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Thermodynamic Modelling of Energy Recovery Options from Digestate at Wastewater Treatment Plants

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EPA RESEARCH PROGRAMME 2014–2020

Thermodynamic Modelling of Energy Recovery Options from Digestate at Wastewater Treatment Plants

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Stringent emission limits, population growth and increasing urbanisation continue to drive the advancement in wastewater treatment (WWT) technologies and waste management frameworks. Today, in Ireland, over 96% of the sludge generated during WWT is spread on agricultural land; however, restrictions set by agricultural quality assurance schemes are encouraging the search for new alternatives. Plants with a capacity greater than 100,000 population equivalent (p.e.) can implement anaerobic digestion (AD) as a means of sludge treatment and energy recovery. Pilot and WWT plant-scale studies have reported biogas yields of between 4 and 10 GJ t^{-1} (1–3 kWh kg^{-1}) for dry sludge through AD of municipal sewage sludge (Qiao *et al*., 2011). However, large-scale biogas plants can consume approximately 40% of their energy yield for their operation, thus diminishing energy efficiency (Berglund and Börjesson, 2006). Thermal technologies for the conversion of either sewage sludge or digestate represent potential routes for both sludge volume reduction and energy recovery. In particular, sludge combustion and/or gasification could provide either thermal or chemical energy for combined heat and power (CHP) generation and could be readily integrated into WWT plants.

This project explores the state-of-the-art combustion (incineration) and gasification technologies used for biomass and waste conversion. This study evaluates not only the technical performance of these technologies, but also the investment and operational costs, and waste generation, treatment and valorisation through recovery of materials and chemicals. Using a pseudo-thermodynamic approach for modelling thermal conversion, the performance of combustion and gasification of sludge and digestate was evaluated under various operational conditions and for a range of solid material properties (e.g. moisture and composition). The model evaluated the technical performance of thermal conversion processes and the integration of energy carriers for power generation and heat recovery through various available technologies, such as steam and gas turbines, and combustion engines. To support local and government authorities in the consideration of these alternatives, different techno-economic indicators, including energy recovery efficiency, treatment costs, levelised cost of electricity generation and the carbon footprint of the WWT and sludge management plants were included and thoroughly compared to identify potential process alternatives.

Gasification and AD–gasification integrated with CHP generation was technically feasible and offered a means to reduce final waste disposal costs and improve the energy efficiency of the WWT plant. The most efficient process concept for energy recovery used internal combustion engines to generate power from energy carriers that were produced from gasification and AD–gasification, i.e. biogas and syngas. The conditions under which electricity generation was maximised were reached by undertaking extensive sludge pretreatment, i.e. drying, which resulted in low heat recovery efficiencies. In contrast, AD integrated with gasification resulted in greater thermal recovery flexibility, leading to conditions in which net surpluses of both electricity and heat were achieved. The combination of AD and gasification offered competitive costs of electricity generation [20–50 c kWh^{-1} (euro cent per kWh)], with a low carbon footprint (< 300 kg CO_2 t^{-1} dry sludge). Internal combustion engines offer great flexibility and competitive power efficiencies at expected scales for energy recovery in WWT facilities (< 10 MW_{el}).

When gasification was used as the only sludge conversion treatment, additional energy for heat generation was required during this process. It was proposed that this additional heat could be generated by co-processing with renewable solid fuels and wastes, i.e. biomass, animal slurries or the organic fraction of municipal solid waste. Biomass rates of between 0.8 and 1 times that of the sludge feed rate were required to meet energy demands with a reduced carbon footprint.

It is important to emphasise that the scale of the facility is vital in meeting sustainability criteria, especially in terms of operational and capital expenditures. The evaluation presented in this study was applied to the largest WWT scale in Ireland (1.6 Mp.e.), such as that of the Ringsend WWT plant, which currently produces approximately 85 t day^{-1} (tpd) of dry sludge (digestate). However, most existing anaerobic digestion facilities have capacities between 40,000 and 150,000 p.e., with sludge generation rates of 20–100 dry tpd, depending on the influent wastewater. Combustion engines offer sufficient flexibility to operate with the power capacities expected for these scales (> 100 kW_{el}). However, installation costs can make the implementation of gasification challenging at small scales. Raw sludge generation rates under 130 tpd led to levelised costs of electricity generation that were slightly above national costs of fossil-based electricity (24 c kWh^{-1}). However, gasification and AD–gasification treatment of sludge was economically competitive, with generation rates above 25 tpd. This challenge of scale may still be overcome through the other approaches that are suggested for future research. On-site thermal pretreatment can facilitate sludge transport to a centralised facility, where energy recovery could offset overall treatment costs in terms of energy and carbon footprint. A centralised gasification facility would offer the possibility of implementing biomass and/or waste co-processing with greater economic and technical efficiencies, while reducing operational challenges. It is also important to note that sludge transport and biomass co-processing will have additional energy penalties, transport costs and carbon footprint effects, which must be taken into account in the evaluation of an optimal sludge transport and treatment network at a county or national level. Use of biomass can result in direct and indirect carbon emissions linked to harvesting, use of fertilisers, land use change, import and transport that were not considered in this study. These may affect the carbon footprint of large-scale plants with high biomass-to-sludge co-processing ratios.

1 Introduction

Severe limitations on the emission of pollutants to water bodies in the future, along with population growth, increasing urbanisation and changes in industrial/agricultural practices, mean that wastewater treatment (WWT) processes are undergoing rapid development. These processes are required to have high removal efficiencies, while functioning within a sustainable system that has minimum impact on the environment and positive economic performance. The concept of a circular economy has led to searches for new ways for valorising waste and recovering resources and energy at all stages of industrial processes. Water management entities are adapting conventional processes or shifting to new strategies in which energy self-sufficiency can be guaranteed at most times (Rygaard *et al*., 2011). This project set out to investigate a series of technologies, e.g. thermal conversion, as new process strategies in which a circular use of WWT plant waste is employed for energy recovery via power/heat generation. The objectives of this work include the following:

- to review and estimate energy requirements in national and international WWT and sludge treatment facilities;
- to review the state of the art of thermal conversion technologies (combustion, pyrolysis and gasification) for the conversion of biomass and wastes to energy;
- to create a modelling tool for the implementation of these technologies in WWT facilities for sludge treatment, with and without anaerobic digestion (AD);
- to evaluate the potential generation of power and heat, coverage of on-site energy demands and cost of treatment (COT)/power generation using thermal and AD processes;
- to identify opportunities and challenges in sludge management practices in Ireland through thermal conversion and integration with AD.

1.1 Project Components and Research Outcomes

This work was carried out using a combined empirical and theoretical approach supported by a literature and technology survey of WWT and thermal conversion processes. The project followed four different stages:

1. *Sludge properties and scale selection*. Sludge characteristics of interest for thermal conversion were selected and representative values and ranges selected based on empirical data collected from the literature and biomass characterisation databases.
2. *Wastewater and sludge treatment and thermal conversion technologies*. State-of-the-art processes for WWT and sludge management in Ireland were reviewed. Technologies for thermal conversion of sludge/digestate and heat and power generation were also reviewed, and heuristics and process conditions were identified and described.
3. *Thermal conversion modelling tool*. Modelling approaches for the prediction of the performance of thermal conversion processes were reviewed. A pseudo-equilibrium model was implemented using MATLAB R2015a and Cantera 2.2.1 software using empirical data for air gasification of biomass and wastes.
4. *Techno-economic evaluation of integrated AD, sludge drying and thermal conversion*. Performance and process design factors were selected, including energy efficiency, energy coverage, specific investments and operational costs, levelised costs of electricity (LCOE) and carbon emissions. Different process outlines were proposed and evaluated to maximise energy coverage and identify deficiencies in the proposed energy integration systems.

Research and dissemination products from this project included the following:

- Peer-reviewed scientific publications outlining the research finding and potential applications of the proposed technologies. These publications are "Integrated thermal conversion and anaerobic digestion for sludge management in wastewater treatment plants" (Dussan and Monaghan, 2017) and "Thermodynamic evaluation of anaerobic digestion and integrated gasification for waste management and energy production within wastewater treatment plants" (Dussan *et al.*, 2016). They also include scientific presentations at the 26th Irish Environmental Researchers' Colloquium (ENVIRON 2016) and the 6th International Conference on Engineering for Waste and Biomass Valorisation (WasteEng16).
- Poster presentations at the NUIG Energy Night 2016, Galway, Ireland, and at the 24th European Biomass Conference and Exhibition (EUBCE 2016), Amsterdam, the Netherlands.
- National dissemination through an evening lecture webinar organised by Engineers Ireland and a poster presentation at the EPA National Water Event 2016.
- Project dissemination online via the Therme research group's website (http://www.nuigalway.ie/therme/projects/old/epasludge/).

1.2 Wastewater and Sludge Treatment in Ireland

Currently, over 500 urban areas in Ireland are provided with WWT (primary, secondary and/or nutrient removal treatment) (EPA, 2015). EU Directive 91/271/EEC requires that wastewater discharges from urban agglomerations greater than 2000 population equivalent (p.e.) discharging to freshwaters and estuaries and greater than 10,000 p.e. discharging to coastal waters must be treated with a minimum of secondary treatment. According to the EPA, 162 facilities with more than 2000 p.e. include secondary treatment technologies, corresponding to 94% of the national wastewater load (EPA, 2015).

Nutrient removal (nitrogen and/or phosphorus) is also provided at 143 of the 162 WWT plants with more that than 2000 p.e. Nutrient removal is generally required under Waste Water Discharge Authorisations issued by the EPA in settlements with a population greater than 10,000 p.e. that discharge effluents to designated sensitive water bodies.

Numbers of WWT plants, average plant capacities per urban area size and treatment extent are shown in Table 1.1. In general, small WWT plants serve small and, in some cases, remote urban areas or settlements of up to 2000 p.e. A small number of facilities serving urban areas of more than 2000 p.e. involve only primary treatment. However, these facilities are expected to be upgraded to comply with the Urban Wastewater Directive in the near future. For urban concentrations of more than 10,000 p.e., plants using only secondary treatment have an average capacity of 157,500 p.e. The design capacity of treatment works in Ireland does not exceed 160,000 p.e. on average, except in the case of the Ringsend WWT facility in Dublin City, which has a total design capacity of 1,640,000 p.e.

Facilities are required to collect and treat sludge generated from primary and secondary treatment before final disposal. These sludge management methods include mechanical processes (thickening, dewatering) and biological and thermal treatment. The main purpose of these operations is to stabilise

Table 1.1. Average plant capacity of wastewater treatment facilities in Ireland (Shannon *et al.*, 2014)

Urban area size	Number of plants in each p.e. range and average capacity per plant/p.e.					
	Primary treatment		Secondary treatment		Secondary treatment and nutrient removal	
	No. of plants	Average p.e.-serving capacity	No. of plants	Average plant capacity	No. of plants	Average plant capacity
Less than 2000 p.e.	233	688	450	827	151	604
Between 2000 and 10,000 p.e.	2	1746	50	4608	120	7176
More than 10,000 p.e.	4	13,500	26	157,545	39	33,066

solids to avoid putrefaction and reduce waste volume, thus decreasing the storage requirement and transport costs when the sludge is taken to disposal or treatment sites. As well as stabilising the sludge, biological processes reduce odour generation and greenhouse gas (GHG) emissions when sludge is stored or disposed of. These processes have the additional advantages of generating either energy and/or stabilised sludge cake, with 15–20% dry solids that can be used for agricultural purposes (soil spreading). Thermal drying represents an optional final treatment stage in which the moisture content in the dewatered or treated sludge/compost is reduced to values around or below 10% to facilitate storage, packaging and transport. Properties and production rates of sludge vary depending on the quality of the wastewater entering the plant, as well as on the treatment operation and the efficiency with which it has been separated. In general, primary sedimentation leads to higher sludge production rates (0.10–0.17 $kg\,m^{-3}$) than from activated sludge or trickling filter (0.06–0.10 $kg\,m^{-3}$) (Metcalf *et al.*, 2014). Further addition of lime for the chemical removal of phosphorus can significantly increase sludge production to between 0.25 and 1.30 $kg\,m^{-3}$ (Metcalf *et al.*, 2014). In Ireland, sludge generation is annually reported by the EPA for each water service authority (city and county councils). Average sludge generation in Ireland is in the order of 0.090 to 0.90 $kg\,m^{-3}$ or 10 to 85 $kg\,p.e.^{-1}\,year^{-1}$ (Shannon *et al.*, 2014).

AD is a vital technology for the improvement of energy efficiency in WWT plants. The Composting & Anaerobic Digestion Association of Ireland (Cré) has carried out several surveys within the waste-handling sector in Ireland to identify the extent of AD use (Cré, 2014). From Cré surveys, it was determined that 303,990 and 331,240 tonnes of organic waste were processed in 2012 and 2013, respectively, by either composting or AD. These materials included mainly brown bin wastes (34%), municipal organic solid wastes (24%), animal slurries and manures (17%) and, to a lesser extent, sewage sludge (SS) (16%) (Cré, 2014).

