivisation needs to be higher at the initiation of an industry to allow supporting infrastructure to be installed, whether charging points, or NGV service stations or support for purchase of EVs or NGVs. The biomethane industry needs the incentives and policy associated with the EV industry as implemented in Norway and more recently Ireland.

Abbreviations

AD – anaerobic digestion
BEV – battery electric vehicle
BtL – biomass to liquid
CHP – combined heat and power
CWS – coastal water scrubbing
ED- energy density
EV – electric vehicles
FFC – fossil fuel comparator
FiT – feed-in tariff
IP – Intellectual property
LCOE – levelized cost of energy
MTOE – million tons oil equivalents
NGV – natural gas vehicles
PHEV – plugin hybrid electric vehicles
PV – photovoltaics
RED – Renewable Energy Directive
RESA – renewable energy sources act
RES-E - renewable energy supply in electricity
RES-H – renewable energy supply in heat
RES-T – renewable energy supply in transport
RWS – rural water scrubbing
SEAI – sustainable energy authority Ireland
SSRH – support scheme renewable heat
TRL – technology readiness level
UWS – urban water scrubbing
WS – water scrubbing

Funding Information

The Environmental Protection Agency, Ireland (EPA 2016-RE-DS-6) with co-funding from Gas Networks Ireland funded this work with additional funding from the Science Foundation Ireland (SFI) MaREI Centre (Grant no. 12/RC/2302 and 16/SP/3829).

ORCID Information:

Karthik Rajendran: [0000-0002-3638-4347](https://orcid.org/0000-0002-3638-4347)

Brian O Gallachoir: [0000-0002-6608-5997](https://orcid.org/0000-0002-6608-5997)

