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Can thermal energy recovery from digestate make renewable gas from household waste more cost effective? A case study for the Republic of Ireland

Alessandro Singlitico [a, b, c], Karla Dussan [d], Richard O'Shea [c, e], David Wall [c, e], Jamie Goggins [a, b, c], Jerry D. Murphy [c, e], Rory F.D. Monaghan [a, b, c, *]

[a] College of Engineering and Informatics, National University of Ireland, Galway, Ireland
[b] Ryan Institute for Environmental, Marine and Energy Research, Galway, Ireland
[c] MaREI Centre for Marine and Renewable Energy, Ireland
[d] Biomass & Energy Efficiency Group, ECN Part of TNO, Netherlands Organisation for Applied Scientific Research TNO, Petten, Netherlands
[e] Environmental Research Institute, School of Engineering, University College Cork, Ireland

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A B S T R A C T

This article assesses the impact of energy recovery from digestate on the economics of biomethane produced from the organic fraction of municipal solid waste. Six waste-to-energy routes are investigated and assumed to be deployed in the regional context of the Republic of Ireland. Anaerobic digestion without energy recovery, and landspreading of dewatered digestate, presents the lowest levelised cost for the biomethane produced, from 86.8 to 108.9 €/MWh, and highest net present value, from 70.6 to 116.4 M€. However, if the digestate is dried, synthetic natural gas production from the digestate through steam gasification, maximising the amount of renewable gas produced, presents the lowest levelised cost, from 93.4 to 113.8 €/MWh, and highest net present value, from 65.5 to 111.8 M€ and highest net present value. Due to the largest substitution of natural gas, this process presents also the largest CO2 emission saving, from 12.1 to 20 kilotonnes of CO2 per annum. Transportation costs of the residues generated, because of the proximity of farm lands in which the digestate is landspread, and because of the small amount of ash generated, are negligible when compared to CapEx, OpEx and energy expenditure. CapEx and OpEx are the most sensitive parameters, and the more the energy demand of the process is not covered the more the expenditure for energy supplies become relevant. Although all the alternatives presented cost greater than natural gas price for household consumers, 70.3 €/MWh, additional revenues for waste management services would make the renewable gas produced profitable.

1. Introduction

1.1. Background

The Landfill Directive (The Council of European Union, 1999) obliged European Union (EU) Member States to reduce the amount of organic waste that they landfill to 35% of 1995 levels by 2016, or 2020 for some countries. Production of biogas represents a mature alternative route for both organic waste management and energy recovery. In 2018, there were more than 17,783 biogas plants in Europe. Biogas can be upgraded into biomethane, which can be injected into the natural gas grid, and use for heating, transport and electricity generation. The EU is the world's leading producer of biomethane, with 540 plants producing an estimated 1.94 billion m^3 annually (European Biogas Association, 2019). The European Biomass Association estimated a current potential of 78 billion m^3 of biogas, with 10 billion m^3 alone derived from the organic fraction of municipal solid waste (OFMSW) (Scarlat et al., 2018).

The sustainability of biomethane is linked to the successful management of the digestate, the remaining non-degraded material after AD, with the goal of reducing economic and environmental impact, by employing a more circular economy (Peng and Pivato, 2019). Digestate is rich in nutrients contained in the original feedstock (N, P, K), and can be used as an organic fertiliser via

* Corresponding author. College of Engineering and Informatics, National University of Ireland, Galway, Ireland.
E-mail address: rory.monaghan@nuigalway.ie (R.F.D. Monaghan).

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Table of abbreviations

AD	Anaerobic digestion
ASH	Ash content
Bio-SNG	Biomass-derived synthetic natural gas
CEPCI	Chemical Engineering Plant Cost Index
CHP	Combined heat and power
DS	Dry solid content
ED	Electoral division
FW	Food waste
GIS	Geographical information system
GW	Garden waste
ICE	Internal combustion engine
LCOE	Levelised cost of the energy
MC	Moisture content
NPV	Net present value
OFMSW	Organic fraction of municipal solid waste
ROI	Republic of Ireland
VS	Volatile solid content
VSD	Volatile solid destruction

Table of symbols

C	Coverage
CapEx	Capital expenditures
CF	Cash flow
d	Distance
DAF	Dry and ash-free
DB	Dry basis
DR	Discount rate
E	Energy
EnEx	Energy expenditures
F	Feedstock
GF	Gate Fee
Inc	Incentives
L	Volumetric percentage of methane leaked
LHV	Lower heating value
LT	Life time
m	Mass
OH	Operating hours
OpEx	Operational expenditures
p	Pressure
P	Price
Q	Heat
SMY	Specific methane yield
T	Temperature
TrEx	Transport expenditures
vol%	Volume percentage
W	Power

Table of subscripts

ARB	As-received basis
BG	Biogas
Bio-SNG	Biomass-derived natural gas
BM	Biomethane
D	Digestate
gas	Natural Gas
i	Biomass origin
in	Inflow
j	Facility site
k	Reuse destination
out	Outflow
R	Residues
RG	Renewable gas
UP	Biomethane upgrade
y	Year

landspreading, but it also contains many contaminants, contained in animal by-products. Therefore, digestate must be thermally treated to remove potential pathogens prior to landspreading, incurring additional energy demand for the AD plant (Lukehurst et al., 2010). Moreover the annual load of nitrogen, contained in the digestate, that can be applied to agricultural land is limited by the European Nitrate Directive 91/676/EEC (European Commission, 1991).

Therefore, despite AD's relative technological simplicity and low costs, when compared to thermochemical treatments such as gasification or incineration, its lower energy recovery and minor waste mass reduction undermine AD's energy and economic efficiency. This is primarily due to the energy demands and costs of additional treatments for the transport and reuse of digestate. Biomethane viability is only possible when the whole supply chain, including collection of OMFSW, its conversion to products and by-products, and transport and reuse of residues, is considered on a spatially-explicit level, including actual constraints (e.g. road distances, landspreading limits, etc.).

1.2. Literature review

In order to investigate the viability of biomethane, assessing the interplay between waste volume minimisation, energy recovery, and the energy penalties and costs necessary for handling wastes, it is necessary that: (i) the pathway of the residues is included in the system boundaries, (ii) thermodynamic models assess the energy recovery from digestate, (iii) a geospatial model is used to evaluate the costs for transporting the residues to available reuse sites (e.g. farm land, incinerators).

Table 1 summarises the techno-economic assessments of biomethane production for OFMSW. In the studies in which the residues end-uses are accounted for, direct use on land is the main method of valorisation; energy recovery is not considered, not even in the case in which the digestate is incinerated (Morero et al., 2017). Moreover, geographical models to assess and optimise transport distances of the feedstock are used only for the Republic of Ireland (O'Shea et al., 2017),for southern Malaysia (Hoo et al., 2019), for Merida (Mexico) (Gutiérrez et al., 2018). In the other studies, in spite of the declared geographical scopes, no geospatial model was developed to optimise and assess the impact of digestate transport: for Rio De Janeiro (Brazil) (Ornelas-ferreira et al., 2020), Thailand (Koido et al., 2018), Argentina (Morero et al., 2017), Republic of Ireland (Browne et al., 2011), Italy (Cucchiella et al., 2018; Cucchiella and Adamo, 2016). The transportation to the end-use location of the digestate generated is not optimised in any of the these studies, thus not accounting the impacts that the volume of the residues and the distances to the end-use sites can have on the biomethane produced.

1.3. Aims and objectives

The reviewed studies captured the costs and profits of the conversion of OFMSW into biomethane, omitted possible energy recovery from the digestate and the optimisation of the allocation of the residues produced. The present work seeks to address this

Table 1
Review of techno-economic assessments of biomethane production from OFMSW.