Irish Water has also surveyed sludge management methods in Ireland. In their study, the production of SS and the management methods used by local WWT authorities in 2014 was investigated (Lane, 2015a). This information is presented in Table 1.2. A significant percentage of the sludge generated in 2014 (50%) was treated by AD, under either mesophilic (30–40°C) or thermophilic (>40°C) conditions. Other pre- and post-treatments of sludge and digestate, respectively, are commonly implemented to improve efficiency and reduce waste generation. Thermal processes (drying, pasteurisation and hydrolysis) are used in the majority of AD facilities. Lime stabilisation (27.7%) and composting (11.5%) are other commonly used methods of sludge management. Composting in itself can be a final treatment method, since composted sludge is widely marketed or distributed to farms for land application. However, lime stabilisation requires transport of the treated sludge to the final disposal site. Lime stabilisation plants are currently exempt from waste permits or licences when the stabilised sludge is used for agricultural purposes (Cré, 2013) and therefore this is the more common practice.

Table 1.2. Sewage sludge management practices in Ireland in 2014 (Lane, 2015a)

Type of treatment	Approximate quantity (tonnes)	Percentage by weight (%)
Autothermal thermophilic AD (ATAD)	226	0.4
AD and thermal drying	2124	4.0
AD and lime stabilisation	4529	8.5
AD and pasteurisation	4239	7.9
Composting	6206	11.5
Lime stabilisation	14,815	27.7
Thermal drying	4904	9.2
Thermal hydrolysis, AD and thermal drying	14,220	26.5
Thermal hydrolysis and AD	1543	2.9
No treatment	737	1.4
Total	53,543	100

Cré has promoted the incorporation of legislative changes to oblige WWT plants of more than 5000 p.e. [300 kg BOD (biochemical oxygen demand) day^{-1}] to implement treatment methods of SS before disposal or use in landspreading. The necessity to improve energy efficiency in WWT facilities, and pressure from government and public sectors to implement sustainable sludge management practices, mean that the implementation of AD in WWT plants has been promoted. However, the presence of this technology in the WWT and organic waste management sectors is still at an early stage in Ireland.

Irish Water provided an account of Irish AD facilities and their current operational status (Lane, 2015b). This information is presented in Table 1.3. WWT plants with capacities above 20,000 p.e. are usually thought to be suitable for sludge treatment using AD. Currently, 44% (18 plants out of 41) are using this type of facility on site (Table 1.3). Among these AD plants, 72% are currently in operation and 56% have incorporated energy recovery capabilities from the biogas produced on site.

1.3 Conclusions

New strategies are being sought to drive the advancement of the WWT sector in Ireland. These must be centred on the improvement of effluent water quality, increased energy efficiency during treatment and the recovery of energy from sludge and digestates. Although there is a need for further development of AD facilities at national level, this technology has great potential as a bridge to integrate more advanced thermal conversion processes, such as combustion, pyrolysis and gasification. This study aimed to investigate the potential and feasibility of thermal conversion for energy recovery by power/heat generation in WWT plants with or without AD, as well as the challenges that the new concepts involve.

Table 1.3. Anaerobic digestion facilities and current status within wastewater treatment plants in Ireland

Area	WWT plant	License	Sludge treatment capacity (p.e.)	Status	Energy recovered from biogas through CHP
Dublin City	Ringsend	D0034-01	1,640,000	Active	Yes
Cork City	Cork City	D0033-01	413,000	Active	No CHP on site
Kildare	Upper Liffey Valley	D0002-01	400,000	Active	CHP out of service
Waterford City	Waterford City	D0022-01	190,000	Active	No CHP on site
Dún Laoghaire	Shanganagh	D0038-01	186,000	Active	Yes
Louth	Dundalk	D0053-01	179,000	Active	Yes
Kildare	Lower Liffey Valley	D0004-01	150,000	Inactive	CHP out of service
Louth	Drogheda	D0041-01	101,000	Active	Yes
Sligo	Sligo	D0014-01	100,000	Active	No CHP on site
Galway City	Galway City	D0050-01	91,600	Active	No CHP on site
South Tipperary	Clonmel	D0035-01	90,000	Active	No CHP on site
Donegal	Letterkenny	D0009-01	80,000	Inactive	Yes
Offaly	Tullamore	D0039-01	80,000	Active	Yes
Fingal	Swords	D0024-01	60,000	Active	CHP out of service
Kerry	Tralee	D0040-01	50,333.	Inactive	Yes
Meath	Navan	D0059-01	50,000	Inactive	Yes
Wicklow	Greystones	D0010-01	30,000	Inactive	Yes
North Tipperary	Roscrea	D0025-01	26,000	Active	Yes

CHP, combined heat and power

2 Thermal Conversion Modelling and Outline of Energy Recovery Systems

This study evaluated the energetic integration of combustion and gasification as final sludge conversion technologies in WWT facilities. A pseudo-equilibrium model was implemented using MATLAB software and thermodynamic properties accessed using Cantera software. This chapter presents a summary of the principles applied for the formulation of the thermal conversion model and process configuration.

2.1 Pseudo-equilibrium Modelling of Thermal Conversion

Thermal conversion reactions of carbonaceous materials, such as biomass and wastes, form gas products, whose composition varies depending on the reactant gas used and reaction conditions. With high oxygen concentrations (combustion), fully oxidised gas products are formed (CO_2, H_2O), with minor concentrations of CO and hydrocarbons, depending on the reactor design and the effectiveness of the gas/solid contact. When low O_2 or mild H_2O concentrations are used instead, the product gas is richer in mildly oxidised compounds (CO, H_2). This product (synthesis gas or syngas) is obtained under gasification conditions and is combustible. The oxidant concentration is commonly evaluated by the equivalence ratio (ER):

$$ER = \frac{\text{Stoichiometric oxygen concentration}}{\text{Actual oxygen concentration}} \qquad \text{(Equation 2.1)}$$

The stoichiometric amount of oxygen refers to the minimum amount of O_2 required to fully oxidise the fuel in the thermal conversion process. Under combustion conditions, ER is ≤ 1, whereas for gasification, ER is commonly > 2.

However, thermal conversion of carbon materials is not an ideal or simple process. A fraction of the feedstock may not be fully converted, leading to residual solid carbon or char, depending on the equipment design and operational conditions. In this situation, the fraction of carbon in the material that is converted to syngas is defined as carbon conversion, X_C:

$$X_C = \frac{\text{mols of carbon in syngas product}}{\text{mols of carbon in biomass}} \qquad \text{(Equation 2.2)}$$

Hydrocarbons (CH_4, C_2H_6, C_2H_4, etc.) and high molecular weight compounds (tars) are also formed because of limitations in the chemical behaviour of the process. Thermodynamic approaches, while quick and easy to use, fail to predict the amount and properties of the syngas. Jand *et al*. (2006) recognised the prediction capability of char and methane content in the final products as major limitations of thermodynamic equilibrium models. In order to resemble realistic carbon conversions and final methane/char yields, these variables were constrained by employing experimental data, as indicated in Figure 2.1. By restraining the amount of carbon converted to syngas and the fraction of carbon converted to methane (CH_4) in the final gas product as functions of the ER, the accuracy and applicability of a thermodynamic equilibrium model was greatly enhanced.

Figure 2.2 shows the carbon conversion, X_C, of different biomass materials as a function of the ER. These were reported by several authors for experimental tests in fluidised bed reactors using different types of biomass (Kersten *et al*., 2003; Li *et al*., 2004; Petersen and Werther, 2005; Jand *et al*., 2006; Campoy *et al*., 2009, 2014; Xue *et al*., 2014). This reactor configuration is preferred, since it allows efficient mixing and high reaction rates, especially with high-ash content fuels, such as wastes and sludge (Belgiorno *et al*., 2003).

Carbon conversion was affected by the ER, because the gasification temperature (T_{GS}) was over 1073 K (800°C). The regression presented in Figure 2.2 was calculated using the assumption that, when stoichiometric or excess oxygen was used (combustion), carbon was entirely oxidised and converted to gas (flue gas).

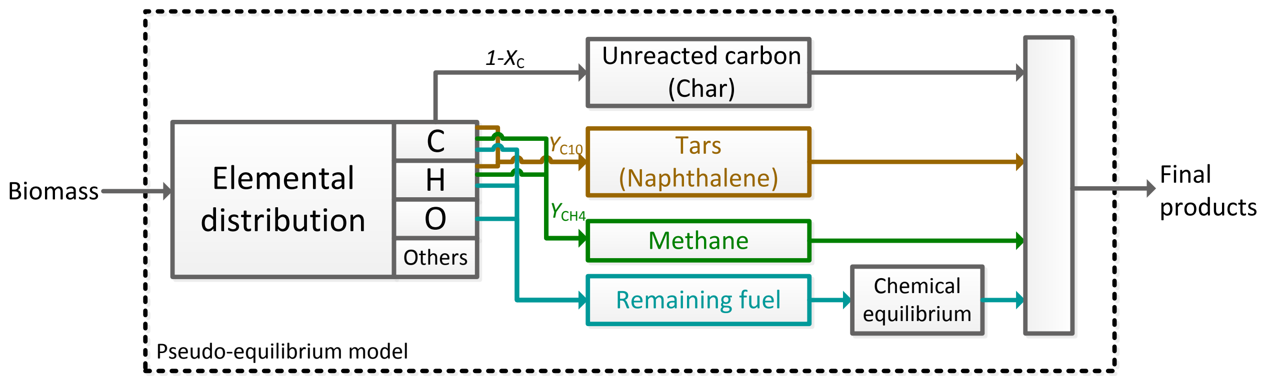

Figure 2.1. Pseudo-equilibrium model for thermal conversion of biomass.

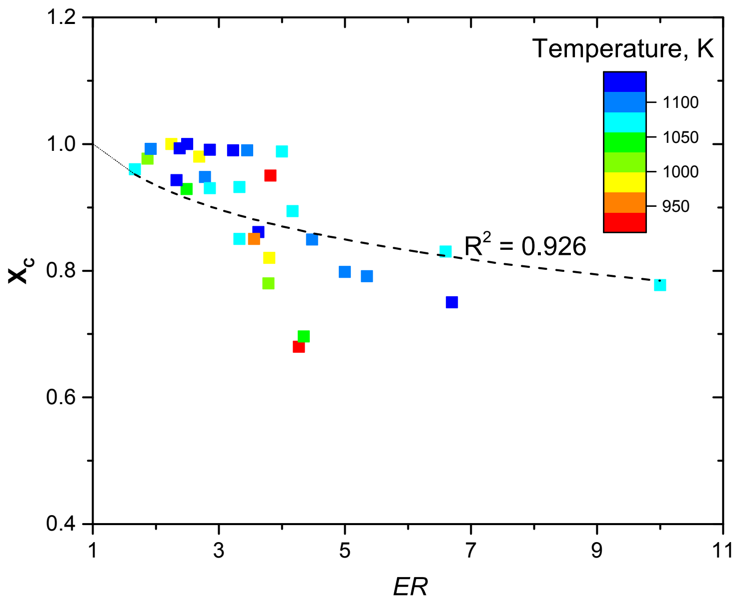

Figure 2.2. Experimental and regressed carbon conversion from air gasification of biomass.

Few experimental studies have reported a complete carbon balance of the biomass gasification tests. Jand *et al*. (2006) reported the residual char yield as the completing balance of the collected tars and syngas (Figure 2.3).

For this limited dataset at T_{GS} between 1073 and 1103 K, the char yield changed inversely with the ER, so that, under depleted oxygen conditions, a higher amount of carbon from the biomass remained as char. This is also evidence of the kinetic limitation of char gasification reactions when reactor design is insufficient to allow effective residence time of the char or when conditions impede the completion of oxidation/gasification reactions (Di Blasi, 2009).

Figure 2.4 summarises the carbon yield as methane reported in the biomass air gasification studies mentioned above. Variability of the methane yield in this case was significant; however, there was no relationship between *ER* or T_{GS} and the methane yield. In most cases, the methane yield was approximately 10%; therefore, it was fixed at this value for further modelling.

Taking into account these findings, the reactivity of the sludge/digestate in the equilibrium model was constrained by defining the carbon conversion as a function of the ER, so that complete conversion can be attained when approaching combustion conditions ($ER \leq 1$). Minimum carbon conversion was limited to 85% when *ER* reaches 4.5. When considering steam gasification, the T_{GS} will mainly dictate the extent of carbon conversion, assuming a minimum steam-to-carbon (SC) molar ratio of 0.6. Assuming an SC ratio

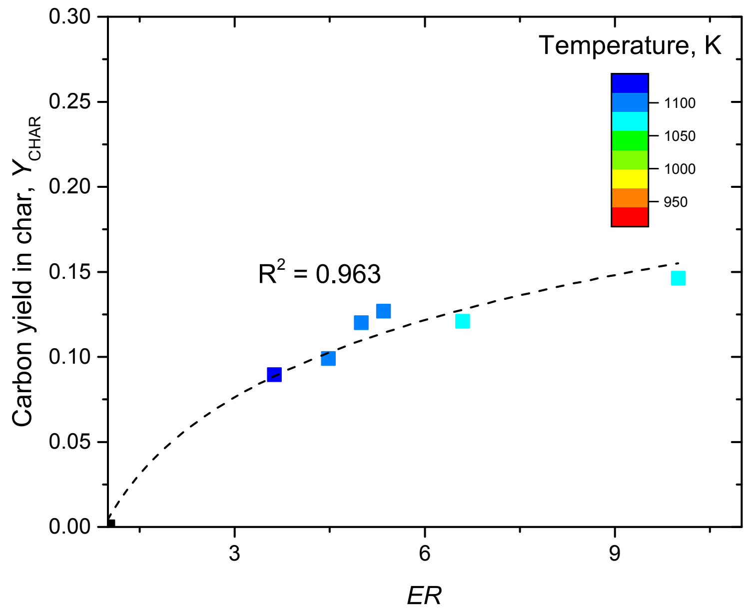

Figure 2.3. Experimental and regressed carbon yield as char following air gasification of sawdust in a fluidised bed reactor (compiled from data in Jand *et al.*, 2006).