Jerry Murphy: 0000-0003-2120-1357

ACCEPTED MANUSCRIPT

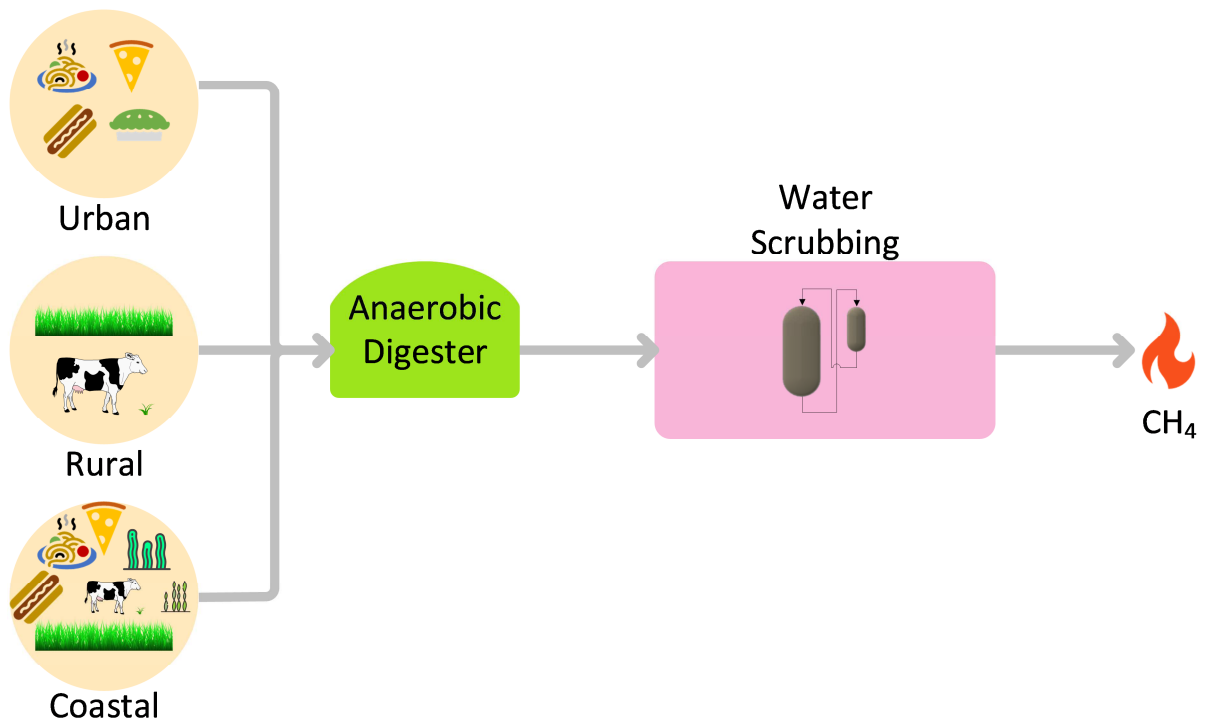


Figure 1. Three scenarios evaluated in this study

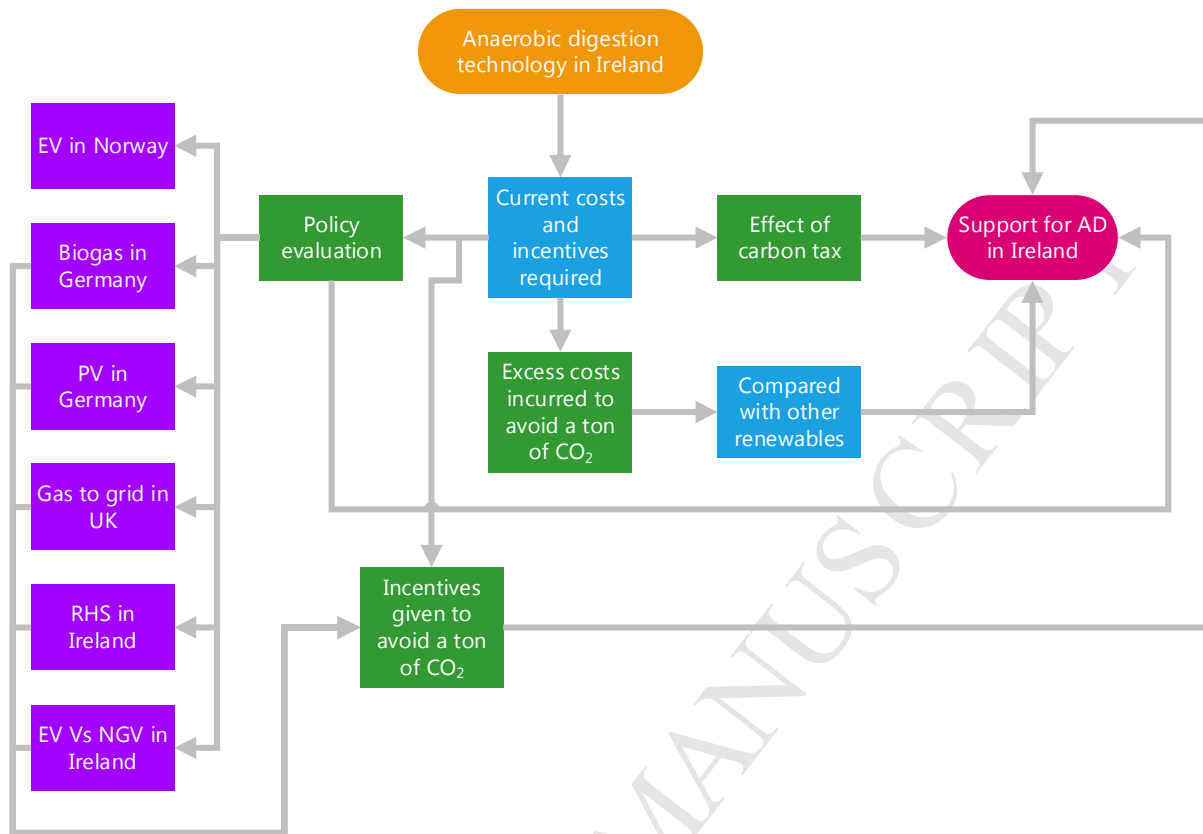


Figure 2. Methodologies used in this study to evaluate the support of AD technology in Ireland

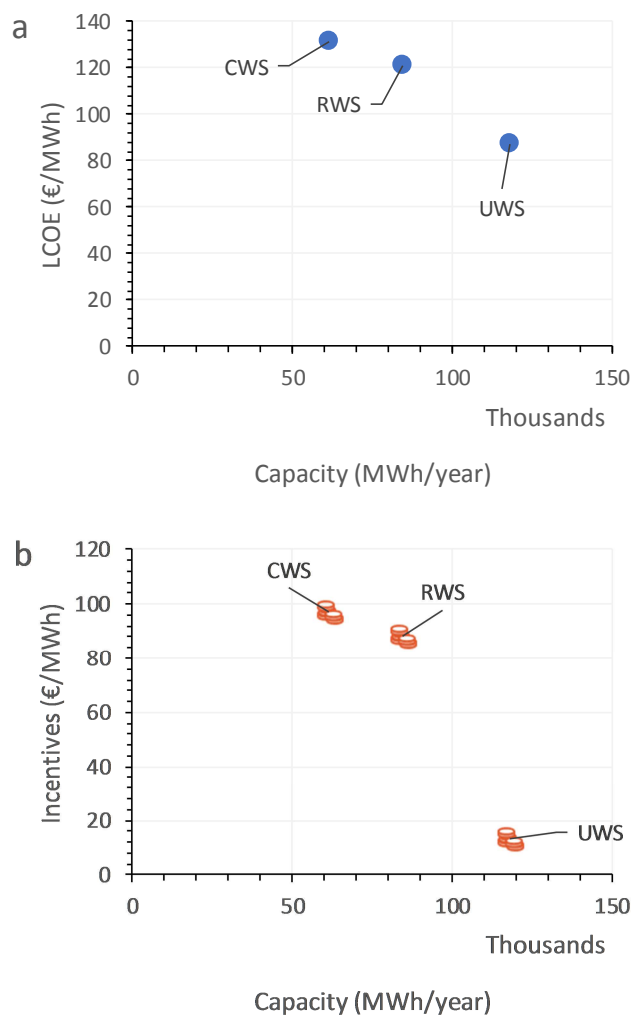


Figure 3. (a) Levelized cost of energy (LCOE) and (b) incentives needed to meet LCOE in the three scenarios evaluated (Rajendran et al., 2019).

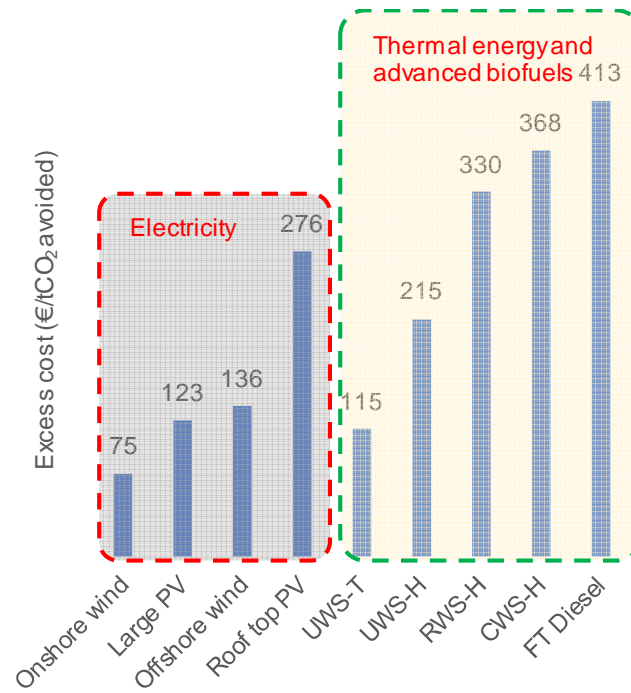


Figure 4. Excess cost to avoid a tonne of CO₂ for different renewable energy technologies (Cambridge Economic Policy Associates Ltd, 2017; Rajendran et al., 2019).

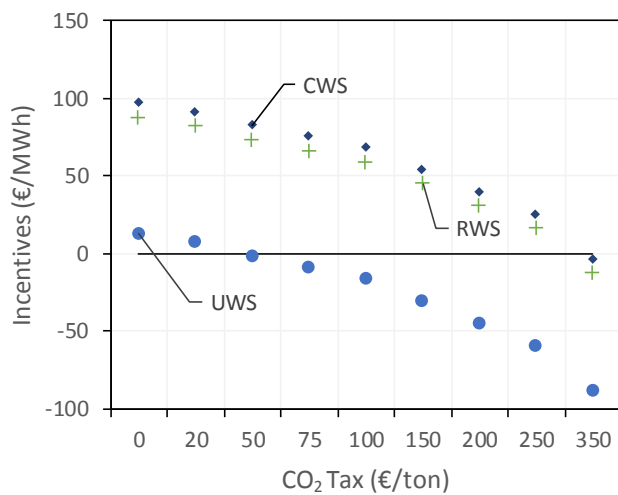


Figure 5. Effect of the carbon tax on the incentives needed to meet a break-even point in €/MWh for biomethane used in renewable heat for three scenarios.