Ref.	Year	Region	Residues end-use	Energy recovery from digestate	Geospatial model for residue transport
Ornelas-ferreira et al. (2020)	2020	BR	✓ (landspreading)	✗	✗
Hoo et al. (2019)	2019	MY	✗	✗	✗
Koido et al. (2018)	2018	TH	✓ (landspreading)	✗	✗
Gutiérrez et al. (2018)	2018	MX	✗	✗	✗
Cucchiella et al. (2018)	2018	IT	✗	✗	✗
Morero et al. (2017)	2017	AR	✓ (landspreading, incineration)	✗	✗
O'Shea et al. (2017) O'Shea et al. (2016a)	2017 2016	IE	✓ (landspreading)	✗	✓ (residue transported back to the OFMSW origin)
Cucchiella and Adamo (2016)	2016	IT	✗	✗	✗
Browne et al. (2011)	2011	IE	✗	✗	✗

✓: evaluated; ✗: not evaluated.
BR: Brazil; MY: Malaysia; TH: Thailand; MX: Mexico; AR: Argentina; IT: Italy; IE: Ireland.

gap in the literature.

The aim of this work is to find the most sustainable biomethane production route from OFMSW, including also digestate treatment and allocation of the residues.

Therefore, the objectives of this work are to:

- Calculate energy and economic performances of viable energy recovery treatments of digestate.
- Calculate the transport cost of the residues to end-use sites in a spatially explicit context, thus considering spatial constraints, such as farm lands, incinerators and landspreading limits.
- Calculate the cost of the biomethane produced, considering the full supply chain and end-use of the residuals for different alternatives.
- Calculate the carbon intensity of the scenarios investigated, as a preliminary environmental assessment.

1.4. Case study and applicability to other regions

This study has been performed on the reference case of the ROI, whose gas transmission operator, Gas Networks Ireland, set a target of 21.5 PJ a^{-1} of renewable gas production by 2024 (Gas Networks Ireland, 2015). This work integrates previous studies based only on AD and biogas upgrading (O'Shea et al., 2016a, 2015) from OFMSW, FW and GW percentages of OFMSW, spatial distribution, and the optimal location of the AD plants. This work is also complementary to previous studies regarding biomass-derived synthetic natural gas (bio-SNG) production, including biomass distribution (Singlitico et al., 2018), techno-economic (Singlitico et al., 2019b) and life cycle assessment-based (Singlitico et al., 2020) supply chain optimisations, representing applied cases in the ROI for a hybrid methodology conceived to lead to a sustainable decarbonisation of the gas grid (Singlitico et al., 2019a).

For all these reasons the ROI has been used as test bench for this study, but when the same inputs are found for other regions, the methodology of this study can be applied to any regional context, using the waste distribution, road networks, and conversion and reuse facilities sites.

2. Materials and methods

Measurements of specific biogas production from the two main components of OFMW, garden waste and food waste, and composition of the digestate are collected experimentally and then used in the thermodynamic model to simulate six different technology routes, in which OMSFW is processed via AD, and the biogas is upgraded to biomethane, while the digestate undergoes thermochemical treatments. These treatments include air and steam gasification, and combustion. The overall thermodynamic and economic performances are then calculated.

Digestate produced by AD technologies, when it is not processed by a further thermochemical treatment, can be spread on farm land as a biofertiliser. Ashes, produced by thermochemical treatments, are used as cement aggregate. The combination of the six technology routes with their relevant reuse alternatives are applied to five OFMSW treatment plants, to which the OFMSW is allocated accordingly to a previous study by O'Shea et al. (O'Shea et al., 2016a). The feedstock transport distances, from their origin locations to the facilities in which they are to be processed, and the residue transport distances, from the plant in which they are generated to the closest residue reuse sites, choosing the shortest road distance is assessed through GIS modelling. Levelised cost of the energy (LCOE) and net present value (NPV) are assessed and compared for a total of thirty scenarios, which include six technology routes and five plants. Fig. 1 shows a representation of the performed work. In the following subsections, the experimental measures, the GIS model, the thermodynamic and cost modelling are described.

2.1. Experimental characterisation

OFMSW is composed of household FW and garden waste (GW), with proportions depending on location (rural or urban) (O'Shea et al., 2015). Samples of FW and GW are collected and processed through a lab-scale AD apparatus. The composition of the digestate produced is then analysed via thermogravimetric analysis. The methane volumetric percentage (C_{CH4}) in the biogas and the specific methane yield (*SMY*) in units of Nm^3 per kg of volatile solid (*VS*) of the two feedstocks are measured weekly.

The proximate and ultimate analysis of FW and GW feedstocks and their digestate are assessed. Proximate analysis is carried out to characterise MC and ash content (*ASH*) following standard procedures (Sluiter et al., 2008a, 2008b). Ultimate analysis recorded the mass percentages of carbon, hydrogen and nitrogen content (C, H, N) are recorded (see Supplementary Material for details).

2.2. GIS-based modelling

Previous studies by O'Shea et al. (O'Shea et al., 2016a, 2015) provided the quantity and distribution of OFMSW available, its composition in GW and FW, and also the optimised locations of five AD plants in which the OFMSW from each electoral division (ED) is allocated (Fig. 2). The biomethane injection points correspond to above ground installations (AGIs) on the gas transmission network, where gas pressure is reduced from transmission pressures of

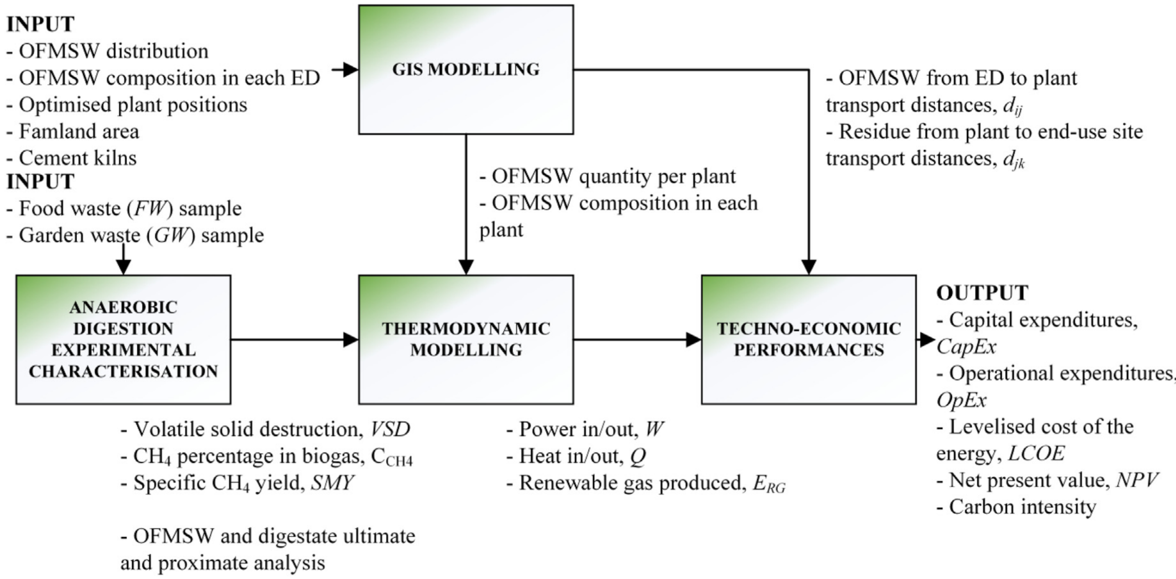

Fig. 1. Flowchart showing the work units and the main data exchange between them.