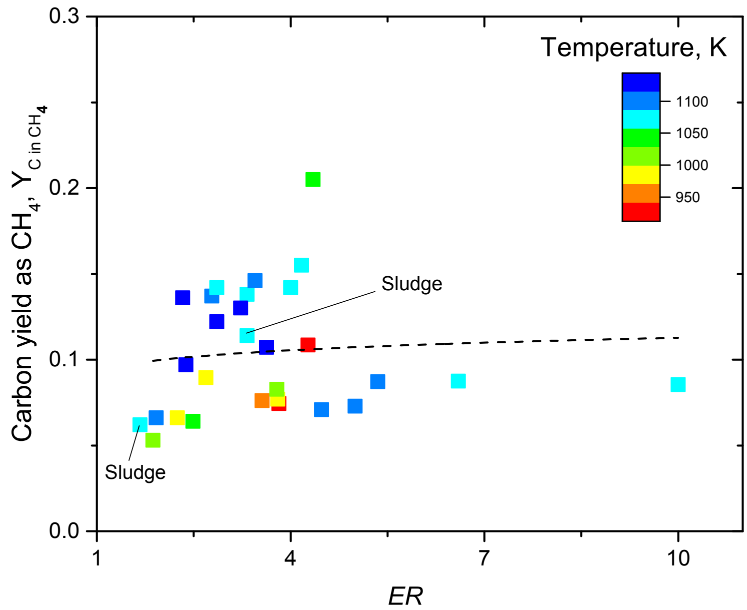

Figure 2.4. Experimental carbon yield as methane following air gasification of different biomass feedstocks.

greater than 1 and T_{GS} greater than 1073 K, carbon conversion can be considered of the same order as observed in air gasification systems at *ER* between 3 and 4. Given the limited experimental data available for gasification systems using both air/O_2 and steam, it was assumed that oxidation reactions affect the carbon conversion more strongly than steam reforming reactions at temperatures between 1023 and 1123 K during gasification.

Char (as pure carbon) and methane yields were also constrained as a function of *ER* and as a fixed fraction, respectively. The excess amount of non-converted carbon was assumed to be transformed to tars, using naphthalene ($C_{10}H_8$) as a model compound. In the estimation protocol, once the non-converted carbon and corresponding hydrogen was subtracted from the incoming fuel, a fixed amount of carbon was retained as methane (Figure 2.1). These constraints, in molar basis, are represented as follows:

$$C_aH_bO_cN_dS_e + y(O_2 + N_2) + zH_2O \rightarrow a \bullet Y_{CHAR}C + a \bullet (1 - X_C - Y_{CHAR})C_{10}H_8 + \text{(Reacting fuel)} \quad \text{(Equation 2.3)}$$

$$\text{Reacting fuel} = (a \bullet X_C)C + (b - 8a \bullet (1 - X_C - Y_{CHAR}))H + cO - dN + eS \quad \text{(Equation 2.4)}$$

The gasification reactor was modelled as a non-stoichiometric equilibrium process using thermodynamic data accessed using MATLAB and Cantera software. The reacting solid fuel (sludge or digestate) and the air/steam/moisture mixture were allowed to attain chemical equilibrium at a constant temperature and pressure [T_{GS}, P_{GS} (gasification/combustion pressure)] in an iterative process to comply with the process mass and energy balance, seeking to minimise the total Gibbs free energy of the syngas product, where i = CO and ns = number of species:

$$\sum_i^{ns} n_i \bar{G}_i = \sum_i^{ns} n_i \bar{G}_i^0 + RT \sum_i^{ns} n_i \ln \frac{f_i}{f^0} \quad \text{(Equation 2.5)}$$

where n corresponds to the moles of gaseous species, G^0 refers to their free energy of formation at the reference state, and f^0 to the gas fugacity (f^0 = 1 bar):

$$f_i = \phi_i x_i P \quad \text{(Equation 2.6)}$$

where x_i corresponds to the molar fractions of gaseous species and P refers to the pressure of the system (P_{GS}). For ideal gases, activity coefficients (ϕ_i) are approximated to 1.

The approximated carbon conversions, and char and methane yields were incorporated into the equilibrium model for the gasification examples in the literature. Figure 2.5 shows a comparison of the syngas composition obtained experimentally from various types of biomass and that predicted using the pseudo-equilibrium model during air gasification.

The major deficiency of the model relates to the prediction of H_2 formation. In all cases, the predicted H_2 concentrations were higher than those observed experimentally. CO_2 and steam reforming of methane and other minor hydrocarbons (C_2H_4, C_2H_6, etc.) occurs at a low rate at temperatures below 1200 K and, therefore, these are commonly found in syngas to a significant extent (<8% v/v). Despite this, the model was capable of estimating the energy content of the syngas with satisfactory accuracy, because of the trade-off between H_2 and CH_4 in contributing to the syngas heating value. This was deemed appropriate as an estimation tool for the purposes of the energy and mass balance analysis in the present study.

2.2 Process Outline of the Thermal Conversion of Sludge/Digestate

The proposed system for energy recovery from sludge and digestate residues from WWT facilities is shown in Figure 2.6. In the first scenario (solid lines), dewatered sludge derived from WWT is dried to below its original moisture content ($y_{M,1}$ = 75%) to increase the chemical efficiency of the thermal conversion. In the second scenario, the sludge produced in the WWT plant was digested anaerobically. The digestate slurry was dewatered to a moisture content of $y_{M,1}$ = 75% and later dried further. This process path is represented in Figure 2.6 with dotted lines.

Biomass drying is carried out in direct or indirect dryers that use hot air, flue gas or steam as heat sources. Theoretical energy consumption associated with this stage is significant: 2.3 MJ kg^{-1} of evaporated water at atmospheric pressure is required (drying at 373 K). This corresponds to 10–60% of the total energy contained in biomass materials and wastes. However, the rate of energy consumption in common dryer systems, such as rotary and flash dryers, can reach over 3 MJ kg^{-1} evaporated water (Li *et al*., 2012). These systems operate at mild to high temperatures (473–873 K) and with high throughput capacities. Other dryer configurations, such as belt conveyors, are preferred, because of their capacity to operate at lower temperatures (303–473 K), their lower heat consumption (1.3–2.5 MJ kg^{-1}) and their easier and safer operation (Li *et al*., 2012). In this study, the dewatered sludge or digestate was dried to a final moisture content ($y_{M,2}$) of between 5% and 50% using heat recovered from heat sources in the system, i.e. syngas from gasification and flue gas from combustion.

After this, the dried sludge or digestate is fed into the thermal conversion stage (combustor/gasifier), in which preheated air is used as the gasifying or combustion agent, depending on the ER. The gasifier or combustor operates at equilibrium temperature (T_{GS}) or at a minimum gasification temperature of 1073 K.

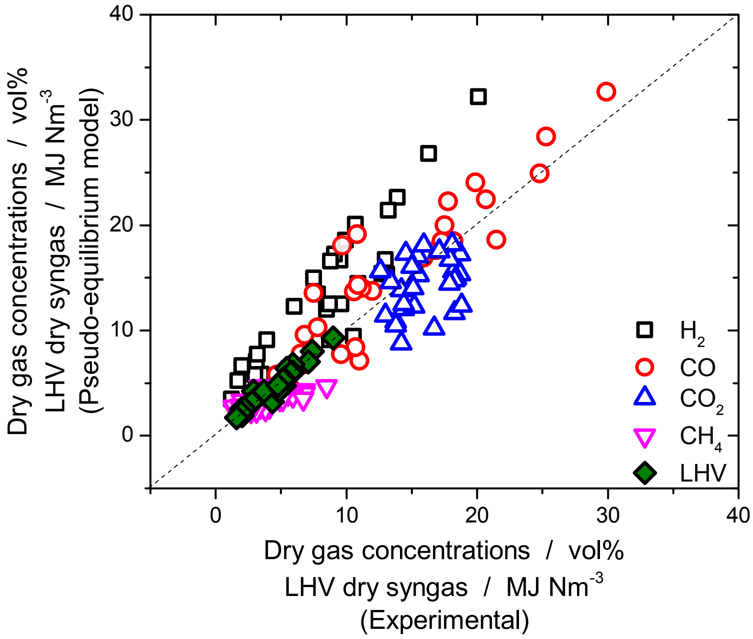

Figure 2.5. Comparison of predictions using a pseudo-equilibrium model with experimental data in air gasification of different biomass at 923–1123 K.

When additional heat is required to attain the minimum gasification temperature (high *ER*), an additional combustor is implemented. In this auxiliary combustor, the char and a fraction of the formed syngas (x_{GS}) are used as fuels to provide the additional energy in the gasifier. The air used in the combustor/gasifier and the auxiliary combustor is preheated in heat exchangers (HE1 and HE2, respectively) using the thermal energy contained in the syngas and the flue gas from the corresponding processes.

Subsequently, the syngas is introduced to the first heat recovery stage (HR1) in which its temperature is reduced to 323 K so that the gas is stripped of H_2S and COS. This gas treatment is carried out using an absorption stage in which aqueous ethanolamine solutions react through an acid–base mechanism with the gaseous sulfur species at low temperatures (Austgen *et al.*, 1991). Energy consumption at this stage relates to the heat used by the reboiler in the stripping system used to regenerate the solvent. For the regeneration of methyldiethanolamine (MDEA) within an integrated gasifier-combined cycle plant, a heat duty of 3.3 MJ kg^{-1} H_2S has been reported in stripping columns operating at temperatures between 350 and 373 K (Fiaschi and Lombardi, 2002). An additional condensation stage is carried out by cooling the syngas to 283 K to remove any residual moisture. The total energy removed from the syngas before and after the gas treatment is considered to be available thermal energy (Q_{HR1}).

After using a fraction of the syngas (x_{GS}) to supply heat to the gasifier when required, the excess syngas is taken to the combined heat and power (CHP) component of the system. Three main systems were considered: (1) reciprocating internal combustion engine (ICE); (2) gas turbine; and (3) steam turbine with/without reheating. After the syngas has passed through the CHP and combustor modules, heat is recovered in HR2 and HR3 by cooling down the exhaust flue gas to the stack temperature (323 K). Heat recovered from the heat sources (Q_{HR1}, Q_{HR2}, Q_{HR3}) will be employed in the WWT stages of sludge/digestate drying, AD and other treatment stages, when required.

Table 2.1 shows a summary of fixed and variable parameters employed in the thermal conversion-CHP systems considered in this study. The system performance was evaluated in terms of overall electrical and heat recovery efficiencies (η_{el} and η_{hr}) and energy coverage (C_{tot}, C_{el} and C_{hr}), defined as follows:

$$\eta_{el} = \frac{W_{CHP}}{m_{feed} \cdot LHV_{feed}} \times 100 \qquad \text{(Equation 2.7)}$$

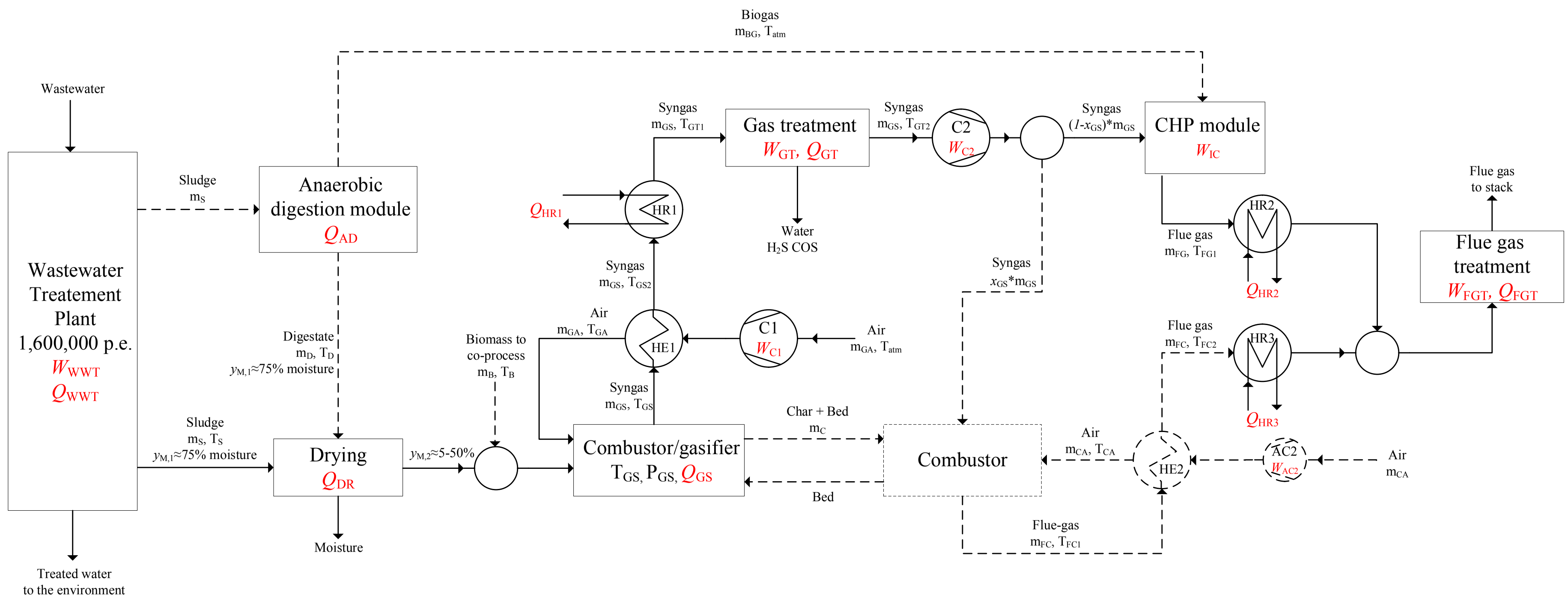

Figure 2.6. Process diagram of energy recovery concept from sludge/digestate conversion through anaerobic digestion and/or thermal conversion. The dotted lines represent additional process stages required when additional heat is required for the operation of the combustor/gasifier.