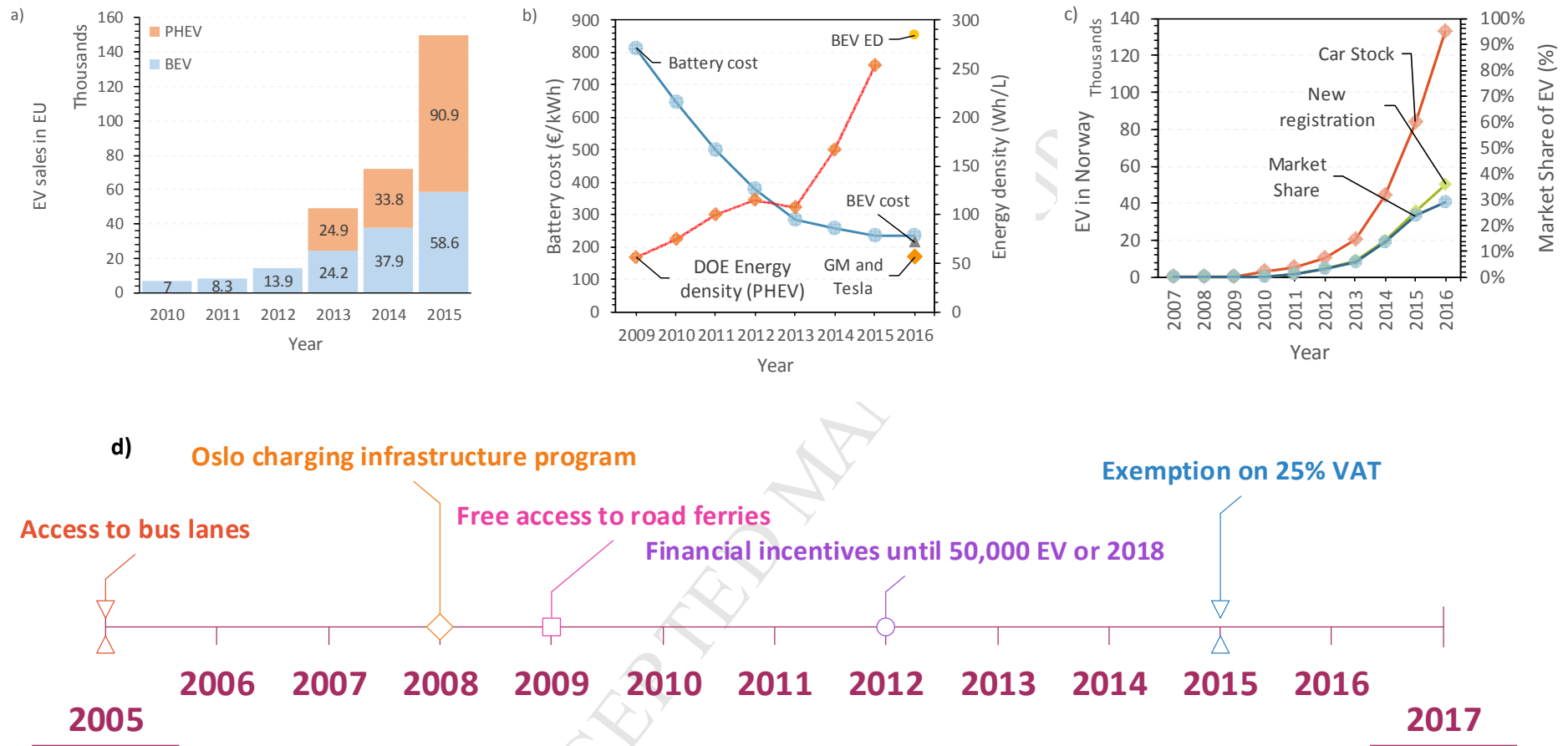


Figure 6. An incentive program that boosted use of EV in Europe with a detailed case study for Norway. (a) EV sales in Europe: PHEV – plug-in hybrid electric vehicles, BEV - battery electric vehicle; (b) change in battery cost and energy density of EV since 2009; (c) EV sales and market share in Norway; (d) policy drivers influencing EV in Norway (IEA, 2017a; EAFO, 2017).