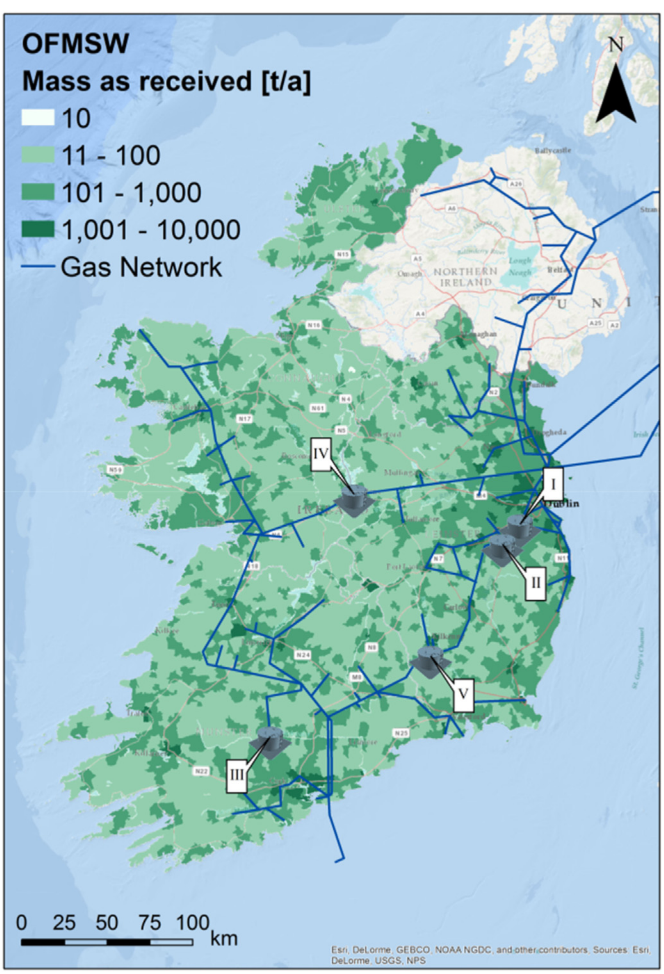

Fig. 2. Map of OFMSW distribution in the ROI and the optimised location of the proposed anaerobic digestion facilities (1–5) along the gas grid.

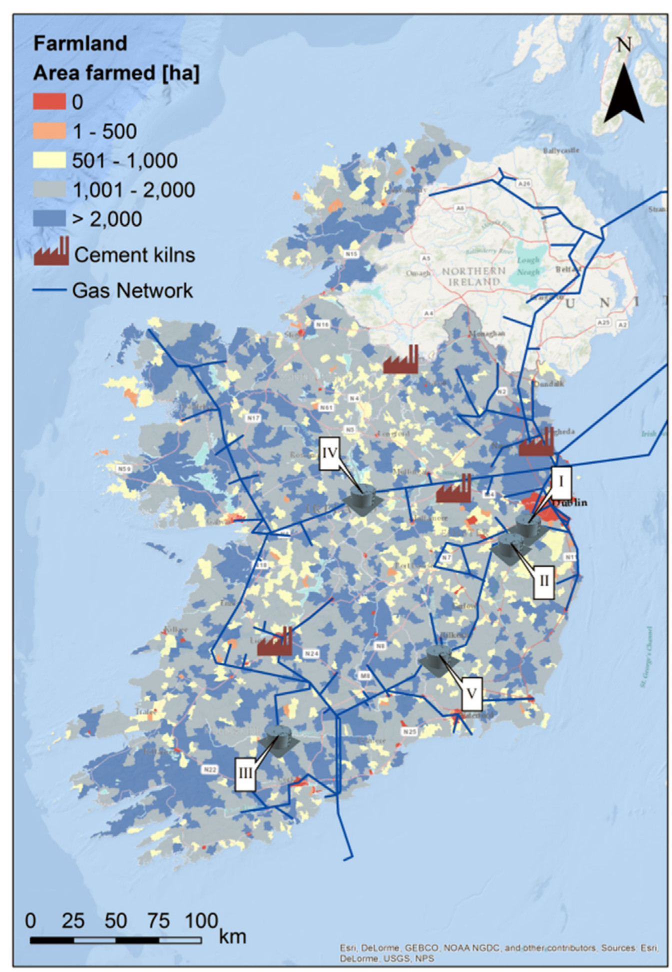

Fig. 3. Area farmed in each ED (sourced from (CSO, 2012)) and cement kilns location.

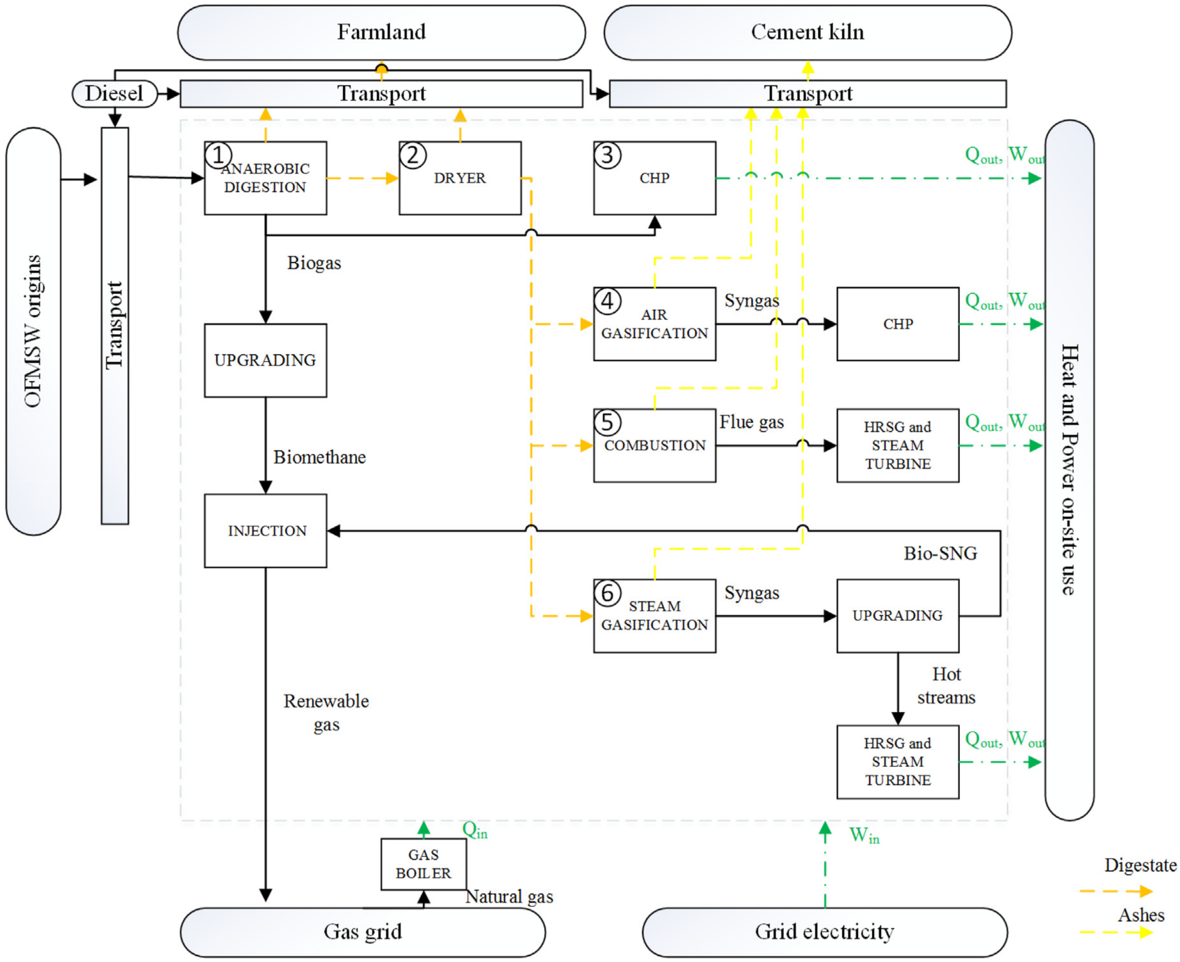

Fig. 4. Flowchart of the materials and energy exchanges, and activities included in the assessment. The numbers in the boxes represent each technology route (T) investigated. Note: stages for energy recovery 3,4,5 and 6 are exclusive.

approximately 70 bar to below 16 bar for onward delivery to distribution networks, which typically operate at 4 bar, with an injection capacity of 560 GWh (Singlitico et al., 2019b).

The road distances from the plant to the end-use site of the residues are optimised considering the shortest path between them. In the scenario of landspreading, digestate is transported by road to the nearest farmed area, considered in the centroid of the ED in which the farm land is located, and landspread within the legal limit of nitrogen in-take of the soil, of 170 kg ha^{-1} y^{-1} (The Department of Agriculture & Food, 2008). The area of farm land in each ED is sourced from the latest Census of Agriculture (CSO, 2012) and is shown in Fig. 3. The road network, consisting of primary, secondary and tertiary roads, is sourced from the free access Open Street Map archive road network (Openstreet Map contributors, 2016).