$$\eta_{hr} = \frac{Q_{HR_1} + Q_{HR_2} + Q_{HR_3} + Q_{FT}}{m_{feed} \cdot LHV_{feed}} \times 100$$

(Equation 2.8)

$$C_{tot} = \frac{W_{CHP,\text{net}} + Q_{\text{HR}_1} + Q_{\text{HR}_2} + Q_{\text{FT}}}{Q_{\text{WWT}} + Q_{\text{AD}} + Q_{\text{DR}} + Q_{\text{GT}} + Q_{\text{GS}} + W_{\text{WWT}} + W_{\text{GT}} + W_{\text{FT}} + \sum_i W_{\text{R}_i}}$$

(Equation 2.9)

$$C_{el} = \frac{W_{CHP,\text{net}}}{W_{\text{WWT}} + W_{\text{GT}} + W_{\text{FT}} + \sum_i W_{\text{R}_i}}$$

(Equation 2.10)

$$C_{hr} = \frac{Q_{\text{HR}_1} + Q_{\text{HR}_2} + Q_{\text{FT}}}{Q_{\text{WWT}} + Q_{\text{AD}} + Q_{\text{DR}} + Q_{\text{GT}} + Q_{\text{GS}}}$$

(Equation 2.11)

where W and Q correspond to the electricity and heat demands or generation, and the subscripts CHP, HR_i, WWT, AD, DR, GT, GS, FT and R_i refer to the CHP unit, heat recovery from heat sources, WWT facility, AD, drying stage, syngas treatment, gasification process, flue gas treatment and other auxiliary demands, respectively, and m_{feed} and LHV_{feed} are the feed rate and the low heating value of dry sludge, respectively.

2.2.1 Internal combustion engines

Typical electrical efficiencies of reciprocating ICEs vary between 25% and 40% LHV of the fuel gas, while thermal outputs correspond to 35–55% LHV. Commonly, engines for large applications have reported high electrical efficiencies and low thermal energy recoveries (Lantz, 2012). However, this may vary depending on the quality of the fuel gas, load level, operation and maintenance. In the first scenario of this study, the electrical efficiency of the engine was defined as a function of the capacity of the system by regressing available data of engine performance (Lantz, 2012; Darrow *et al.*, 2015).

The exhaust flue gas temperature was defined as a function of the engine capacity, given that less energy is generally transformed into work at lower engine capacities. Engines with a base load electric capacity of 100 kW have reported exhaust temperatures of 923 K, while at larger capacities (> 9 MW), the temperature reported was around 623 K (Darrow *et al.*, 2015).

2.2.2 Gas turbines

In gas turbines, the available syngas is burnt in a combustor with excess air to guarantee the turbine inlet temperature (1373–1773 K). Although current gas turbine designs for natural gas have reported pressure ratios well above 20:1 (Taamallah *et al.*, 2015), the challenges involved in the use of syngas as a fuel in conventional and fit-for-purpose turbines restrict their performance. Gas turbines designed for low-BTU (British thermal unit) fuels (syngas) with non- or partially-premixed flames (170–880 MW) have reported pressure ratios between 12:1 and 17:1 and efficiencies between 35% and 40% (Taamallah *et al.*, 2015). In the present study, pressure ratio, turbine inlet pressure and temperature were varied to reach electrical efficiencies as observed for conventional natural gas turbines of similar capacities.

2.2.3 Steam turbines

For the steam cycle, a gas boiler is used to burn the available syngas and generate steam. Typical industrial and CHP fuel boilers operate with overall efficiencies of 70–85% (Darrow *et al.*, 2015). However, the electrical efficiencies of steam turbines depend on the steam cycle design, pressure ratio and regime of the steam turbine.

Since heat is required in the system, a back-pressure steam turbine configuration was considered in this study. Superheated steam at 40 to 125 bar was produced and the pressure ratio in the turbine was such that low-pressure steam was exhausted from the turbine at 1.5 to 5 bar and used for heat requirements in the WWT plant.

The steam was superheated to reach maximum steam temperature: 723 K for combustion or 923 K for gasification. Temperature was lower for a sludge combustion system due to corrosion and damage of the heat recovery–steam generation (HRSG) system by chlorine and sulfur in the combustion flue gas. Taking into account that syngas was scrubbed prior to the CHP component, the steam temperature considered in the steam cycle was higher when analysing the gasification–steam cycle system.

Table 2.1. Operational parameters of the gasification–CHP systems

Component	Value or range
WWT plant[a]	
Installed capacity	1,600,000 p.e.
Sludge generation	130 dry tpd
Digestate generation	85 dry tpd
Energy consumption ($W_{WWT} + Q_{WWT}$)	50,400 MWh year^{-1}; 83% electricity, 17% heat[b]
Biogas production	37,500 m^3 day^{-1} (65% CH_4, 35% CO_2)
Gasification–combustion	
Moisture content in feed ($y_{M,2}$)	5–50% w.b.
ER	Combustion: 0.5–1.0; gasification: 1.5–4.5
Minimum gasifier temperature ($T_{GS,min}$)	1073 K
Gasifier/combustor pressure (P_{GS})	1.2 bar
Gasifier/combustor pressure drop	0.1 bar
ER in combustor	0.9
Air temperature to gasifier (T_{GA})	873 K
Air temperature to combustor (T_{CA})	873 K
CHP system 1: ICE	
Inlet combustion engine pressure (P_{IE})	1.2 bar
ER	0.9
Electrical efficiency in combustion engine (η_{EE})	$0.41–0.16\exp(-1.3 \times 10^{-3} W_{CHP})$
Exhaust flue gas temperature (T_{FG1})	$391.7–4.3 \times 10^{-3} W_{CHP} + 305.7\exp(1.6 \times 10^{-3} W_{CHP})$
CHP system 2: gas turbine	
ER in combustor	0.9
Inlet gas turbine pressure (P_{IGT})	20–35 bar
Inlet gas turbine temperature (T_{IGT})	1373–1773 K
Pressure ratio in gas turbine (PR_{GT})	5–25
Isentropic gas turbine efficiency (η_{SGT})	85%

Table 2.1. Continued

Component	Value or range
CHP system 3: boiler-steam turbine	
ER in boiler	0.8
Overall boiler efficiency (LHV) (η_B)	80%
Isentropic steam turbine efficiency η_{SST})	62%
Inlet steam pressure (P_{IS})	40–60 bar (direct sludge/digestate combustion); 60–125 bar (syngas combustion)
Maximum steam temperature in turbine ($T_{max,ST}$)	723 K (450°C) (direct sludge/digestate combustion); 923 K (650°C) (syngas combustion)
Steam pressure for utilities (P_S)	1.5–5 bar
Other specifications	
Drying heat (Q_{DR})	3.3 MJ kg^{-1} evaporated H_2O
Flue gas temperature to stack	423 K
Flue gas pressure to stack	1.1 bar
Compressor isentropic efficiency (η_{SC})	75%
Maximum pressure ratio in compressor[c] (PR_C)	2.3–3.0
Centrifugal pump efficiency (η_{SCP})	75%
Maximum total sulfur in cleaned syngas	1000 ppmv
Sulfur removal energy (H_{GT})	3.3 MJ kg^{-1} removed H_2S
Gas treatment temperature (T_{GT1})	323 K
Temperature drop in gas treatment (ΔT_{GT})	8 K
Pressure drop in gas treatment (ΔP_{GT})	0.01 bar
Pressure drop in heat exchangers (ΔP_{HE})	0.02 bar
Temperature of selective catalytic reduction (T_{SCR})	673 K
Temperature of SO_2 scrubbing (T_{DSO})	443 K
Maximum gas temperature in ESP (T_{ESP})	423 K
Energy consumption by ESP (W_{ESP})	0.450 kWm^{-3} s^{-1} flue gas

[a]Estimated for a WWT plant operating with activated sludge process, tertiary WWT, centrifugal sludge dewatering and mesophilic AD (311 K) with thermal pretreatment (323 K).

[b]Heating corresponds to that required at the AD stage.

[c]This is required for the outlet compressor temperature to be 433 K or higher when another compressor stage follows. Inter-stage cooling temperature is 20 K higher than ambient temperature (288 K).

ESP, electrostatic precipitator; ppmv, parts per million by volume; w.b., wet basis.

2.2.4 Feedstocks: sludge, digestate, wastes and biomass

This study focused on the use of SS and digestate from WWT plants. These materials contain low carbon [30–40% d.b. (dry basis)] and high ash contents (> 15% d.b.), which is in contrast to the levels found in conventional biomass. This directly affects the energy content of the sludge and digestates when used as solid fuels and thus the quality of the produced syngas. In addition, the dewatered moisture content of sludge/digestate affects the overall energy efficiency of the process. In this study, a dewatered moisture content of 75% was considered (Werther and Ogada, 1999). Other biomass and wastes were taken into account for co-processing. Table 2.2 shows the properties of the waste and biomass materials considered in this study.

2.2.5 Costs of treatment and costs of electricity for sludge-to-energy systems

Capital cost data were gathered through a literature survey and were updated and converted to reflect equivalent costs in euros for 2015. For these approximations, national consumer price indices (CPIs) and average international exchange rates for 2015 were used.[1] Equipment costs for the different modules were taken from the literature as free-on-board (FOB). Factors were applied to estimate direct and indirect costs associated with the modules, covering materials and labour required for installation, as well as other indirect costs (interest during commission, contractor fees, contingency, commissioning), so that:

$$TCC = FOB \times (1 + \alpha_{TC}) \qquad \text{(Equation 2.12)}$$

where *TCC* is the total capital cost of the equipment considered, *FOB* refers to the FOB cost of the equipment or system, and α_{TC} refers to the correction factor for total direct and indirect costs associated with the system ($\alpha_{TC} = 0.8$) (Bridgwater *et al.*, 2002; Yassin *et al.*, 2009).

Investment costs for combustion plants were based on facilities processing biomass and wastes using fluidised bed reactors and including the CHP system (steam cycle) for electricity generation (van den Broek *et al.*, 1996; Granatstein, 2004; Junginger *et al.*, 2006). Investment costs for fluidised bed gasifiers included costs associated with the feeding mechanism, the reactor and the syngas cleaning system (Bridgwater *et al.*, 2002). Installation costs of AD plants (including ICE modules) were taken from a survey of the literature and corresponded to agricultural and waste treatment

Table 2.2. Final analysis of waste and biomass materials used as fuel[a]

Content	SS	SS digestate[b]	PM	PL	PM digestate[b]	PL digestate[b]	*Miscanthus*	Willow pellets
Moisture (wt%)	75	75	40	40	75	75	25	25
C (wt% d.b.)	36.5	31.0	40.3	36.2	33.8	28.5	47.3	49.0
H (wt% d.b.)	5.2	3.4	5.2	5.2	4.6	3.7	5.4	6.0
O (wt% d.b.)	22.3	21.8	32.0	32.0	20.4	23.7	41.5	42.8
N (wt% d.b.)	5.0	6.1	2.7	4.6	4.7	7.6	0.6	0.5
S (wt% d.b.)	1.5	1.8	0.5	0.6	0.9	1.1	0.1	0.2
Ash (wt% d.b.)	29.5	35.9	20.3	21.3	35.6	35.3	5.1	1.5
LHV[c] (MJ dry kg^{-1})	13.6	10.1	12.9	11.7	12.4	9.1	13.9	14.9

[a]Taken from the ECN biomass database (ECN, 2015).

[b]Estimated by a mass balance after the biogas production specified in Table 2.1.

[c]Estimated by the Scheurer's empirical equation for biomass heating value (Friedl *et al.*, 2005).

d.b., dry basis; PL, poultry litter; PM, pig manure; wt%, percentage by weight.