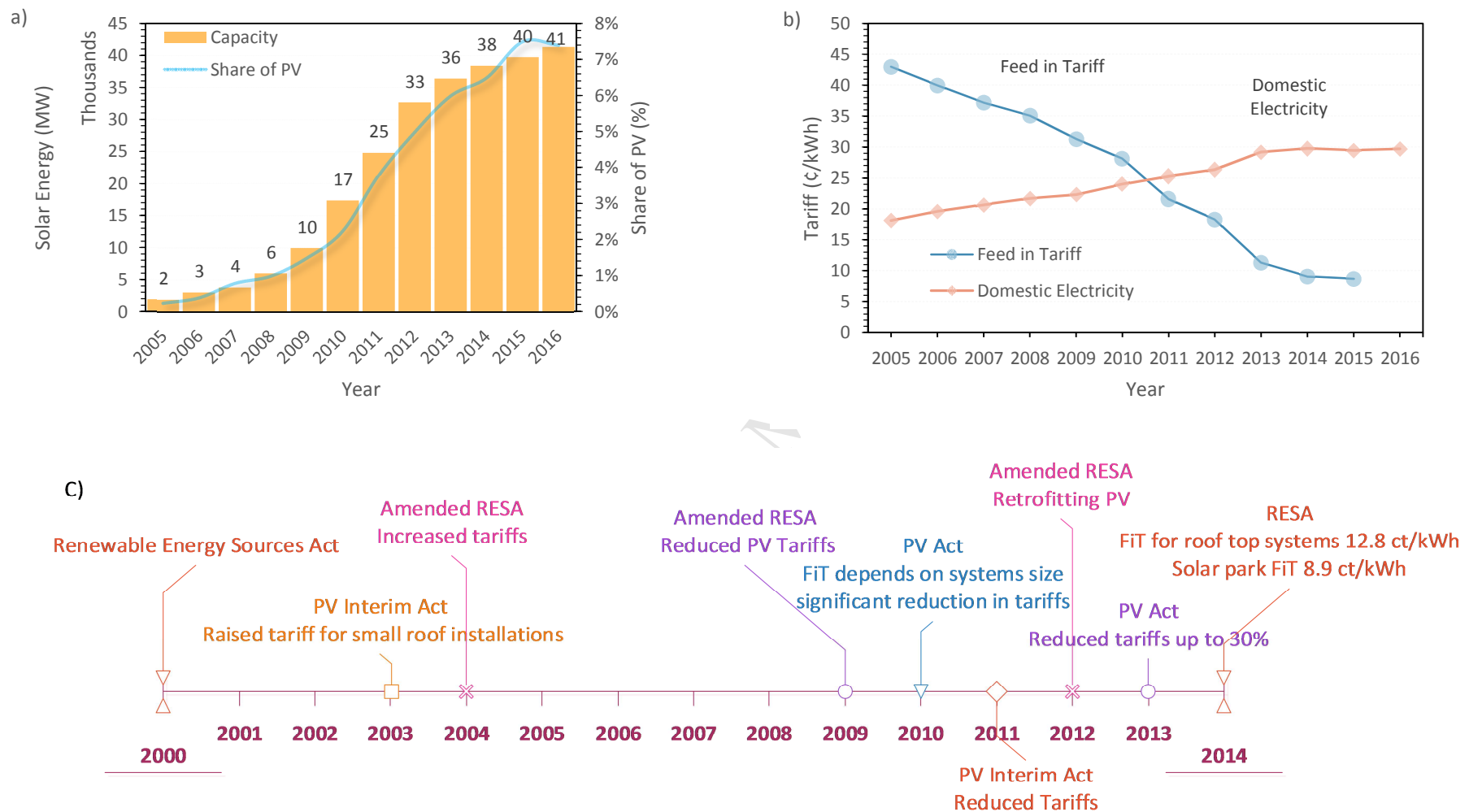


Figure 7. (a) Installed solar energy capacity and share of PV electricity in Germany; (b) Historical feed-in tariff for PV and domestic electricity prices in Germany; (c) Policies implemented and amended in relation to PV since 2000. (IEA, 2017b, EPIA, 2014).

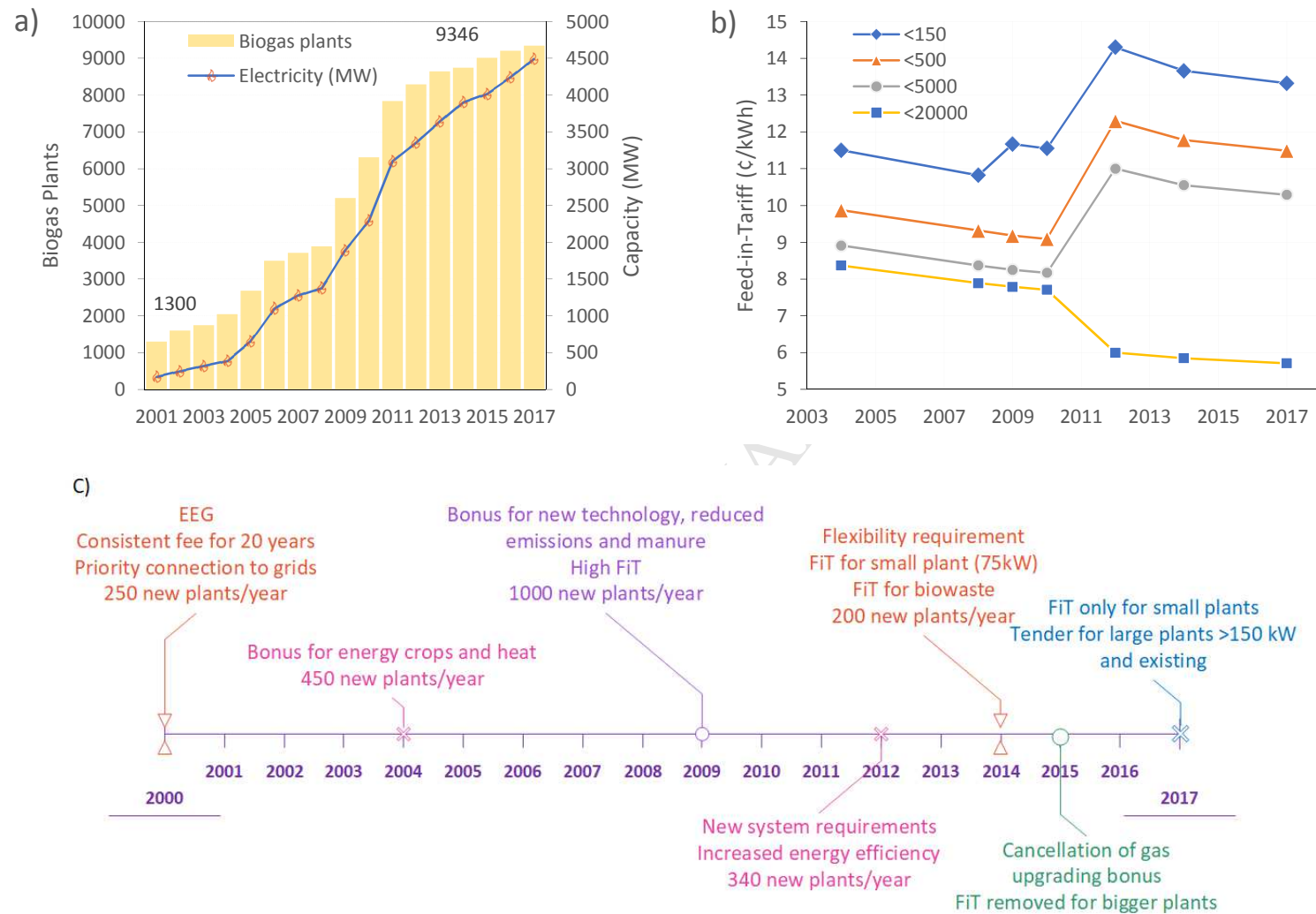


Figure 8. (a) Number of biogas plants installed and the electricity production capacity from the plant; (b) changes in the feed-in tariff for different capacities; (c) policies implemented and amended in relation to biogas in Germany. (Fachverband Biogas, 2017).