Spatial distributions and transportation distances were assessed with ArcGIS 10.3 (ESRI, 2015), considering a total of 3409 EDs as the minimal geographical units in the ROI for statistical purposes (CSO, 2011). All of the resources found in each ED are considered uniformly distributed inside its area. The coordinate reference system utilised in the GIS was the IRENET95/Irish Transverse Mercator (EPSG 2157).

2.3. Thermodynamic modelling

The experimental characterisation of OFMSW and its digestate are used as inputs for the thermodynamic models, in which the mass and energy balances of six technology routes are simulated, using Matlab R2016a (The MathWorks Inc., 2016), with the Cantera 2.2.1 add-on for thermochemical calculations (Goodwin et al., 2017).

Six technology routes (T) are simulated, presented as alternatives for conversion of OFMSW to biomethane and energy recovery from the digestate generated. Fig. 4 shows the main stages involved in the conversion processes investigated. T1 is the simplest case in which OFMSW is digested, producing biogas and digestate. The former is upgraded to biomethane and the latter is landspread. In T2, the digestate is landspread after been dried to a MC of 10%. T3, T4, T5, T6 represent separated alternatives for energy recovery. In T3 part of the biogas is combusted in a combined heat and power (CHP) system based on an internal combustion engine (ICE) and heat recovery to fully cover the power demand of the process, also partially satisfying the heat demand with the excess of heat. In T4, T5 and T6 the energy is recovered from the digestate. In T4 the dried digestate is processed via air gasification, and the syngas produced is combusted in a CHP system. In T5 the dried digestate is combusted, and the heat is recovered through heat recovery steam generation (HRSG). The heat recovered generates pressurized steam, then expanded in a turbine, producing heat and power. In T6 the dried digestate undergoes steam gasification and the syngas produced is upgraded to bio-SNG. The hot streams from the upgrading process are used as heat source for a HRSG providing heat and power; the bio-SNG is injected in the natural gas grid along with biomethane.

Table 2
Main operational parameter for each stage of the conversion process.

Anaerobic digestion system Model type: black-box Power consumption: 5.4 kJ kg^{-1} (screening) +20 kJ kg^{-1} (hammer mill) + 5 kJ kg^{-1} (pasteurizaion) +21.6 (pumping/maceration/mixing) + 78.6 kJ kg^{-1} (dewatering) kJ kg^{-1} Heat consumption: 157 kJ kg^{-1} (pasteurization) MC = 75% (dewatered digestate) (Cvetković et al., 2016) (Pierie et al., 2016)	**Biogas upgrading (amine scrubber)** O'Shea et al. (2017) Model type: black-box Power consumption: 396 kJ Nm^3_{biogas} Heat consumption: 360 kJ Nm^3_{biogas} V_{CH4} = 99.9%v L_{CH4} = 0.5% V_{CH4}
Injection Pierie et al. (2016) Model type: black-box Power consumption: 432 kJ Nm^3 p = 16 bar	**Dryer** Dussan and Monaghan (2017a) Model type: black-box Heat consumption: 3300 kJ kg^{-1}_{H2O} MC_{out} = 10% (dried digestate)
CHP Dussan and Monaghan (2017a) Model type: Gibbs free energy minimisation Reactor type: isothermal p = 1.2 bar ER = 1.1 Electrical efficiency: $0.41 - 0.16 \cdot \exp(-1.3 \cdot 10-3 \cdot \dot{W}_{out})$ T_{out} [K] $= 391.7 - 4.3 \cdot 10 - 3 \cdot \dot{W}_{out} + 305.7 \cdot \exp(1.6 \cdot 10-3 \cdot \dot{W}_{out})$ T_{lim} = 150 °C	**Air Gasification** Dussan and Monaghan (2017a) Model type: pseudo-equilibrium model Reactor type: isothermal ER = 0.43 p = 1.2 bar T_{air} = 600 °C Δp = 0.1 bar T = 800 °C
Combustion Dussan and Monaghan (2017a) Model type: Gibbs free energy minimisation Reactor type: isothermal ER = 1.1 T = 873 K Δp = 0.1 bar Heat consumption: 3300 MJ kg^{-1}_{H2S} (sulphur removal) Dussan and Monaghan (2017a)	**HRSG and steam turbine** Singlitico et al. (2019b) Boiler efficiency: 80% Mechanical efficiency: 98% Isentropic efficiency: 75% p_{in} = 100/25/6 bar p_{out} = 2 bar T_{in} = 580 °C
Steam gasification Singlitico et al. (2019b) Including a gasifier and a combustor (see **Supplementary Material**). **Syngas upgrading** Including scrubber, adsorption bed, olefin hydrogenation, hydrodesulphurisation, H_2S removal, guard bed, water-gas shift reactor, prereforming, CO_2 removal, methanation, gas dryer (see **Supplementary Material**).	**Miscellaneous** Dussan and Monaghan (2017a) T = 400 °C (selective catalytic reduction) Win = 0.450 kW (Nm3 s-1)-1 (electrostatic precipitator) Pump isentropic efficiency: 75% Compressor isentropic efficiency: 75% NOx removal: 95%

The residues of the six technology routes are then reused: landspread, in case of digestate, or used in cement kilns, in case of ashes.

The thermodynamic model for AD is inputted with the calculated experimental values and the volume of methane, V_{CH_4}, and biogas, V_{BG}, produced in units of Nm^3 calculated with Eq. (1) and Eq. (2).

$$V_{CH_4} = m_{ARB,\ F} \cdot \frac{DS}{100} \cdot \frac{VS}{100} \cdot SMY \tag{1}$$

$$V_{BG} = \frac{V_{CH_4}}{\frac{Vol\%_{CH_4}}{100}} \tag{2}$$

Where $m_{ARB,\ OFMSW}$ is the mass of feedstock on an as-received basis in units of kilogram per annum (O'Shea et al., 2015); DS is the dry solid content as a percentage of the mass of feedstock on as-received basis; VS is the volatile solid content as a percentage of the mass of feedstock on dry basis; SMY is the specific methane yield in units of Nm^3 per kilogram of volatile solid; $Vol\%_{CH_4}$ is the methane volumetric percentage in the biogas.

The capacity of biomethane production, $\dot{E}_{BM}$, in unit of MW is calculate with Eq. (3).

$$\dot{E}_{BM} = V_{CH_4} \cdot \left(1 - \frac{L_{CH_4}}{100}\right) \cdot LHV_{CH_4} \cdot \frac{1}{3600} \cdot \frac{1}{OH} \tag{3}$$

Where V_{CH_4} is the volume of methane calculated with Eq. (1), L_{CH_4} is the methane leaked as a percentage of total volume of methane, LHV_{CH_4} is the lower heating value of methane equal to 35.8 MJ Nm^3 (Waldheim and Nilsson, 2001), and OH is the operating hours, assumed to be 7500 h per annum.

The amount of digestate on dry basis produced in the AD process, $m_{DB,D}$, is calculated with Eq. (4).

$$m_{DB,D} = m_{ARB,\ F} \cdot \frac{DS}{100} \cdot \left(\frac{VS}{100} \cdot \left(1 - \frac{VSD}{100}\right) + \left(1 - \frac{VS}{100}\right)\right) \tag{4}$$

Where $m_{ARB,\ F}$ is the mass of the feedstock processed per annum on an as-received basis, sourced from a previous article by O'Shea et al. (O'Shea et al., 2015), and VSD is volatile solid destruction as a percentage of the volatile solid in the feedstock and experimentally measured.

In T4, T5 and T6, the digestate, dewatered and dried, undergoes thermochemical treatments, in which the ultimate and proximate analyses measured are used as inputs for the respective models. For T4 and T5, the model for air gasification and combustion are sourced from (Dussan and Monaghan, 2017a). For T6, the model for steam gasification and upgrading of the syngas into bio-SNG is sourced from (Singlitico et al., 2019b). The main operational parameters used, and power and heat demands for each unit are listed

Table 3
Cost inventory for the main stages involved actualised for 2018. CapEx in unit of k€ and OpEx in unit of k€ per annum.