1 Prices and consumption (Statistics Sweden) (available online: http://www.scb.se/en_/Finding-statistics/Statistics-by-subject-area/Prices-and-Consumption/); consumer prices indices (Office for National Statistics, UK) (available online: https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/czvl/mm23); CPI data from 1913 to 2016 (US Inflation Calculator) (available online: http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/); consumer price index (Statistics Denmark) (available online: http://www.dst.dk/en/Statistik/emner/priser-og-forbrug/forbrugerpriser/forbrugerprisindeks); and euro foreign exchange reference rates (European Central Bank) (available online: https://www.ecb.europa.eu/stats/exchange/eurofxref/html/index.en.html).

plants (Hjort-Gregersen, 1999; Alakangas and Flyktman, 2001; Walla *et al*., 2006). FOB costs of CHP systems (ICE, gas and steam turbines, and combined cycles) were also gathered from the literature and calculated to reflect overall price variation as a function of design capacity or generated electricity (Bridgwater *et al*., 2002; ESMAP, 2009; Darrow *et al*., 2015; NTC, 2015). The data were used to calculate the investment costs of these systems as a function of either feed capacity (MW_{fuel}) or electricity generation (MW_{el}).

Operational and maintenance (O&M) costs for all the process stages were either gathered from the literature or estimated using the energy and mass balances of the operations involved at each stage of the system (van Ree *et al*., 1995; Bridgwater *et al*., 2002; US-NREL, 2006; Tippayawong *et al*., 2007; Yassin *et al*., 2009; Darrow *et al*., 2015). Appendix 1 summarises the expressions and values used for estimation of capital and O&M costs. Capital was amortised for a project period of 20 years with an annual interest of 5%. COT and LCOE were estimated after correcting the capital and O&M costs with a fixed annual inflation rate of 1% and using the annualised costs and sludge feed rate and annual net power generation, respectively:

$$COT = \frac{\left[\sum_i O\&M_i\right]_{yearly}}{m_{sludge,yearly}}, \left[€ton^{-1}\right] \quad \text{(Equation 2.13)}$$

$$COE = \frac{\left[\sum_i TCC_i + \sum_i O\&M_i\right]_{yearly}}{\left[W_{CHP} - \sum_i W_{R_i}\right]_{yearly}}, \left[c€kWh^{-1}\right] \quad \text{(Equation 2.14)}$$

$$SCI = \frac{\sum_i TCC_i}{W_{CHP} - \sum_i W_{R_i}}, \left[k€kW^{-1}\right] \quad \text{(Equation 2.15)}$$

The costs of disposal of separated ash from combustion or gasification and solid residues generated in the removal of sulfur oxide gases (SO_X) gases were also taken into account. Landfill gate fees were assumed to be €80 t^{-1}, in addition to the levy of €75 t^{-1} for waste disposed at landfilling facilities in Ireland (EEA, 2013; Government of Ireland, 2013).

2.2.6 *Carbon emissions due to energy consumption and energy savings in thermal conversion systems*

Carbon dioxide equivalent emissions were estimated, taking into account the energy balance of the process and the emissions factors associated with Irish energy. Table 2.3 lists the energy conversion factors used in this study. Energy demands were converted to the equivalent amount of primary energy, while energy generated on site was considered direct energy (1 kWh renewable energy = 1 kWh primary energy). Net carbon emissions were estimated in two bases: per m^3 of treated wastewater in the facility or per tonne of dried sludge:

$$\text{Carbon emissions}_{per\ m^3} = \frac{\sum_i f_{EI} \cdot f_{PE} \cdot W_{R_i} + \sum_i f_H \cdot f_{PE} \cdot Q_{R_i}}{V_{ww}} \quad \text{(Equation 2.16)}$$

$$\text{Carbon emissions}_{per\ t} = \frac{\sum_i f_{EI} \cdot f_{PE} \cdot W_{R_i} + \sum_i f_H \cdot f_{PE} \cdot Q_{R_i}}{m_{feed}} \quad \text{(Equation 2.17)}$$

$$\text{Carbon savings}_{per\ m^3} = \frac{f_{EI} \cdot W_{IC} + \sum_i f_H \cdot Q_{HR_i}}{V_{ww}} \quad \text{(Equation 2.18)}$$

Table 2.3. Energy and emission factors for Ireland

Energy and emission factors	
Electricity	
f_{EI}	0.522 kg CO_2 kWh^{-1}
f_{PE}	2.37 kJ PE kJ^{-1}
Heat and natural gas	
f_H	0.445 kg CO_2 kWh^{-1}
f_{PH}	1.375 kJ PE kJ^{-1}

f_{EI}, factor of equivalent carbon dioxide emission per unit of output electricity; f_H, factor of equivalent carbon dioxide emission per unit of heat used; f_{PE}, factor of primary energy consumed per unit of output electricity; f_{PH}, factor of primary energy consumed per unit of heat used; PE, primary energy.

$$\text{Carbon savings}_{per\ t} = \frac{f_{EI} \cdot W_{IC} + \sum_i f_H \cdot Q_{HR_i}}{m_{feed}}$$

(Equation 2.19)

$$\text{Net emissions} = \text{Carbon emissions} - \text{Carbon savings}$$

(Equation 2.20)

2.3 Conclusions

A thermodynamic pseudo-equilibrium model was built to predict the energy value of the syngas generated from a wide range of solid fuels, biomass and wastes in fluidised bed gasifiers. Descriptions were presented for the empirical and thermodynamic assumptions that were used in the construction of the computational energy recovery model. The pseudo-equilibrium model for gasification was integrated with these modular modelling tools to describe the performance of the complete system. User-defined inputs include sludge properties and operational conditions, such as ambient temperature, influent wastewater, sludge generation rate and biomass co-processing, among others. The following chapter will present a techno-economic analysis of the system generated with the use of this model.

3 Thermal Conversion of Sludge and Integration with AD in WWT Plants

WWT plants consume up to 180 MJ (50 kWh) per person and produce over 27 Mt of sludge every year in Europe (Shi, 2011; Eurostat, 2012). This sector is undergoing continuous change due to more rigorous environmental regulations on effluent quality, population growth and increased urbanisation. Technologies for sludge treatment include thickening and dewatering, as well as biological processes, such as AD and composting. A WWT facility can produce between 10 and 60 kg dry SS per p.e. every year (Shannon *et al*., 2014). After thickening and dewatering, these 60 kg SS can occupy over 240 litres (25% w/w dry solids), requiring about 50 MJ (14 kWh) for transport to a disposal site 50 km away (Houillon and Jolliet, 2005). This is an increase of nearly 30% in the energy consumed by the WWT plant and in the indirect carbon footprint of the treatment process.

Plants with a capacity greater than 100,000 p.e. or sludge hub centres importing sludge from a region may be suitable for implementing AD to manage sludge and improve energy efficiency. Pilot and WWT plant scale studies have reported biogas yields between 4 and 10 GJ t^{-1} (1–3 kWh kg^{-1}) for dry sludge through AD of municipal SS (Qiao *et al*., 2011). However, large-scale biogas plants can consume up to 40% of this energy for their operation, thus diminishing energy efficiency (Berglund and Börjesson, 2006).

Thermal technologies for the conversion of either SS or anaerobic digestate represent potential methods for both sludge volume reduction and energy recovery. In particular, sludge combustion and gasification could provide either thermal or chemical energy for CHP generation, which could be readily integrated to WWT plants.

3.1 Sludge and Waste Incineration

Incineration has been used as a sludge management technology following further restrictions on land spreading of sludge residues in several European countries. Sludge volume is readily reduced through auto-thermal oxidation of sludge in multiple hearth or fluidised-bed incinerators when operating at high temperatures (> 1000 K). All organic content in the sludge is oxidised and the inorganic components are obtained in the form of a stabilised bottom or fly ash (10–30% w/w d.b.).

These technologies have been widely implemented for municipal waste disposal in the last decade, representing, in some cases, a self-sustained energy supply for sludge drying and disposal (Werther and Ogada, 1999). However, emissions arising from the high nitrogen and heavy metal content in SS and wastes require additional stages of flue-gas cleaning, e.g. catalytic and non-catalytic NO_x (nitrogen oxide gases) reduction, tar/polycyclic aromatic hydrocarbons reduction, staged combustion and adsorption (Sänger *et al*., 2001; Yao *et al*., 2004; Deng *et al*., 2009).

These technologies have been implemented in Canada, Germany, the Netherlands and the USA, where facilities with low or zero additional fuel consumption requirements operate at scales over 100 dry tpd (Burrowes *et al*., 2010; Dangtran *et al*., 2011). An example of this is the Müllverwertung Rugenberger (MVR) incineration plant in Hamburg, Germany. This facility uses a vertical incinerator equipped with a flue-gas cleaning system (catalytic NO_x reduction, HCl- and SO_2-scrubbing, bag filters), which can process 510 dry tpd of waste to generate 46 MW of steam and 4 MW of electricity (Zwahr, 2003). This plant has achieved sustainable operation through extensive recovery of by-products from the wastes and flue gas treatment, including technical grade hydrochloric acid, scrap metals, slag and gypsum.

3.2 Gasification of Biomass and Wastes

Gasification represents an alternative to overcome the challenges of flue-gas emissions from combustion. Through this conversion process, the sludge is volatilised at temperatures between 950 and 1200 K under oxidant-lean environments to produce syngas (Huber *et al*., 2006). Because of the weak oxidative character of the process, the formation of the toxic gases NO_x and SO_x is avoided. In this case, treatment of the syngas treatment consisted of H_2S removal prior to any further use as fuel.

In a similar way to combustion, gasification reduces the sludge volume prior to final disposal, since it converts over 80% of the organic fraction to syngas fuel, while fixing any potential harmful metals and inorganic components, i.e. Cd, Co, As and Hg, in the char and ash/slag residue (Marrero *et al*., 2004). Several technologies are available for gasification and these have been gradually implemented for biomass conversion and integration in energy and fuel production (Kopyscinski *et al*., 2010), including fixed (downdraft/updraft) reactors, fluidised-bed (FB) gasifiers and entrained-flow reactors. FB gasification is the most attractive technology for biomass and waste because of its flexibility for treating different qualities of solid fuels, economy of scale and effective process configuration. FB gasification has been explored in the technical evaluation of sludge conversion (Dogru *et al*., 2002; Petersen, 2004; Petersen and Werther, 2005; Nilsson *et al*., 2012; Campoy *et al*., 2014).

3.3 Thermal Conversion for Waste Management and Energy Recovery

One of the main challenges of thermal conversion processes lies in the poor energy quality of sludge (10–15 $MJ\,kg^{-1}$ dry sludge) and its high moisture content after dewatering (70–80% w/w). The carbon content of sludge, and therefore its energy content, is known to be reduced following AD. Although half the volatile content of the sludge is converted through AD, moisture content in the digestate after dewatering is similar to that of dewatered raw sludge. Sludge drying not only represents a high energy penalty for thermal conversion, but is also subject to technical limitations, principally those related to the poor solid properties of mildly dried sludge (35–40% w/w moisture) (Werther and Ogada, 1999). Combustion within WWT plants that implement AD has been identified as sustainable for biosolids management, since it improves the energy balance (up to 83% energy coverage) and reduces the carbon footprint (~ 4 kg CO_2 $year^{-1}$) (Burrowes *et al*., 2010; Stillwell *et al*., 2010). Nevertheless, investment costs for both AD and thermal conversion can be prohibitive when compared with those of conventional thermal technologies, such as incineration in grate furnaces (Burrowes *et al*., 2010; Shi, 2011).

The present study evaluated the energetic integration of combustion and gasification as final sludge conversion technologies within WWT facilities that include AD and/or drying as primary management processes. Different CHP systems were considered for the transformation of biogas and/or syngas to heat and electricity.

A parametric optimisation of sludge/digestate gasification or combustion was carried out using the electrical and heat recovery efficiencies of the proposed systems for on-site energy demands, as proposed in Chapter 2. Air gasification using an indirect heat supply utilising char/syngas was simulated through a pseudo-equilibrium thermodynamic model implemented using Cantera and MATLAB software.

The effects of operational parameters (*ER*, T_{GS} and sludge drying extent) and of fuel properties [hydrogen to carbon molar ratio (H/C), oxygen to hydrogen molar ratio (O/H) and ash content] on the efficiency of the thermal conversion were evaluated, as well as the effects of the operational conditions for the CHP components. An economic analysis was performed to compare the COT and costs of electricity (COE), when produced, to determine the most suitable process configurations for implementation in medium to large WWT plants.