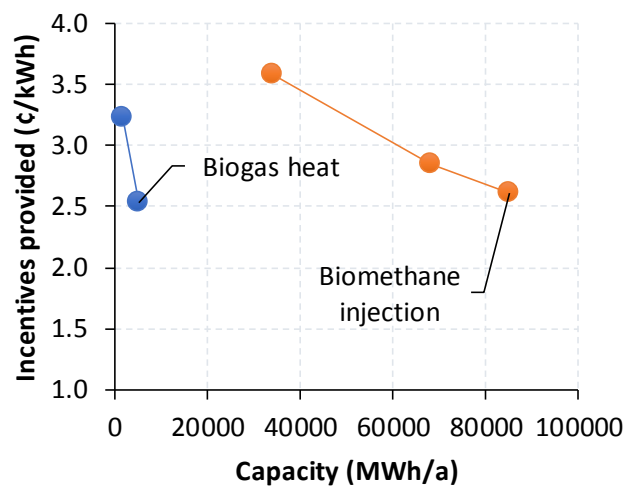


Figure 9. Renewable heat incentive scheme in the UK. (OGEM, 2017).

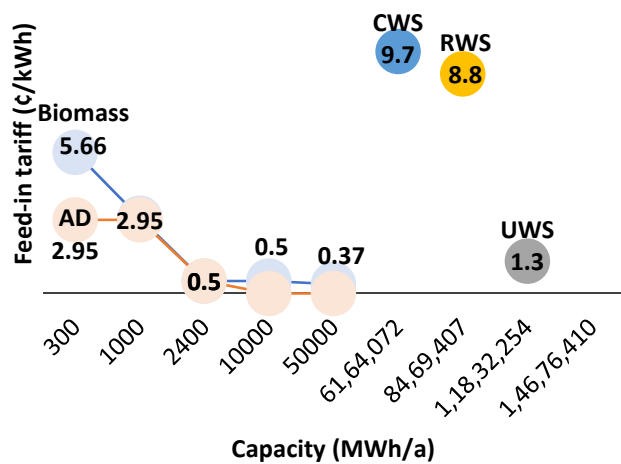
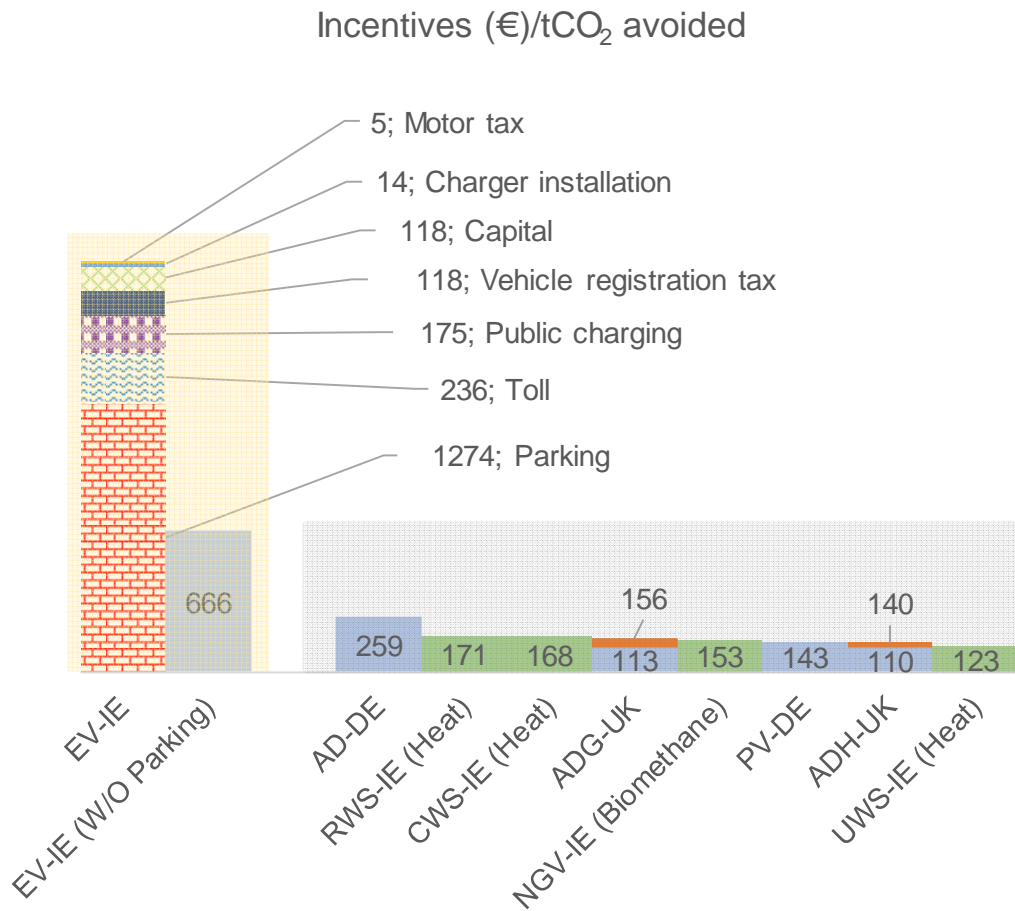


Figure 10. Proposed feed-in tariff for renewable heat in Ireland compared with the incentives needed for conventional upgrading methods.



The green coloured bars show the incentives needed in an Irish context. The blue coloured bars highlight the compared renewable technologies, while the orange coloured bars represent the upper bound values of incentives provided.

Figure 11. Comparison of different policies and the incentives to avoid a tonne of CO₂

(DTTAS, 2018b; IEA, 2017b; IEA 2017c; Rajendran et al., 2019; OGEM, 2017; DCCAE, 2017).

Table 1. Energy generation and avoided emissions from different resources in an Irish context (O'Shea et al., 2016).