Anaerobic digestion system Browne et al. (2011) CapEx: $0.2935 \cdot \dot{m}_{ARB,F}$ OpEx: $0.025 \cdot \dot{m}_{ARB,F}$ $\dot{m}_{ARB,F}: \left[\frac{t}{a}\right]$	**Biogas upgrading (amine scrubber)** (Bauer et al., 2013) (O'Shea et al., 2017) CapEx: $193 \cdot \dot{V}_{BG}{}^{0.373}$ OpEx: 101.3 $\dot{V}_{BG}: \left[\frac{Nm^3}{h}\right]$
Injection O'Shea et al. (2017) CapEx: 1, 892 k€	**Dryer** Singlitico et al. (2019b) CapEx: $362 \cdot \left(\frac{\dot{m}_{DB,D}}{1,100}\right)^{0.72} \cdot IF \cdot (1 + IC)$ $\dot{m}_{DB,D}: \left[\frac{t}{day}\right]$; IF (installation factor): 2.47; IC (indirect costs): 0.219
CHP Dussan and Monaghan (2017b) CapEx: $2,231 \cdot W_{out}{}^{0.836}$OpEx: • Labour*: $n \cdot sal \cdot 0.485 \cdot W_{out}{}^{0.836}$ • O&M: $140 \cdot W_{out}{}^{0.782}$ $W_{out}: [MW]$	**Air Gasification** Dussan and Monaghan (2017b) CapEx: $34 \cdot \dot{m}_{DB,F}{}^{0.698}$ OpEx: • Labour[a]: $n \cdot sal \cdot 0.04 \cdot \dot{m}_{DB,F}{}^{0.475}$ • O&M: $0.05 \cdot CapEx$ • Material: DFR $\cdot \dot{m}_{DB,F} \cdot P_{dol} \cdot$ OH $\dot{m}_{DB,F}: \left[\frac{kg}{h}\right]$; P_{dol} (price dolomite):0.0758 $\frac{k€}{kg}$; *DFR* (dolomite to feedstock ratio): 0.032 $\frac{kg}{kg}$; OH : $\left[\frac{h}{a}\right]$
Combustion Dussan and Monaghan (2017b) CapEx: $502.6 \cdot (\dot{m}_{ARB,F} \cdot LHV)^{0.769}$ OpEx: • Labour[a]: $n \cdot sal \cdot \dot{m}_{ARB,F} \cdot LHV \cdot (0.3 - 0.49 ln(\dot{m}_{ARB,F} \cdot LHV))$ • Maintenance: $0.03 \cdot CapEx$ $\dot{m}_{ARB,F}: \left[\frac{kg}{s}\right]$; $LHV: \left[\frac{MJ}{kg}\right]$	**HRSG and steam turbine** Dussan and Monaghan (2017b) CapEx: $8,300 \cdot \left(\frac{\dot{W}_{out}}{10.3}\right)^{0.7} \cdot 2$ OpEx: • Labour[a]: $n \cdot sal \cdot \dot{W}_{out} \cdot (0.93 - 0.19 \cdot \ln(\dot{W}_{out}))$ • O&M: $0.0055 \cdot \dot{W}_{out}$ $W_{out}: [MW]$
Steam gasification Including a steam gasifier and a combustor (see **Supplementary Material**). **Syngas upgrading** Including scrubber, adsorption bed, olefin hydrogenation, hydrodesulphurisation, H_2S removal, guard bed, water-gas shift reactor, prereforming, CO_2 removal, methanation, gas dryer (see **Supplementary Material**).	**DeNOx system (for T3,T4,T5)** Dussan and Monaghan (2017b) CapEx $DeNO_X$: $380 \cdot \dot{W}_{out}$ OpEx $DeNO_X$: • O&M: $3,5 \cdot \dot{W}_{out}$ • Material: $3,1 \cdot \dot{W}_{out}$ $\dot{W}_{out}$ $[MW]$

[a] *n*: number of shifts per day, 3; *sal*: salary per worker on the plant, 45.3 k€ a^{-1} (Dussan and Monaghan (2017a)).

Table 4
Measurements obtained through experiments for the AD of FW and GW.

Indicator	FW	GW
Volatile solids destruction, *VSD* [%]	84.6	85.8
CH_4 percentage in biogas, C_{CH4} [%]	59	55
Specific CH_4 yield, *SMY* [Nm^3 $kg^{-1}_{VSadded}$]	0.455	0.34

in Table 2.

2.4. Techno-economic performance

The capacity of the renewable gas produced from the full system, $\dot{E}_{RG}$, is calculated by summing biomethane and bio-SNG production in units of MW. Heat and power required, $\dot{Q}_{in}$ and $\dot{W}_{in}$, are the sums of all the heat and power demand from each unit involved and the ancillary equipment. The power is produced by the CHP or the steam turbine ($\dot{W}_{out}$), and heat is recovered from flue gases or from the cooling of main streams ($\dot{Q}_{out}$). The coverage of power and heat demand with power and heat generated on-site, C_W and C_Q respectively, are calculated in Eq. (6) and Eq. (7) and presented as percentages.

$$C_W = \frac{\dot{W}_{out}}{\dot{W}_{in}} \tag{6}$$

$$C_Q = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} \tag{7}$$

Economic indicators of the proposed systems included Net Present Value, *NPV*, in units of Euro, calculated with Eq. (8), and levelised cost of energy, *LCOE*, in units of Euro per MWh of renewable gas generated, calculated with Eq. (9).

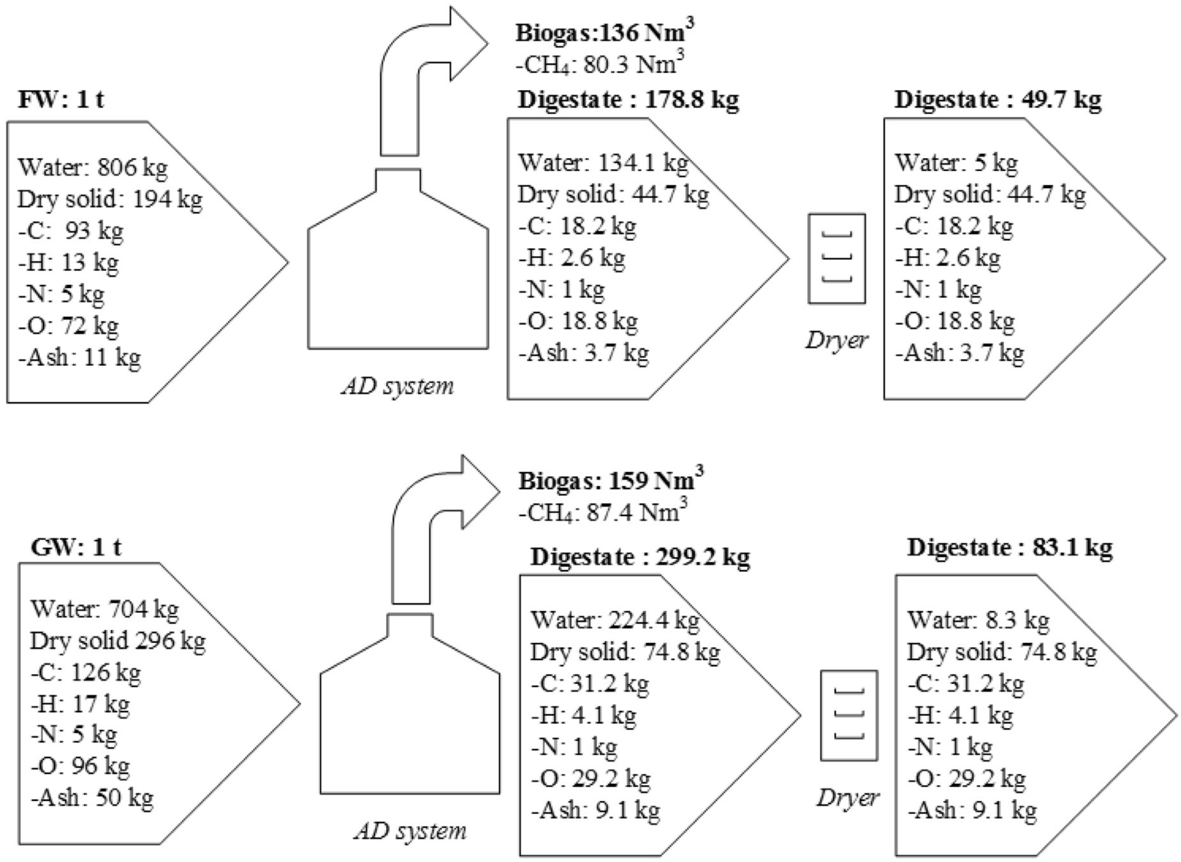

Fig. 5. Experimental characterisation results of food waste (FW) and garden waste (GW) and corresponding digestate composition.