3.4 Gasification Performance of Sludge and Digestate

In this study, the reaction temperature of the gasification stage (T_{GS}) was determined using the model of an ideal reactor in which heat was provided by oxidation reactions involving O_2. However, low equilibrium temperatures were attained when low O_2 concentrations were used ($ER > 1.7$–2). The reactivity or kinetics of char gasification and water–gas shift reactions are greatly affected by temperature. As a result, carrying out the process at temperatures lower than 950 K would be impractical, requiring long reaction times to reach equilibrium or appropriate conversions. A minimum T_{GS} of 1073 K was maintained to guarantee the validity of the pseudo-equilibrium model. Figure 3.1 shows the predicted gasification

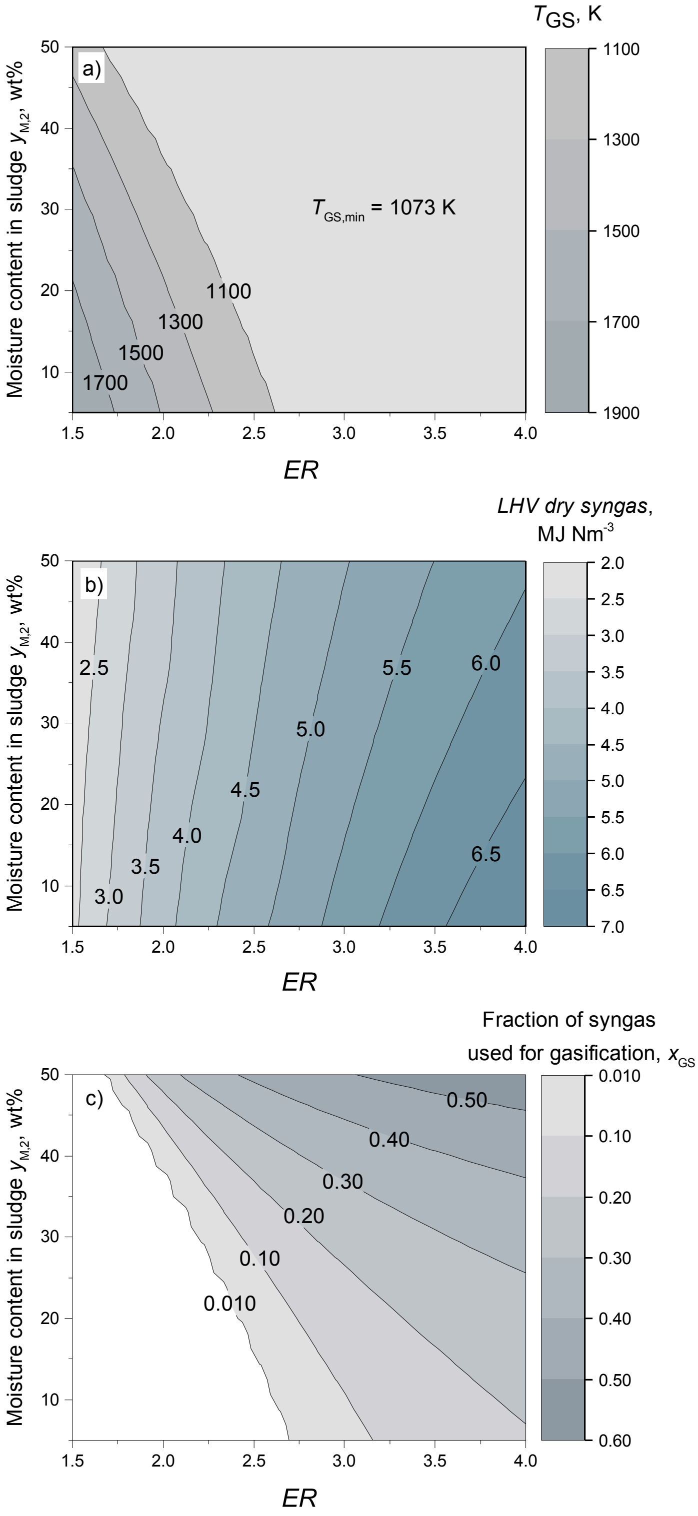

Figure 3.1. Performance of gasification of sludge as a function of the equivalence ratio and moisture content of the sludge: (a) gasification temperature (T_{GS}); (b) low heating value of syngas; and (c) fraction of syngas used in the combustion module to provide heat to gasification.

performance as a function of *ER* and moisture content ($y_{M,2}$) of the SS in the reactor.

Temperatures between 1100 and 1700 K were attained at mild gasification conditions (*ER* = 1.5–2.5). Above *ER* = 2–2.5, an external heat source was required to maintain the minimum T_{GS}.

The energy content of the syngas (LHV) varied between 2.5 and 7 MJ Nm^{-3} at the conditions evaluated. Low moisture contents and high ERs resulted in improved syngas quality. At low ERs, oxidation pathways prevailed, leading to the formation of CO_2, H_2O and low-LHV syngas. Under these conditions, the water content of the feed had a minor influence on syngas composition. At high ERs, the negative effect of moisture content was evident. High concentrations of water or moisture altered the equilibrium of the water–gas shift reaction, with the result that CO was consumed and CO_2 was produced, leading to a decrease in the syngas LHV.

The unreacted carbon (char) and a fraction of the syngas (x_{GS}) were combusted in the combustor component of the indirect gasifier to reach the minimum gasification temperature at high ERs. The syngas fraction used for the SS gasifier reached over 50% at $ER = 4$ and $y_{M,2} = 50\%$. Because the syngas quality was higher at low moisture contents, a smaller amount of syngas was required under these conditions. For digestates, the heating value of the produced syngas was reduced to 2–6 MJ Nm^{-3}. The x_{GS} syngas fraction used to heat the gasifier was then required at lower ERs than those when using SS. At $ER = 4$, between 20% and 75% of the syngas was combusted to maintain the minimum T_{GS} during the gasification process.

3.5 Integration of CHP Technologies for Energy Recovery in WWT Plants

Eight different energy recovery technologies were evaluated within the case scenarios of the WWT plant proposed in Figure 2.6. Firstly, only thermal conversion pathways (Cases TC1–4) were considered, where sludge was the feed to the system:

- Case TC1: sludge combustion and a steam cycle were used to recover heat as steam and electricity through a steam turbine.
- Case TC2: sludge gasification and a syngas-fuelled boiler (HRSG) were used to recover heat as steam and electricity through a steam turbine.
- Case TC3: sludge gasification and a syngas-fuelled reciprocating ICE were used to recover electricity and heat from the exhaust gases.
- Case TC4: sludge gasification and a syngas-fuelled gas turbine were used to recover electricity and heat from the exhaust gases.

In addition, AD was considered a first stage for the thermal conversion for the anaerobic digestion coupled with thermal conversion (ADTC) alternatives:

- Case ADTC1: sludge was digested and the digestate was dried and combusted. Biogas was combusted. Heat was recovered to generate steam used in steam turbines and in process demands.
- Case ADTC2: sludge was digested and the digestate was dried and gasified. Syngas and biogas were used in a boiler to generate steam and electricity in a steam turbine.
- Case ADTC3: sludge was digested and the digestate was dried and gasified. Biogas and syngas were used as fuel in an ICE to generate electricity. Heat was recovered from the exhaust gases.
- Case ADTC4: sludge was digested and the digestate was dried and gasified. Biogas and syngas were combusted in a gas turbine to generate electricity. Heat was recovered from the exhaust gases.

The scenario in which only AD and drying of the dewatered sludge were performed was used as a benchmark and will be referred to as Case AD.

The comparison of the energy recovery technologies was carried out using a range of performance indicators. For the thermal conversion, the SS and sludge digestate properties presented in Table 2.2 were used. ER and feed moisture content ($y_{M,2}$) were used as the main variable parameters for combustion and gasification. For the steam cycle, the maximum steam temperature (T_{ST}) and pressure (P_{ST}) were also varied to observe the performance of power generation and heat recovery. For gas turbines, the pressure ratio (PR_{GT}), and the inlet gas temperature (T_{IGT}) and pressure (P_{IGT}) were also varied. Variation in ICE performance was included in the calculation because of the dependence of power efficiency and heat recovery on the theoretical installed capacity. Figure 3.2 shows the correlations between the heat recovery (η_{hr}), power efficiency (η_{el}) and electrical efficiency (η_{el}) for Cases TC1–4 and Cases ADTC1–4.

In this analysis, it was observed that:

- There was an inverse proportionality between heat recovery and electricity generation.

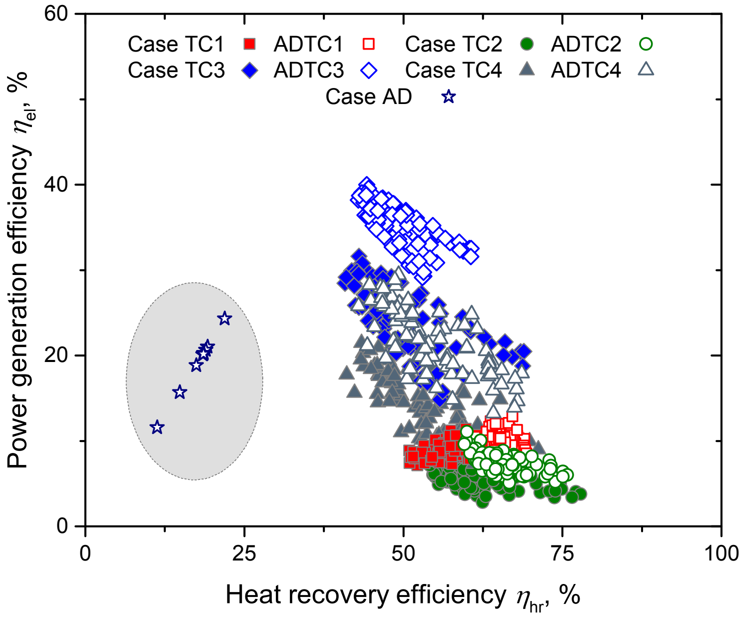

Figure 3.2. Total energy recovery efficiency ($\eta_{el} + \eta_{hr}$) and electrical efficiency (η_{el}) for Cases TC1–4 (full symbols) and ADTC1–4 (empty symbols).

- Heat recovery efficiencies of between 35% and 75% were achieved, with corresponding power efficiencies of between 2% and 40%.
- When gasification was performed, integration of AD with thermal conversion increased electricity generation by 30–70% for a given heat recovery efficiency.
- AD integration with combustion and steam cycles marginally increased net electricity generation while improving heat recovery by 15%.
- Poor power generation with high heat recovery was predicted for Cases TC1 and TC2 and for Cases ADTC1 and ADTC2, because of the low power generation capacity of the steam turbines.
- Cases TC3, TC4, ADTC3 and ADTC34 reported higher combined electricity generation and heat recovery efficiencies due to higher power efficiencies (20–40%) than those of steam turbines (5–12%) at these scales (3–8 MW_{el}).

Figure 3.3 shows the correlation between heat coverage (C_{hr}) and electricity coverage (C_{el}) of the energy demands of the WWT plant for each case. Coverage factors below 100% represent a system configuration in which the energy harvested from the sludge was not sufficient to cover utility demands (heat and electricity deficits) for the whole plant, whereas values above 100% indicate an overall energy surplus that could be used to provide electricity to the grid or heat for external demands, e.g. district heating.

In relation to the coverage of energy demands, it was found that:

- The highest power coverage was attained only when heat coverage was lower than 100%. This implied that additional fuel would be required to offset heat demands during operation.
- Cases TC1–4 and ADTC1–4 reported higher efficiencies for power generation and greater heat integration flexibility on site than for Case AD.
- A certain window of conditions for Cases TC3, ADTC3 and ADTC4 resulted in excess electricity and heat (top right quadrant of Figure 3.3). Cases TC3 and TC4 fulfilled between 30% and 135% of electricity demands, while providing 80–150% of the required heat.
- The cases TC1, TC2, ADTC1 and ADTC2 resulted in scenarios in which up to 45% of the electricity on site was provided, and heat demands, including sludge drying and AD heat, were fulfilled in excess (100–180%).
- Steam turbine systems led to high excess heat recovery rates of up to 5 MJ kg^{-1} or 1400 kWh t^{-1} dry sludge, in addition to process demands. To put it in context, a sludge conversion facility (130 tpd) relying on combustion/gasification and steam cycle could provide heat to 5000 household units

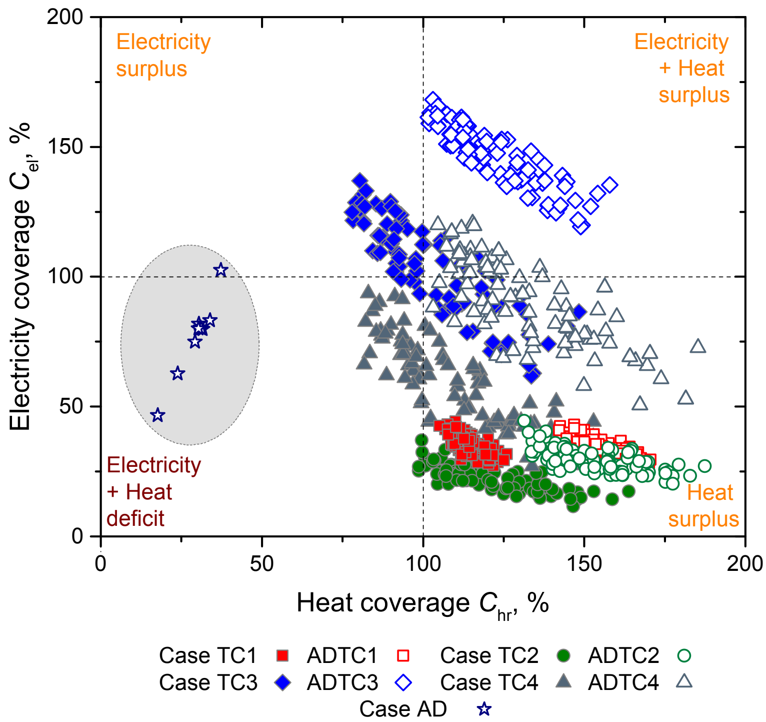

Figure 3.3. Heat coverage (C_{hr}) and electricity coverage (C_{el}) for Cases TC1–4 (full symbols) and Cases ADTC1–4 (empty symbols).