		Unit	Food Waste	Grass Silage	Slurry
This study	Capacity	t/a	100,000	75,000	65,000
	Avoided Emissions	tCO ₂ /a	34,077	24,392	
	Energy	MWh/a	118,323	84,694	
Functional unit	Avoided emissions	tCO ₂ /t	0.34	0.17	
	Energy	MWh/t	1.18	0.60	
Resource estimation	Resource	t/a	6,428,000	31,300,000	28,500,000
	Energy	MWh/a	7,605,802	36,176,437	
	Avoided Emissions	tCO ₂ /a	2,190,463	10,418,823	

Appendix

Box 1. Calculation of excess costs incurred to avoid a tonne of CO₂ for renewable heat**Fossil Fuel Comparator (European Commission, 2017)**

FFC for heat = 80 gCO₂/MJ (or 80/0.2777 =) 288 kgCO₂/MWh;

FFC for transport = 94 gCO₂/MJ (or 94/0.2777 =) 338 kgCO₂/MWh;

FFC for electricity = 183 gCO₂/MJ (or 182/0.2777 =) 656 kgCO₂/MWh;

LCOE of FFC = 25 €/MWh for natural gas; 48 €/MWh for diesel in transport; 40 €/MWh for combined cycle gas turbine (electricity) (OpenEI, 2013).

LCOE of Renewable methane (Rajendran et al., 2019)

LCOE Urban (UWS)– 87 €/MWh; Rural (RWS)- 121 €/MWh; Coastal (CWS) –131 €/MWh

Cost of GHG savings of renewable gaseous methane for scenario UWS for renewable heat

GHG savings = 288 kgCO₂/MWh

Excess cost occurred = LCOE of Urban – LCOE of FFC = 87 – 25 = 62 €/MWh

Excess cost / tonne CO₂ avoided = 62 €/MWh / 0.288 tCO₂/MWh = **215 €/ tCO₂ avoided**

Box 2. Carbon tax calculation for biomethane from UWS for use in thermal energy

FFC emission = 80 gCO₂/MJ or = 0.288 tCO₂/kWh (Heat) (European Commission, 2017)

Current carbon tax in Ireland for FFC = 20 €/ tonne CO₂ released (EPA Ireland, 2015)

Upper bound value of carbon tax used in this study = 350 €/tonne CO₂ released

Capacity of energy produced from UWS = 118,323 MWh/a (refer figure 3a. UWS)

Comparative amount of CO₂ avoided from FFC = Capacity of energy × (FFC emission) =
118,323 MWh/a × (0.288) tCO₂/MWh = 34,077 tonne CO₂ /a

Carbon tax per MWh at 20 €/tonne CO₂ = Tonne CO₂ avoided × carbon tax / capacity
= 34,077 × 20 / 118,323 = 5.76 €/MWh

Incentives needed for UWS in the base case = 13 €/MWh

Incentives needed after carbon tax = Initial incentives – carbon tax credit
= 13 - 5.76 = 7.24 €/MWh

Incentives needed after upper bound carbon tax (350 €/tonne CO₂) = 13 - 100.8
= -87.8 €/MWh

Note: The negative value infers that the carbon tax credit from FFC will add a positive cash flow to the renewable methane.

Box 3. Incentives calculations for PHEV

Assumptions:

Annual distance travelled	20,000 km
Lifetime of EV	20 years
Parking hours	150 h/month
Public charging time	1 h/day
Charging speed (7 kW)	40 km/h or 6 kWh/h
Energy needed by EV	0.124 kWh/km

Capital incentives = 5000 €; Annualized incentives (1) = $5000/20 = 250$ €/a (SEAI, 2018)

Charger installation incentives = 600 € (SEAI, 2018); Annualized incentives (2) = $600/20 = 30$ €/a

Vehicle registration incentives = 5000 €; Annualized incentives (3) = $5000/20 = 250$ €/a (VRT, 2018)

Parking incentives (4) = 1.5 (€/h) \times 150 (h/month) \times $12 = 2700$ €/a (IPA, 2010)

Motor tax for PHEV = 170 €/a; Motor tax for NGV = 180 €/a (Environment Community and Local Government, 2016)

Motor tax incentives (5) = $180 - 170 = 10$ €/a

Night-time electricity rate = 8.4 ¢/kWh; Daytime electricity rate = 17 ¢/kWh

Night time charging incentives (6) = 6 (kWh/h) \times 8.4 (¢/kWh) \times 1 (h/day) \times 365 days
= 184 €/a

Daytime charging incentives (7) = 6 (kWh/h) \times 17 (¢/kWh) \times 1 (h/day) \times 365 days
= 372 €/a

Toll incentives (8) = € 500/a (DTTAS, 2018b)

Total annual incentives (1+2+3+4+5+6 or 7 +8) = **3924 – 4112 €/a**

CO₂ emissions of a VW Golf diesel car = 106 gCO₂/km; Fuel efficiency = 4.1 L/100km (VCA, 2018)

Diesel car emission for 20,000 km = 106 gCO₂/km × 20000 km = 2.12 tCO₂/a

Avoided emissions = Diesel car emissions = 2.12tCO₂/a

Incentives based on emissions avoided (Min) = Total incentives / avoided emissions

= 3924/2.12 = **1851 €/tCO₂avoided**

Incentives based on emissions avoided (Max) = 4112/2.12 = **1940 €/tCO₂avoided**

Box 4. Incentive calculations for NGV operating on biomethane

Fuel Efficiency of NGV = 3.5 kg/100 km; Density of NG = 0.8 kg/m³ (CNG Europe, 2018).

Fuel efficiency of NGV = 3.5/0.8 = 4.4 m³/100 km

Total fuel needed to drive 20,000 km = 880 m³/a

Incentives on biomethane fuel consumption (Higher end) = 2.95 ¢/kWh = 29.5 ¢/m³ (SSRH, Ireland)

Total incentives (1) = 880 m³/a × 29.5 ¢/m³ = 260 €/a

Avoided emissions (2) = Diesel car emissions = 2.12 tCO₂/a (Box 3)

Incentives based on emissions avoided (Biomethane) = (1)/ (2) = 260€/a /2.12 tCO₂/a = **123**

€/tCO₂avoided

References:

Ardolino, F., Parrillo, F., Arena, U., 2018. Biowaste-to-biomethane or biowaste-to-energy? An LCA study on anaerobic digestion of organic waste. *J. Clean Prod.* 174, 462-476.

Bloomberg, S., Bernstein, P., Tuladhar, S.D., King, M., Heidell, J., 2013. Impacts of Renewable Energy Subsidies/Incentives on Costs of Achieving Renewables Goals. Available in: http://www.nera.com/content/dam/nera/publications/archive2/PUB_Renewable_Energy_Subsidies_Incentives_0913.pdf. (Accessed 11-10-2018).