Table 5
Closest reuse facilities resulting from the GIS model. The resulting techno-economic performances are summarised in Table 6, and discussed.

>Plant	Reuse site distance [km]	
	Farm land	Cement kiln
	For digestate landspreading	For ash reuse
I	2.6	56
II	5.4	54.3
III	1.1	59.7
IV	1.8 (0.44% of the digestate) 4.1 (0.56% of the digestate)	58.5
V	5.5	115.8

$$NPV = \sum_{y=0}^{LT} \frac{CF_{in,y} - CF_{out,y}}{(1+DR)^y} \quad (8)$$

$$LCOE = \frac{\sum_{y=0}^{LT} \frac{CF_{out,y}}{(1+DR)^y}}{\sum_{y=0}^{LT} \frac{E_{RG}}{(1+DR)^y}} \quad (9)$$

Where LT is the life time of the plant, equal to 20 years in this study (Zamalloa et al., 2011); E_{RG} is the annual energy of the renewable gas produced in units of MWh, obtained using the thermodynamic model; DR is the discount rate, equal to 8% in this study (Zamalloa et al., 2011); and $CF_{in,y}$ and $CF_{out,y}$ are the cash inflow and outflow at year y, in units of Euro per annum.

$CF_{in,y}$ is calculated with Eq. (10).

$$CF_{in} = E_{RG} \cdot (P_{gas} + Inc_{gas}) + m_{ARB,F} \cdot GF \quad (10)$$

Where P_{gas} is the revenue earned by selling the renewable gas produced and assumed to have a market value of 28 € MWh^{-1} (O'Shea et al., 2016a); Inc_{gas} is the value of the Biofuel Obligation Certificates, earned through the Biofuel Obligation Scheme for renewable gas sourced from waste, and assumed to be equal to 78 € MWh^{-1} (O'Shea et al., 2016a); GF is the gate fee of 75 € t^{-1} that could be charged for accepting OFMSW to the facility, equal to the gate fee that would incur for disposing OFMSW in a landfill (Minister for the Environment Community and Local Government, 2015), and $m_{ARB,F}$ is the mass on an as-received basis of OFMSW in units of tonnes per annum.

$CF_{out,y}$ is calculated with Eq. (11).

$$CF_{out} = CapEx + OpEx + EnEx + TrEx \quad (11)$$

Where $CapEx$ and $OpEx$ are calculated for each technological route and for each plant, according to the results of the thermodynamic models and costs equations shown in Table 3. $CapEx$ is considered to be entirely allocated at year 0 (O'Shea et al., 2016a) in Eq. (8) an Eq. (9).

The cost for the energy use, $EnEx$, is calculated in Eq. (12).

$$EnEx = \frac{(Q_{in} - Q_{out})}{\eta_{boi}} \cdot P_{NG} + (W_{in} - W_{out}) \cdot P_{El} \quad (12)$$

Where Q_{in} and W_{in}, are the heat and electrical energy demand, Q_{out} and W_{out}, are the heat and electrical energy generated, in units of MWh; η_{boi} is the efficiency of the gas boiler, 80% (Dussan and Monaghan, 2017a), P_{NG} and P_{el} are the costs of natural gas and

Table 6
Techno-economic performances for the five plants considered (PI–V) for each technology route (T1-6).

	PI						PII					
	T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6
E_{RG} [MW]	14.4	14.4	11.8	14.4	14.4	17.0	14.4	14.4	11.8	14.4	14.4	17.0
Residues[t]	30439	8455	8455	803	803	803	30495	8471	8471	800	800	800
W_{in} [MW]	0.74	0.74	0.90	0.80	0.83	0.92	0.74	0.74	0.90	0.80	0.83	0.92
Q_{in} [MW]	1.01	3.70	3.66	3.70	3.70	3.70	1.01	3.71	3.66	3.71	3.71	3.71
C_W [%]	0%	0%	100%	116%	100%	58%	0%	0%	100%	116%	100%	58%
C_Q [%]	0%	0%	25%	51%	43%	26%	0%	0%	25%	51%	43%	26%
CapEx [M€]	43.2	43.3	47.3	56.0	51.7	57.5	43.2	43.3	47.3	56.0	51.7	50.4
OpEx [M€ a^{-1}]	3.4	3.6	3.8	4.2	3.8	4.5	3.4	3.6	3.8	4.2	3.8	4.5
EnEx [M€ a^{-1}]	1.1	1.8	0.7	0.4	0.6	1.2	1.1	1.8	0.7	0.4	0.6	1.2
TrEx [M€ a^{-1}]	0.43	0.43	0.42	0.43	0.43	0.43	1.25	1.23	1.23	1.23	1.23	1.22
NPV [M€]	116.4	107.5	92.6	102.9	109.0	111.8	108.5	99.7	84.8	95.1	101.3	104.1
LCOE [€ MWh^{-1}]	86.8	95.1	109.9	99.6	93.7	93.4	94.2	102.5	118.9	106.8	101.1	99.6
	PIII						**PIV**					
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
E_{RG} [MW]	13.7	13.7	11.2	13.7	13.7	16.2	12.4	12.4	10.2	12.4	12.4	14.7
Residues[t]	28910	8031	8031	759	759	759	26164	7268	7268	687	687	687
W_{in} [MW]	0.71	0.71	0.85	0.76	0.78	0.88	0.64	0.64	0.77	0.69	0.71	0.80
Q_{in} [MW]	0.96	3.52	3.48	3.52	3.52	2.97	0.88	3.19	3.15	3.19	3.19	3.19
C_W [%]	0%	0%	100%	115%	100%	58%	0%	0%	100%	113%	100%	58%
C_Q [%]	0%	0%	25%	51%	43%	26%	0%	0%	26%	51%	43%	26%
CapEx [M€]	41.1	41.4	45.20	53.6	49.5	55.1	37.9	38.0	41.5	49.3	45.6	44.5
OpEx [M€ a^{-1}]	3.3	3.4	3.6	4.0	3.7	4.3	3.0	3.1	3.3	3.7	3.3	3.9
EnEx [M€ a^{-1}]	1.0	1.8	0.7	0.3	0.5	1.1	0.9	1.6	0.6	0.3	0..5	1.1
TrEx [M€ a^{-1}]	1.33	1.32	1.32	1.33	1.33	1.33	1.59	1.58	1.58	1.58	1.58	1.58
NPV [M€]	101.5	93.0	78.7	88.3	94.3	96.7	88.0	80.4	67.1	75.6	81.3	83.0
LCOE [€ MWh^{-1}]	95.9	104.4	121.3	109.0	103.1	101.5	100.6	108.9	127.3	114.1	107.9	105.9
	PV											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**						
E_{RG} [MW]	10.9	10.9	8.8	10.9	10.9	12.9						
Residues[t]	22826	6341	6341	594	594	594						
W_{in} [MW]	0.56	0.56	0.68	0.61	0.63	0.70						
Q_{in} [MW]	0.77	2.78	2.75	2.78	2.79	2.78						
C_W [%]	0%	0%	100%	109%	99%	57%						
C_Q [%]	0%	0%	27%	52%	52%	26%						
CapEx [M€]	33.8	33.9	37.0	39.0	40.7	45.6						
OpEx [M€ a^{-1}]	2.6	2.8	2.9	3.3	3.0	3.5						
EnEx [M€ a^{-1}]	0.8	1.4	0.5	0.3	0.4	0.9						
TrEx [M€ a^{-1}]	2.00	1.98	1.98	1.99	1.99	1.99						
NPV [M€]	70.6	64.1	52.1	59.2	64.5	65.5						
LCOE [€ MWh^{-1}]	108.9	117.1	138.0	123.1	116.5	113.8						

electricity from the grid equivalent to 36 € MWh^{-1} and 145.5 € MWh^{-1}, as average prices for industrial use in 2018 (Sustainable Energy Authority of Ireland, 2019).