(13,000 kWh year^{-1} per dwelling) (Howley *et al.*, 2015).

- Using steam turbines, combustion led to a more efficient scenario than gasification, achieving similar heat to and higher electricity coverage than Cases TC2 and ADTC2.
- The higher chemical efficiency provided by the formation of methane through AD simultaneously increased the heat and electricity coverage, as well as the nominal CHP capacity in Cases ADTC3 and ADTC4.
- Cases TC4 and ADTC4 reported lower net electricity generation than Cases TC3 and ADTC3. Within the range of CHP capacities explored (3–8 MW_{el}), gas turbines reported lower efficiencies (25–35% LHV) than ICEs (40–42% LHV) (Darrow *et al.*, 2015).

3.6 Economic Performance of Thermal Conversion Systems Integrated with AD

Figure 3.4 shows the specific capital investment (SCI) and the COT for the different technologies as functions of their corresponding total energy recovery efficiency. It was found that:

- Lowest SCI costs were reported by Cases TC1 and ADTC1 (€280,000 and €430,000 tpd^{-1}, respectively). Given the trajectory and development stage of combustion technologies, investment costs were 50% lower for Case TC1 than for Case TC2 (€565,000 tpd^{-1}). For a 20 MWth biomass conversion process, installation costs of combustion units are up to 2.8 times lower than those of FB gasifiers (Bridgwater *et al.*, 2002).
- The SCI costs for Cases TC3, TC4, ADTC3 and ADTC4, were between €740,000 and €1,050,000 tpd^{-1}. Investment costs were more sensitive to process conditions.
- Cases ADTC1–4 had SCI costs that were higher than in the corresponding Cases TC1–4. In particular, Case ADTC1 reported SCI costs that were 60% greater than those of Case TC1. SCI costs of cases ADTC3 and ADTC4 were 25–30% higher than in the corresponding Cases TC1–4.
- Similar trends were observed for COT, considering that annual O&M costs constituted between 3%

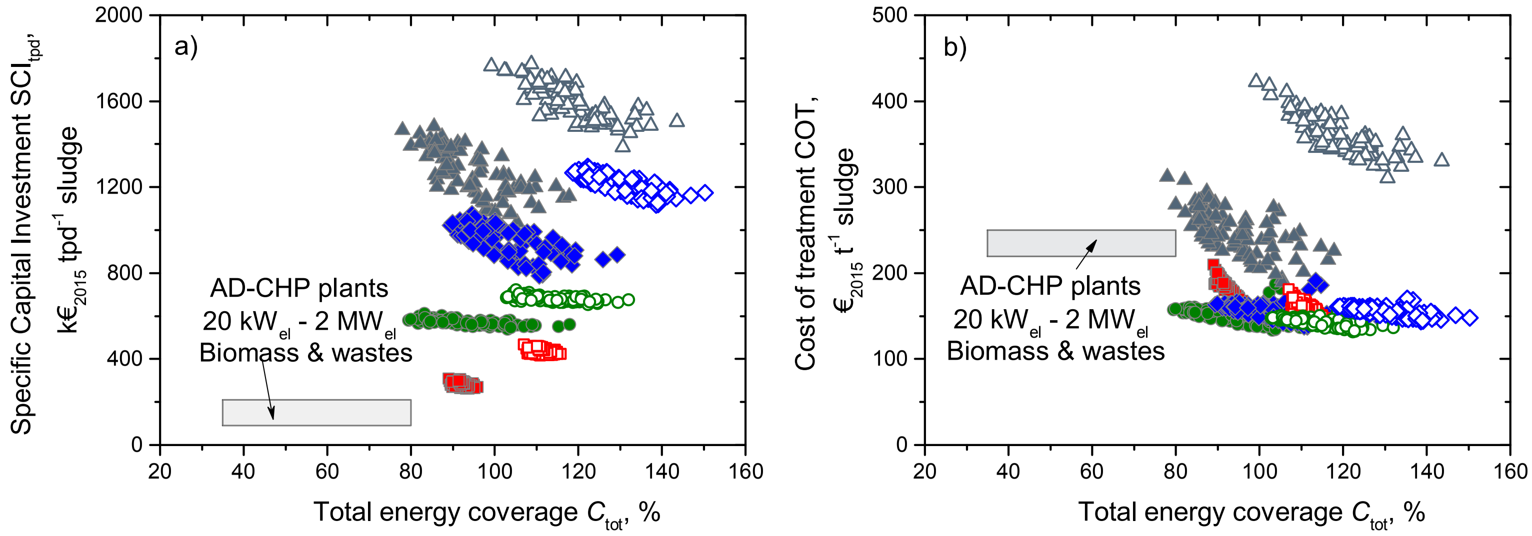

Figure 3.4. Specific capital investment (SCI) and cost of treatment (COT) as functions of the total energy recovery efficiency of the thermal conversion systems.

and 20% of the total capital costs of the complete thermal conversion/ADTC systems.

- Cases TC2, TC3, ADTC2 and ADTC3 reported the lowest treatment costs (€145–160 t^{-1} sludge).
- Using syngas for the steam cycle reduced the COT by up to 25% (€160–200 t^{-1} sludge).
- Case TC4 reported COTs between €190 and €300 t^{-1} sludge, while introducing AD increased these costs by 40%.
- Conditions at which electricity generation was maximised in Cases TC3 and TC4 led to an increase in the COT, while conditions at which their COT was minimised resulted in low electricity production.

It is also necessary to analyse the potential of the sludge management site to operate as an electricity generation facility. For this analysis, SCI costs were expressed in terms of potential power generation and the LCOE was estimated. Figure 3.5 shows SCI per kW (SCI_{kW}) and COE as functions of the electrical efficiency of these systems. It was found that:

- Configurations using gasification had a direct correlation between SCI_{kW} and the efficiency of the system, regardless of the CHP technology.
- For electricity coverage above 100%, SCI_{kW} reached a minimum value of €40,000 kW^{-1}, while costs as high as €200,000 kW^{-1} were observed at the lower end of the efficiency scale.
- All SCI_{kW} costs at high energy coverage levels were well above the range of investment costs reported for AD-based plants using biomass and wastes, commonly between €5000 and €30,000 kW^{-1} (Hjort-Gregersen, 1999; Walla *et al.*, 2006).
- The combination of gasification with AD increased the SCI costs of Cases TC3 and TC4 by less than 20% for any electrical efficiency level.
- Similar trends were observed for COE. Cases TC3 and ADTC3 with high electrical efficiencies reported COEs between 20 and 45 c kWh^{-1}.
- The higher electrical efficiency achieved by the implementation of AD led to lower electricity costs.
- COE for Cases TC3 and ADTC3 were within the known COE from AD-CHP plants converting biomass and wastes, commonly between 5 and 52 c kWh^{-1} (Krich *et al.*, 2005; Walla *et al.*, 2006; Beddoes *et al.*, 2007; MacDonald, 2010; Arup, 2011; US EIA, 2015). However, thermal conversion technologies offer the advantage of operating with capacities greater than 2 MW, unlike AD plants.
- CHP technologies for biomass-based electricity generation have reported potential levelised costs between 9 and 20 c kWh^{-1}, which are in agreement with the estimations presented in this report (Arup, 2011; US EIA, 2015).

3.7 Carbon Emissions Due to WWT Plant Operation with Thermal Conversion Systems Integrated with AD

Net carbon emissions were also estimated as kg CO_2 equivalent per m^3 of wastewater treated in the WWT facility. Only emissions associated with electricity and heat consumption/production were estimated, without taking into account intrinsic emissions from biological WWT, indirect emissions due to chemicals/biomass usage or actual CO_2 stack emissions from the CHP module. As a reference, biogenic carbon emissions associated with biological treatment and nitrogen removal from wastewater as treated in the Ringsend plant were estimated to be approximately 350–370 g CO_2 m^{-3} (RTI International, 2010).

Figure 3.6 shows the associated net carbon emissions as a function of the electrical and heat recovery efficiencies of Cases TC1–4 and Cases ADTC1–4.

Given the operational parameters defined in Table 2.1, the WWT facility considered here would also emit about 367 g CO_2 m^{-3} (890 kg CO_2 t^{-1}) as per the emission factors defined for the Irish energy mix, including emissions associated with AD and sludge drying (20–35 wt% as final moisture content). The introduction of a CHP module for energy recovery in the base case would reduce carbon emissions to 146–215 g CO_2 m^{-3} or 350–520 kg CO_2 t^{-1} dry sludge, depending on CHP efficiency and the extent of drying.

The introduction of thermal conversion as a treatment had significant impacts on the overall carbon footprint:

- Cases TC1, TC2 and TC3 and Cases ADTC1, ADTC2 and ADTC3 showed an overall carbon footprint that was lower than the maximum carbon footprint of the base case scenario.
- Carbon footprints above 220 g CO_2 m^{-3} were reached when the electrical efficiency was maximised in all cases.

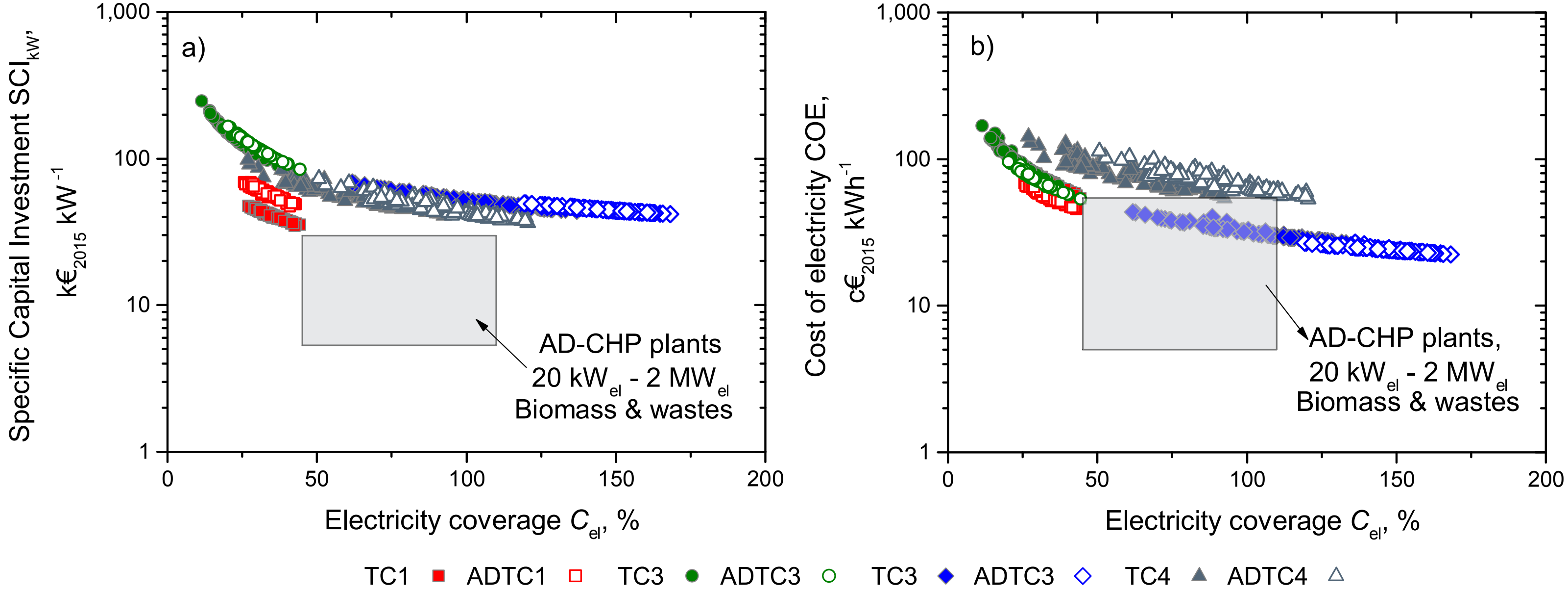

Figure 3.5. Specific capital investment (SCI) and costs of electricity as functions of electrical efficiency and net electricity generation for Cases TC3, TC4, ADTC3 and ADTC4.

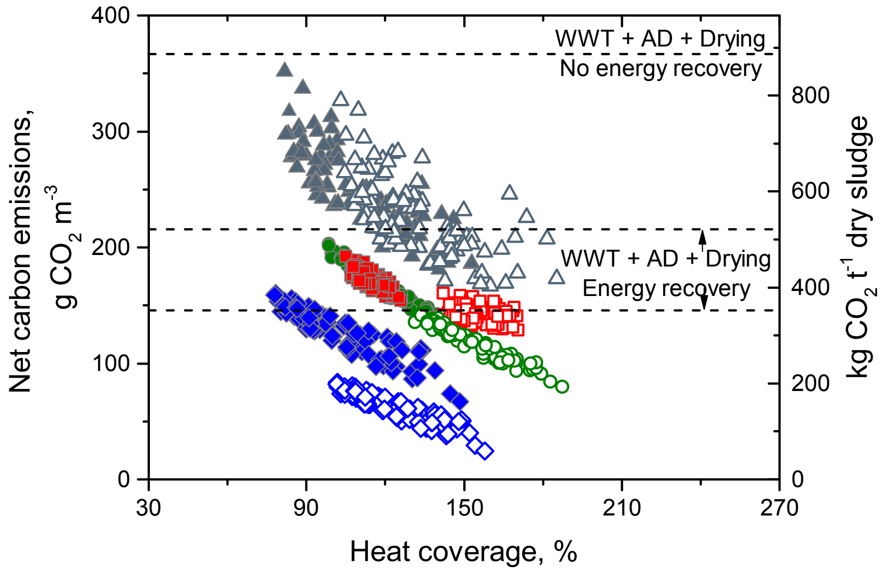

Figure 3.6. Net emissions associated with Irish energy for sludge treatment in Cases TC1–4 and Cases ADTC1–4.