Cambridge Economic Policy Associates Ltd, 2017. Economic analysis to underpin a new renewable electricity support scheme in Ireland. DEPARTMENT OF COMMUNICATIONS, CLIMATE ACTION AND ENVIRONMENT, Dublin, Ireland, pp. 1-153.

Capodaglio, A.G., Callegari, A., Lopez, M.V., 2016. European framework for the diffusion of biogas uses: emerging technologies, acceptance, incentive strategies, and institutional-regulatory support. *Sustainability* 8(4), 298.

CNG Europe, 2018. List of Volkswagen cars on natural gas CNG. Available in: <http://cngueurope.com/natural-gas-vehicles/volkswagen/>. (Accessed 06-04-2018).

Cucchiella, F., D'Adamo, I., Gastaldi, M., Miliacca, M., 2018. A profitability analysis of small-scale plants for biomethane injection into the gas grid. *J. Clean Prod.* 184, 179-187.

DCCAE, 2017. Support Scheme for Renewable Heat. Available in: <https://www.dccae.gov.ie/documents/Support%20Scheme%20for%20Renewable%20Heat%20Overview.pdf>. (Accessed 17-02-2018).

DTTAS, (2018a). Ministers Naughten and Ross reaffirm commitment to Electric Vehicle transition. Available in: <http://www.dttas.ie/press-releases/2017/ministers-ross-and-naughten-reaffirm-commitment-electric-vehicle-transition>. (Accessed 11-10-2018).

DTTAS, (2018b). Electric Vehicle Toll Incentive Information. Available in: <http://www.dttas.ie/sites/default/files/press-releases/ev-toll-incentive-leaflet.pdf> (Accessed 11-10-2018).

EAFO, 2017. European Alternative Fuels Observatory (EAFO). Norway, Available In: <http://www.eafo.eu/content/norway> (Accessed 17-02-2018).

Engdahl, K., 2013. Biogas policies, incentives and barriers. Master thesis; Department of Technology and Society Environmental and Energy Systems Studies Lund University. Lund, Sweden.

Environment Community and Local Government, 2016. Motor Taxation http://www.housing.gov.ie/sites/default/files/publications/files/20170626_amended_motor_tax_rates_01_january_2016_0.pdf. (Accessed 11-10-2018).

EPA Ireland, 2015. Ireland's Greenhouse Gas Emission Projections 2014-2035. Environmental Protection Agency Ireland, Dublin, Ireland, pp. 1-17.

EPIA, 2014. European Photovoltaic Industry Association (EPIA) Global Market Outlook for Photovoltaics 2014-2018. Available In: <https://www.webcitation.org/6QGSvAF7w> (Accessed: 11-10-2018).

European Commission, 2017. ANNEXES to the Proposal for a Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (recast) Brussels, Belgium, pp. 1-108.

EV Norway, 2017. Norwegian EV policy: Since the early 1990's the incentive program have been gradually introduced by a broad coalition of different political parties. Available in: <https://elbil.no/english/norwegian-ev-policy/> (Accessed 17-02-2018).

Fachverband Biogas, 2017. German Biogas Association.

Gas Networks Ireland, 2018. The Causeway Project. Delivering sustainable transport for Ireland with a CNG refuelling network. Available in: <https://www.gasnetworks.ie/business/natural-gas-in-transport/the-causeway-project/> (Accessed 07-11-2018).

Glynn, J., Gargiulo, M., Chiodi, A., Deane, P., Rogan, F., Ó Gallachóir, B., 2018. Zero carbon energy system pathways for Ireland consistent with the Paris Agreement. Climate Policy, 1-13.

Hoo, P.Y., Hashim, H., Ho, W.S., 2018. Opportunities and challenges: Landfill gas to biomethane injection into natural gas distribution grid through pipeline. J. Clean Prod. 175, 409-419.

IEA, 2000. Renewable Energy Sources Act. Available in: <https://www.iea.org/policiesandmeasures/pams/germany/name-21702-en.php> . (Accessed 17-02-2018).

IEA, 2004. Renewable Energy Sources Act 2004. Available In: <https://www.iea.org/policiesandmeasures/pams/germany/name-22369-en.php> . (Accessed 17-02-2018).

IEA, 2009. Renewable Energy Sources Act 2009. Available In: <https://www.iea.org/policiesandmeasures/pams/germany/name-24289-en.php>. (Accessed 17-02-2018).

IEA, 2012. Renewable Energy Sources Act 2012. Available In: <https://www.iea.org/policiesandmeasures/pams/germany/name-25107-en.php>. (Accessed 17-02-2018).

- IEA, 2014. Renewable Energy Sources Act 2014. Available In: <https://www.iea.org/policiesandmeasures/pams/germany/name-145053-en.php>. (Accessed 17-02-2018).
- IEA, 2017a. Global EV Outlook 2017 Two million and counting. pp. 1-71. Available In: <https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>. (Accessed 11-10-2018).
- IEA, 2017b. 2017 Amendment of the Renewable Energy Sources Act (EEG 2017) Available In: <http://www.iea.org/policiesandmeasures/renewableenergy/?country=germany>. (Accessed 17-02-2018).
- IEA, 2017c. 2017 Amendment of the Renewable Energy Sources Act (EEG 2017) Available In: <https://www.iea.org/policiesandmeasures/pams/germany/name-158567-en.php>. (Accessed 17-02-2018).
- IEA, 2018. Electric Vehicles <https://www.iea.org/tcep/transport/evs/>. (Accessed 08-10-2018).
- IEA Bioenergy, 2018. Fossil vs biogenic CO2 emissions. Available In: <https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/> (Accessed 07-10-2018).
- IEA Task 37, 2017. Biogas Plant List <http://task37.ieabioenergy.com/plant-list.html>. (Accessed 07-10-2018).
- IMF, 2018. GDP per capita, current prices. Available In: <http://www.imf.org/external/datamapper/NGDPDPC@WEO/OEMDC/ADVEC/WEOWORLD/NOR>. (Accessed 17-02-2018).
- IPA, 2010. The Irish Car Parking Sector Market Report 2010. Available In: <http://www.parkingireland.ie/wp-content/themes/irishparking/img/files/Market-Report-2010.pdf>. (Accessed 04-04-2018).
- IRENA, 2015. Renewable Energy Prospects: Germany. Available In: http://www.irena.org/documentdownloads/publications/irena_remap_germany_report_2015.pdf (Accessed 17-02-2018).
- KPMG International, 2015. Taxes and incentives for renewable energy. KPMG, pp. 1-84.
- Löschel, A., 2016. Energy Costs in Germany and Europe. Available In: <https://assets.kpmg.com/content/dam/kpmg/pdf/2015/09/taxes-and-incentives-2015-web-v2.pdf>. (Accessed 11-10-2018).