The transportation cost, *TrEx*, is calculated in Eq. (13).

$$TrEx = \left(m_{ARB,F,i} \cdot d_{ij} + m_{ARB,\ R,j} \cdot d_{jk}\right) \cdot T \tag{13}$$

Where *TrEx* is the sum of the cost of transporting the feedstock from its origins *i* to the plant *j* and the mass of the residues produced in the plant *j*, $m_{ARB,\ R,j}$, digestate or ashes, from the plant *j* to its final destination *k* (where *k* is farm lands or cement kilns) in units of tonne; *T* is the cost of transport in units of euro per tonne transported per kilometre travelled, considering empty return, equal to 0.181 € t^{-1} km^{-1} (O'Shea et al., 2016a). The distances of the OFMSW origin to the plant, d_{ij} are calculated with the GIS software considering the origin-destination matrix produced by the optimisation of O'Shea et al. (O'Shea et al., 2016a), with road distances calculated with ArcGIS. The distance of the plant to the closest reuse site, d_{jk}, is calculated in the GIS model using the shortest-path algorithm. Both d_{ij} and d_{jk} are in units of kilometre.

3. Results and discussion

3.1. Techno-economic results

The results of the AD tests on FW and GW are detailed in Table 4.

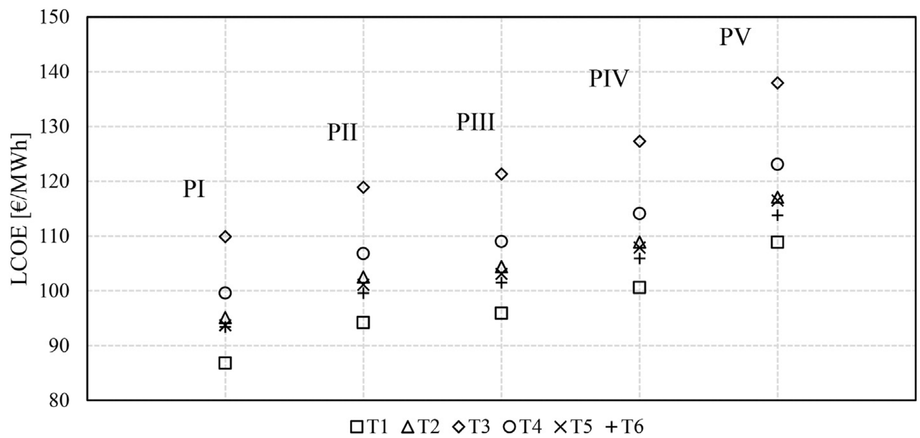

Fig. 6. Resulting LCOE for the five plants (P), and the six technology routes (T).

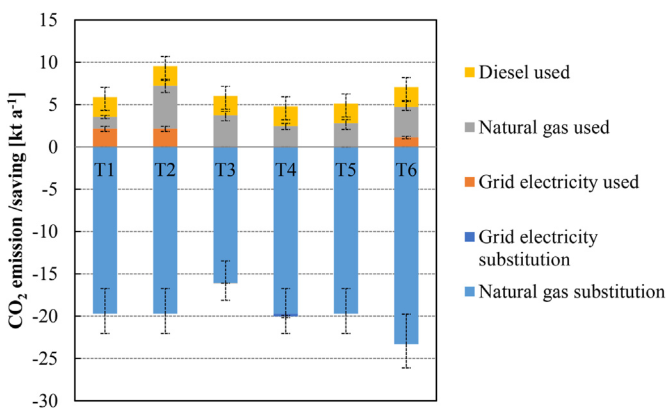

Fig. 7. Average CO_2 emissions (positive) and savings (negative) between each plant for each technology route (T). Whiskers show the maximum and minimum values registered for each technological route.

The recorded pH values were within recommended limits of pH 7–8. The alkaline ratios were below 0.3, indicating a stable digestion process (Drosg, 2013). The *SMY* achieved was similar to those in prior literature utilising separated household FW from a different location, which reported 0.36 Nm^3 kg^{-1} of volatile solid (O'Shea et al., 2016b).

Fig. 5 shows the mass balances and composition of feedstock, digestate and the production of biogas. Ash content was relatively reduced in both FW and GW. This is likely related to leaching of minerals to the water phase removed after dewatering of the digestate. In addition to this, carbon content in the digestate was reduced, as expected by the conversion of some of the organic fraction of the substrates during AD. These inputs are used then to perform the thermodynamic model of the processes and calculate *CapEx*, *OpEx* and *EnEx*.

The closest locations for landspreading or incineration at cement kilns from each plant are identified with the GIS model and shown in Table 5. In the case of landspreading for PIV, the digestate produced is transported to two farms so as not to exceed the limit of N in-take of the farm land.

The resulting LCOE is shown in Fig. 6. T1 is the configuration that minimises the LCOE, from 86.8 € MWh^{-1} for PI, to 108.9 € MWh^{-1} for PV. T3 shows the highest LCOEs ranging from 109.9 € MWh^{-1} for PI, to 138 € MWh^{-1}, for PV, due to the additional cost for the CHP system used to combust part of the biogas, and the use of biogas on-site that decreases the net amount of energy produced. It can also be observed that the LCOE for each plant within the same technological route increases from PI to PV, due to the increasing transportation costs from PI to PV, from 0.43 M€ a^{-1} to 1.99 M€ a^{-1}, and the reduction in size, from a biomethane production of 14.4 MW–10.9 MW respectively, which penalises due to economies of scale.

The energy capacity of the five plants is proportional to the amount of feedstock processed, see Table 3. For T1, T2, T4 and T5, the biomethane output is the same, while for T3, biomethane output is reduced by 18% on average because of the use on site of biogas. T6 presents the additional production of bio-SNG, increasing the capacity by 18% when added to biomethane. The amount of energy produced, and consequentially the revenues from its sale, influence LCOE and NPV calculations, presenting the second best technological route in terms of LCOE and NPV. Although all the technological routes are greater than the average price of gas for household consumers of 70.3 € MWh^{-1} (Sustainable Energy Authority of Ireland, 2019), additional revenues coming from the assumed gate fee and incentive, makes the renewable gas produced profitable.

The best energy recovery is observed in T4 in which the digestate is gasified and the syngas is combusted in an CHP system providing 51% of the thermal power required and approximately 116% of the power for all the plants, exceeding the demand.

T1 and T2 present the lowest CapEx, since they are the simplest configurations, however they present higher OpEx when compared to T3, T4 and T5, due to the absence of thermal and energy production on-site, thus necessitating the purchase of natural gas and electricity from the grid. Gasification-based process, T4 and T6, present the highest CapEx, due to the complexity of the processes.

Energy expenditures highly affect T3, in which digestate is dried with no energy recovery, and T6, which presents less intensive energy recovery compared to T3, T4 and T5, that leads to the use of external sources of energy.

The transport costs of the feedstock to the plant in which the feedstock is allocated is the same for each technology, and it is increasing from PI to PV due to the allocation choices adopted in the model by O'Shea et al. (O'Shea et al., 2016a), in which the allocation of the resources is performed by saturation of the capacities of each plant from PI to PV. The costs related to the transport of the residues to the reuse sites is orders of magnitudes lower than the transportation of the feedstocks to the respective plants. This depends on the mass reduction of the feedstock when compared to the residues, as well as the proximity in case of landspreading of digestate on farm land (where the maximum distance is for PV of 5.5 km). The cost of transportation of the ashes is negligible when