Mayer, J.N., Philipps, S., Hussein, N.S., Schlegl, T., Senkpiel, C., 2015. Current and Future Cost of Photovoltaics, in: Mayer, J.N. (Ed.). Fraunhofer ISE Agora Energiewende, Germany, pp. 1-82. Available In: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Agora_Energiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf. (Accessed 11-10-2018).

Norden, 2014. Nordic action on climate change. Available In: <http://norden.diva-portal.org/smash/get/diva2:768493/FULLTEXT01.pdf>. (Accessed 08-10-2018).

O'Shea, R., Kilgallon, I., Wall, D., Murphy, J.D., 2016. Quantification and location of a renewable gas industry based on digestion of wastes in Ireland. *Appl. Energ.* 175, 229-239.

O'Shea, R., Wall, D., I.Kilgallon, J. Browne, Murphy, J.D. (2017) Assessing the total theoretical, and financially viable resource of biomethane for injection to a natural gas network in a region. *Appl. Energ.* 188, 237 – 256.

OGEM, 2017. Tariffs and Payments: Non-Domestic RHI. <https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-non-domestic-rhi>. (Accessed 04-04-2018).

OpenEI, 2013. Transparent cost database, <https://openei.org/apps/TCDB/#>. (Accessed 19-11-2017).

Rajendran, K., Browne, J., Murphy, J.D., 2019. What is the level of incentivisation required for biomethane upgrading technologies with carbon capture and reuse? *Renewable Energy*. 133, 951-963. <https://doi.org/10.1016/j.renene.2018.10.091>

Rotunno, P., Lanzini, A., Leone, P., 2017. Energy and economic analysis of a water scrubbing based biogas upgrading process for biomethane injection into the gas grid or use as transportation fuel. *Renew. Energ.* 102, 417-432.

Scheer, J., Clancy, M., Gaffney, F., 2016. Ireland's Energy Targets - Progress, Ambition & Impacts. Sustainable Energy Authority of Ireland, Dublin, Ireland, pp. 1-30. Available In: https://www.seai.ie/resources/publications/Ireland_s-Energy-Targets-Progress-Ambition-and-Impacts.pdf. (Accessed 17-02-2018).

SEAI, 2016a. Economic Assessment of Biogas and Biomethane in Ireland. Sustainable Energy Authority Ireland, Dublin, Ireland, pp. 1-2. Available In: <https://www.seai.ie/resources/publications/Summary-Assessment-of-the-Cost-and-Benefits-of-Biogas-and-Biomeathane-in-Ireland.pdf>. (Accessed 17-02-2018).

SEAI, 2016b. Ireland's Energy Targets. Available In: <https://www.seai.ie/about/irelands-energy-targets/>. (Accessed 17-02-2018).

- SEAI, 2016c. Renewable Electricity in Ireland 2015. Available In: <http://www.seai.ie/resources/publications/Renewable-Electricity-in-Ireland-2015.pdf>. (Accessed 17-02-2018).
- SEAI, 2017a. Energy Statistics. Available In: <https://www.seai.ie/resources/energy-data/>. (Accessed 11-11-2017).
- SEAI, 2017b. Support Scheme Renewable Heat. Available in: <https://www.seai.ie/sustainable-solutions/support-scheme-renewable-/>. (Accessed 17-02-2018).
- SEAI, 2018. Electric Vehicle Grant Values. Available In: <https://www.seai.ie/grants/electric-vehicle-grants/grant-amounts/>. (Accessed 04-04-2018).
- Statista, 2015. Total sales of electric vehicles in the European Union (EU) from 2010* to 2015** (in thousand units). Available In: <https://www.statista.com/statistics/642799/eu-total-sales-electric-vehicles/>. (Accessed 17-02-2018).
- Statista, 2017. Electricity prices for households in Germany from 2010 to 2017, semi-annually (in euro cents per kilowatt-hour). Available In: <https://www.statista.com/statistics/418078/electricity-prices-for-households-in-germany/>. (Accessed 17-02-2018).
- Statistics Norway, 2011. Generation and consumption of electricity. <http://www.ssb.no/en/energi-og-industri/statistikker/elektrisitetaar/aar/2013-03-20?fane=tabell&sort=nummer&tabell=169462>. (Accessed 17-02-2018).
- VCA, 2018. Find fuel consumption and emissions information on a new or used car. <http://carfueldata.direct.gov.uk/search-new-or-used-cars.aspx?vid=40603>. (Accessed 06-04-2018).
- VRT, 2018. Hybrid & Electric Vehicles, VRT Repayment Rates. <https://www.vrt.ie/home/vehicle-registration-tax-in-detail/vehicle-registration-tax-rates/hybrid-electric-vehicles-vrt-repayment-rates/>. (Accessed 30-04-2018).
- Wall, D.M., Allen, E., Straccialini, B., O’Kiely, P., Murphy, J.D., 2014. Optimisation of digester performance with increasing organic loading rate for mono-and co-digestion of grass silage and dairy slurry. *Bioresour. Technol.* 173, 422-428.
- Wall, D., Dumont M., Murphy, J.D. (2018) Green Gas: facilitating a future green gas grid through the production of renewable gas. Murphy, J.D. (Ed.) IEA Bioenergy Task 37, 2018:2
- Wirth, H., 2018. Recent Facts about Photovoltaics in Germany. Fraunhofer ISE, Germany, pp. 1-89. Available in: <https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/recent-facts-about-photovoltaics-in-germany.pdf>. (Accessed 11-10-2018).

Highlights

Incentives should be provided with cognisance of the level of emissions avoided.

Electricity from wind has an excess cost over fossil fuel per tCO₂ avoided of €75.

Fischer Tropsch (FT) diesel has an excess cost of €413/tCO₂ avoided.

Biomethane for renewable heat needs incentives of between 123 and 171 €/tCO₂ avoided.

The support for electric vehicles in Ireland is in the range 666-1940 €/tCO₂ avoided.