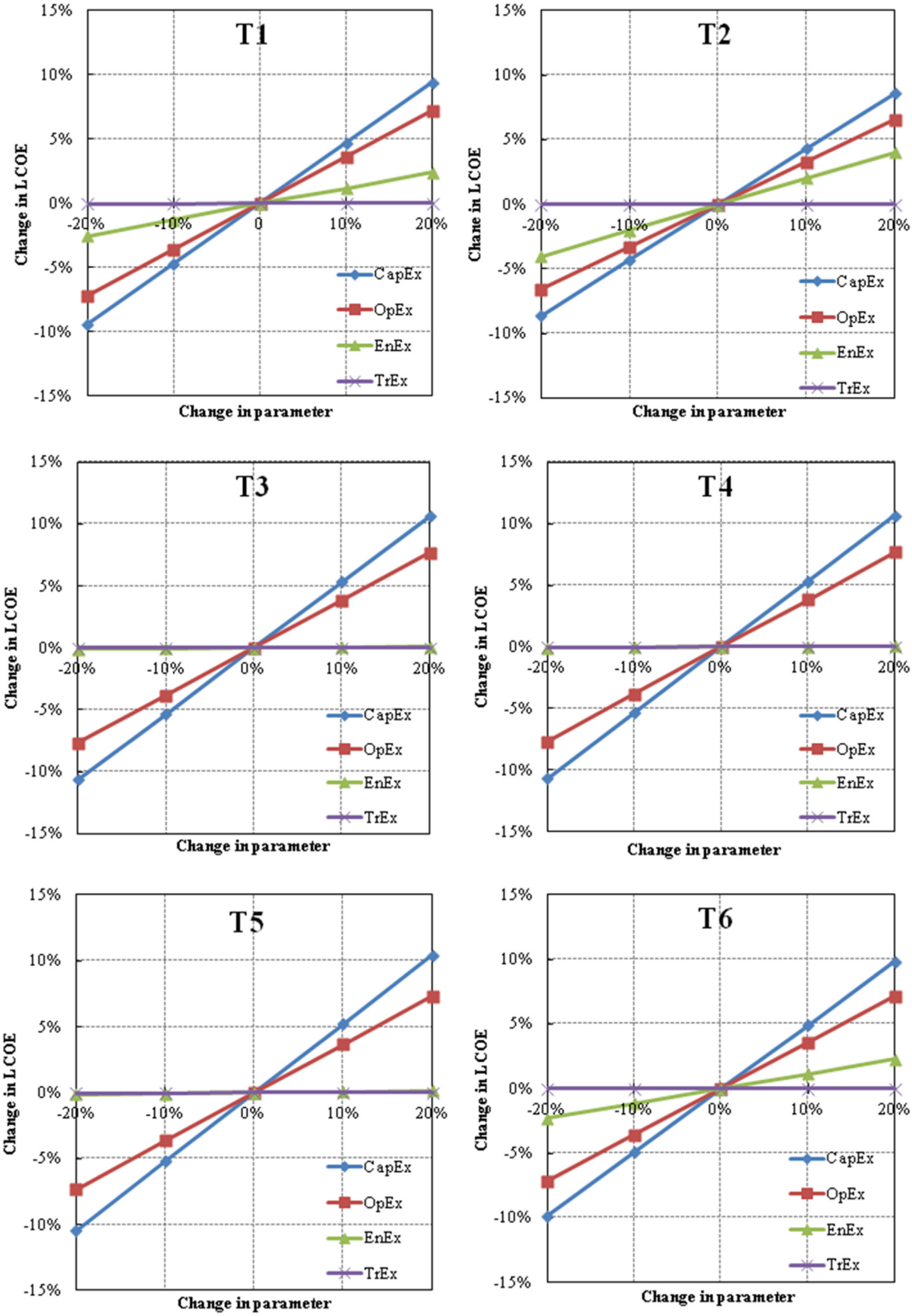

Fig. 8. Sensitivity analysis for plant showing the impact on LCOE of change in CapEx, OpEx, EnEx and TrEx. Note: in TrEx only the costs related to the transport of residues has been varied to focus on the impact the different residues generated.

compared to the transportation of the feedstock, capital and operational expenditures even for distances up to over 100 km.

3.2. Carbon intensity

In this section, CO_2 emissions saved/generated from each technological route are calculated. The emission factors (Sustainable Energy Authority of Ireland, 2018) for the energy uses are assumed to be: 204.7 g of CO_2 per kWh of natural gas, 436.6 g of CO_2 per kWh of grid electricity (of which 69.9% is generated from fossil sources: mainly natural gas, coal and peat), 263.9 g of CO_2 per kWh of diesel used. These values represent the amount of CO_2 that will be released per kWh of energy of a given fuel, representing 96% of the energy-related CO_2 emissions, thus excluding nitrous oxide and methane CO_2 equivalent emissions (Sustainable Energy Authority of Ireland, 2018).

The CO_2 emissions are calculated by multiplying the emission factors by the natural gas and grid electricity used in the conversion system, and diesel used for transport. The CO_2 emissions savings are calculated assumed to be those emissions displaced by the substitution of natural gas to renewable gas and grid electricity to the excess electricity co-produced in the conversion process. Direct CO_2 emissions from the combustion of biogas or digestate are not accounted since considered biogenic, and emissions from methane leakage and nitrous oxide generated from the combustion are excluded in order to be consistent with the emission factors used for the fossil fuels. The average values in Fig. 7 show that T4 and T6, are the most environmentally beneficial solution. The largest net CO_2 savings are found for 11.4−19 and 12.1−19.9 kt of CO_2 emissions per annum from PI to PV respectively; due to a better energy recovery in T4 (air gasification) and a larger amount of renewable gas produced in T6 (bio-SNG production). The longer the transport distances from the case of PI to PV, the larger the CO_2 emissions, from 0.8 to 3.5 kt per annum.

3.3. Sensitivity analysis

A sensitivity analysis is performed, analysing the impact on LCOE of the expenditures investigated: CapEx, OpEx, EnEx and TrEx of the residues. The results are shown in Fig. 8 for all the technological routes of PI. For all the cases LCOE is more sensitive to CapEx and OpEx variations, EnEx becomes relevant only in T2, in which the energy demand for drying the digestate is not covered by any on-site generation of heat and power, and in T6, in which heat and power demand are both only covered partially. Variation of LCOE caused by TrEx of residues to the end-use sites is negligible, considering that in the reference case the farm land for the disposal of digestate (T1, T2, T3) is 2.6 km from the plant, and the incinerator for the reuse of ashes (T4, T5 and T6) is 56 km from the plant.

4. Conclusion

This work presented a techno-economic comparison of advanced waste-to-energy conversion routes for OFMSW with the aim of finding the technology route that minimises the levelised cost of the renewable gas produced. This was performed on the reference case of the ROI, integrating a previous study based only on AD and biogas upgrading.

According to the techno-economic performance the reference case CapEx and OpEx play a major role when compared to energy and transportation expenditure. However, the lower the energy recovery, the greater the influence of the expenditure for energy supplies, natural gas and grid electricity. Thus the simplest case of AD and landspreading of dewatered digestate, is the solution that minimises the LCOE. However, when the digestate is dried, the energy recovery by thermochemical treatment of the digestate offer a more cost-effective solution than only biogas combustion, which presents a loss of net energy produced and increases the LCOE.Additional energy from the bio-SNG from the digestate, which also produces additional power and heat, decreases the LCOE. In the case of bio-SNG route, a total installed capacity of 77.76 MW of renewable gas can be delivered, equivalent to 2.1 PJ a^{-1}, corresponding to9.8% of the Gas Networks Ireland target of 21.5 PJ a^{-1} of renewable gas production by 2024, saving 83.55 kt of CO_2 emissions annually.

4.1. Limits and future work

This work is intended to be a techno-economic assessment of different waste-to-energy configurations to improve the AD of OFMSW, thus calculating and comparing costs and energy production of the different cases.

- The impact on soil of wet or dry digestate on land as a substitute of mineral fertiliser needs to be assessed.
- The digestate is considered to be distributed to the farms with no additional revenue, but in the case of an additional upgrading of the digestate into biofertiliser, it would turn into a source of revenue.
- Landspreading of fly ashe might be considered after a deeper investigation on the trade-off between nutrients and contaminants.
- This study presents the carbon intensity of each conversion alternative as a preliminary environmental assessment. However, a more detailed life cycle assessment is necessary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Alessandro Singlitico: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Karla Dussan:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing. **Richard O'Shea:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing. **David Wall:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing. **Jamie Goggins:** Writing - review & editing, Supervision, Project administration, Writing - review & editing, Supervision, Project administration. **Jerry D. Murphy:** Writing - review & editing, Supervision. **Rory F.D. Monaghan:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.121198.

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