- The use of gas turbines led to an increase in the carbon footprint, due to electricity consumption in auxiliary equipment. For certain conditions, Cases TC4 and ADTC4 reached carbon emission rates of between 170 and 340 g CO_2 m^{-3} (400–800 kg CO_2 t^{-1} sludge), well above the expected emissions of the WWT–AD facility with energy recovery.

3.8 Advantages and Disadvantages of Thermal Conversion Process Configurations

Some advantages and challenges were identified in the application of the proposed cases:

- Thermal conversion routes facilitate waste disposal by reducing the net amount of final solid waste (fly-ash). For AD, only 40–50% of the chemical energy contained in the sludge can be converted to biogas. For a methane productivity of 210 Nm^3 t^{-1} of volatile solids (VS), about 25% of the solid is converted to biogas. Given appropriate process optimisation, combustion and gasification converts over 80% of the organic content of biomass and wastes to energy carriers, leaving only a small fraction of unreacted carbon (char) and stabilised ash for final disposal, thus reducing waste disposal costs.
- In this study, optimal operation conditions were such that a sufficiently rich syngas was produced with an appropriate drying heat penalty. This is particularly important for ICEs, in which heating value and syngas productivity ultimately dictate efficiency.
- For other CHP modules, however, other parameters also played important roles in determining the final efficiency. For gas turbines (Cases TC4 and ADTC4), the inlet pressure of the syngas to the turbine (P_{IGT}), as well as the pressure ratio (PR_{GT}), determine the extension of the energy recovered in the generator. Nonetheless, final efficiency will be affected by the performance conditions at which CHP modules for low energy content syngas are commonly or potentially built for.
- Special designs are required in gas turbine combustors to manage low- to medium-BTU gas fuels (100–500 BTU scf^{-1}, 3.5–20 MJ Nm^{-3}). These modified systems are currently available only for large installations (> 100 MW_{el}) (Taamallah *et al.*, 2015). High H_2 concentrations and large variations in syngas composition can lead to significant changes in the transport and thermochemical properties of the gas. Further development of this technology is required to make syngas-fuelled turbines available for smaller scales (1–100 MW_{el}), with competitive costs and efficiencies.

- ICEs with low to mid-range compression ratios and direct injection systems can be readily adapted to low-BTU gases, either in dual fuel diesel engines (≤90% syngas) or syngas-only spark ignition engines (Hagos *et al*., 2014).

3.9 Optimisation of Energy Recovery Systems Using Gasification and CHP Modules

Thermal conversion following gasification with an ICE was the scenario selected for further analysis because of its energy efficiency, inexpensive operational costs and low carbon footprint. Table 3.1 gives a summary of the process configuration and performance indicators under which net electricity balance was maximised. For this system, it was observed that:

- The combined implementation of AD and gasification doubled electricity generation and electricity coverage.
- Carbon mitigation was significant and offered great potential in diminishing the environmental effects of WWT.

It is important to highlight that uncertainties concerning the sludge properties, sludge production and process control are important in recognising challenges prior to process design and during process operation. The sensitivities of the performance indicators (η_{el}, η_{hr}, C_{el} and C_{hr}) to variations in process parameters within ±20% of the operational range are presented in Figure 3.7. The base case scenario considered the sludge properties shown in Table 2.2 and the conditions shown in Table 3.1. In this analysis, it was observed that:

Table 3.1. Process configurations for maximising electricity generation for internal combustion engines

Process configuration	Gasification	AD + gasification	Units
Energy and emission indicators			
Electricity coverage (C_{el})	133.2	164.2	%
Heat coverage (C_{hr})	83.3	107.4	%
Gross electrical efficiency (η_{el})	30.6	39.1	%
Gross heat recovery efficiency (η_{hr})	45.2	46.0	%
Carbon emissions	332	169	kg CO_2 t^{-1}
Process figures			
Dried sludge feed rate	130	130	tpd
Dry syngas production	3.4	3.2	$m^3 s^{-1}$
LHV of syngas	4.8	5.1	MJ Nm^{-3}
CHP design capacity	6.3	8.0	MW
Auxiliary power	294	352	kW
Gas treatment power	8.5	7.6	kW
WWT power	4.6	4.8	MW
Recovered heat	11.7	12.4	MW
Auxiliary heat	11.3	8.5	MW
Gas treatment heat	2.4	3.1	MW
Economic indicators			
Capital costs	137.8	166.5	M€
O&M	7825	7663	k€ $year^{-1}$
Specific investment costs	21.9	20.8	k€ kW^{-1}
	1060	1281	k€ tpd^{-1}
COT	165	161	€ t^{-1}
COE	26.7	22.8	c kWh^{-1}

- The power efficiency was strongly affected by *ER* following a non-linear correlation. An increase of *ER* led not only to an improvement in the chemical efficiency of the conversion, but also to an increase in the heat demands of the gasifier.
- The heat recovery efficiency was slightly decreased with a lower ER (–2.5%). However, an increase above 5% for this variable did not affect η_{hr}. Changes in *ER* induced similar effects on C_{hr} as for η_{hr}.
- Increasing T_{GS} led to an improvement of the heat recovery by promoting heat exchange from syngas. When using T_{GS} = 1123 K, the heat recovery efficiency increased by more than 3%.
- Electricity coverage was affected mainly when reducing *ER* and increasing T_{GS}. A decrease of 10% in these variables (*ER* = 2.2, T_{GS} = 1023 K) decreased the power coverage by 8% and 3%, respectively.
- Higher ash and oxygen contents in the sludge reduced the power and heat coverage by 4% to 9%, which was a result of the effects these properties have on the sludge energy content.
- The initial sludge moisture content ($y_{M,1}$) affected the heat coverage by modifying the heat duty of the drying stage. When using $y_{M,1}$ = 77%, the C_{hr} was significantly reduced (–10%).
- The final sludge moisture content ($y_{M,2}$) had minor effects on the heat coverage within the evaluated range (the effects were less than ± 3%).
- Sludge feed rate affected the electrical and heat recovery efficiencies marginally; an increase of 20% increased electrical efficiency and reduced heat recovery efficiency by less than 1.5%, respectively.

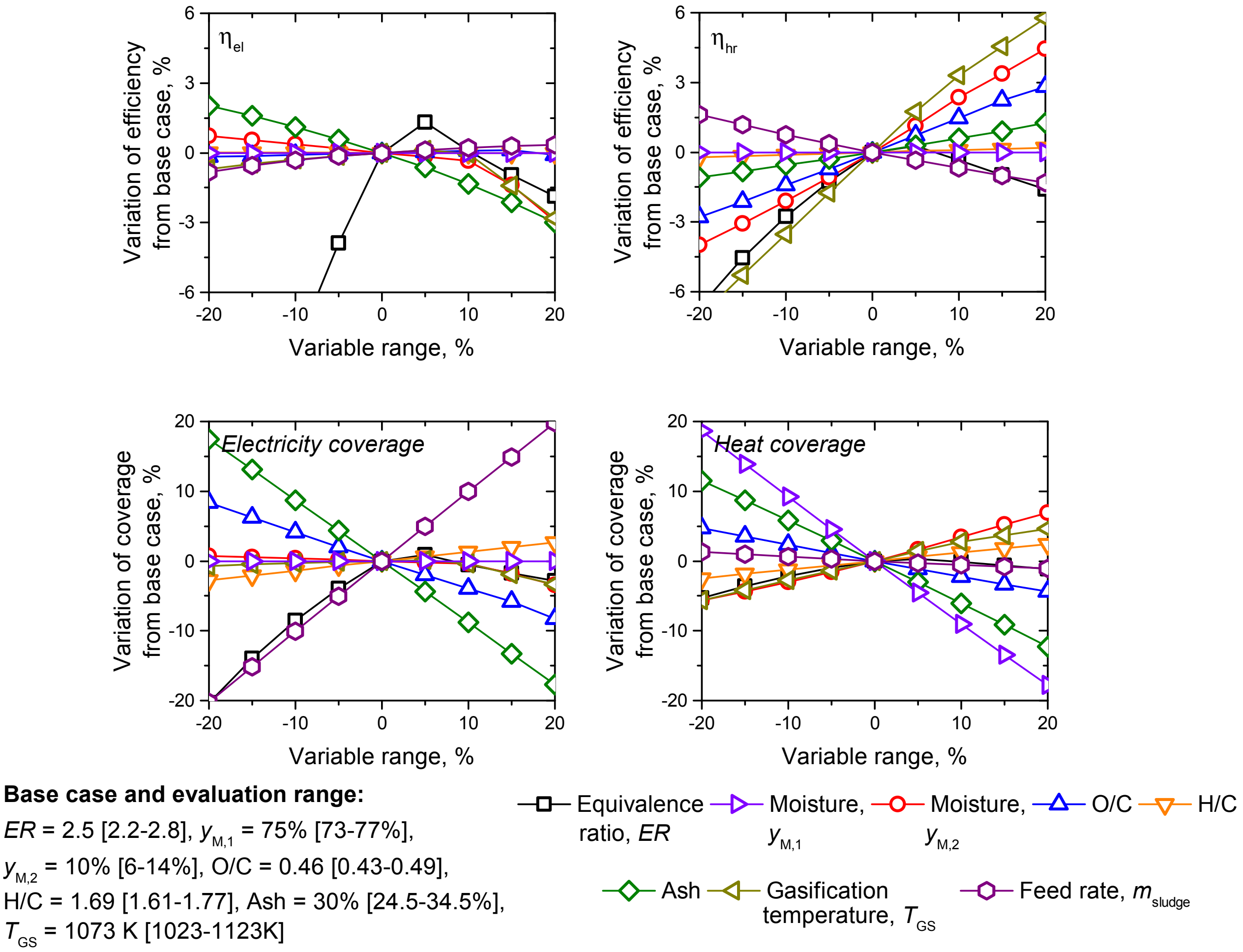

Figure 3.7. Sensitivity of efficiencies and energy coverage levels using gasification and internal combustion engines as functions of process parameters: equivalence ratio (*ER*), sludge moisture contents ($y_{M,1}$ and $y_{M,2}$), gasification temperature (T_{GS}), sludge feed rate, and sludge properties (O/C, H/C and ash content).

- An increase in m_{sludge} from 130 to 156 tpd improved C_{el} by 20%. This would apply to the case in which the sludge feed rate is increased without altering the electricity consumption. A further examination of the sludge feed rate is presented in Appendix 2.
- Sludge properties affected C_{hr} because of their influence on the sludge energy content. When the ash content increased from 29.5 to 34.5%, the heat coverage decreased by 6%. Increasing the O/C and H/C molar ratios slightly affected the heat recovery (< 2%).

The contribution of heat demands to COT, COE and the carbon footprint was higher than that of electricity demands under the examined conditions (intermediate *ER*, low $y_{M,2}$). This is particularly important when considering variations not only in the influent wastewater quality, but also in the consequent sludge properties and process demands required to meet effluent requirements. Variations can include higher inorganic and initial moisture contents ($y_{M,1}$), which are directly connected to the heat demands. For further consideration, Appendix 3 and Appendix 4 present additional analyses on the sensitivity of other performance indicators, such as syngas LHV, cold gas efficiency (CGE), COT, COE and carbon emissions.

3.10 Biomass and Waste Co-processing for Improving Energy Efficiency and Reducing Carbon Footprint

The use of biomass and waste in co-processing with the on-site sludge was considered to improve the process efficiency. Two biomass materials, willow pellets (WIL) and *Miscanthus* (MIS), as well as poultry litter (PL) were used (Table 2.2). WIL and MIS were assumed to be commercially available in Ireland, at costs of €200 and €75 per tonne, respectively. For PL, a minimum gate fee of €65 t^{-1} was considered to be established by the levy for waste disposal at landfilling facilities in Ireland (EEA, 2013; Government of Ireland, 2013). However, it would be necessary to consider the costs associated with the acquisition of PL if this becomes a fuel commodity in the future.

The objective of this analysis was to evaluate the biomass-to-sludge mass ratio (B:SS) required to offset the heat demands of the process and reduce the carbon footprint. Given the associated biomass costs or fees, the effect of biomass co-processing on COE was also considered. Figure 3.8 shows C_{hr}, net carbon emissions and COE as functions of the amount of co-processed biomass. It was observed that:

- The implementation of biomass or waste co-processing allowed an increase in the installed capacity of the CHP system. Feeding equal quantities of biomass and sludge (B:SS = 1) increased the capacity over 10 MW_{el}, depending on the biomass heating value.
- Levels of at least B:SS = 0.18 for WIL or MIS and B:SS = 0.3 for PL were required to reach complete heat coverage.
- The addition of biosolids reduced the carbon footprint, resulting in negative values when using B:SS > 0.5. These negative values were effectively equal to zero carbon footprints because of plant energy demands.
- The type of biomass used during co-processing was important in defining treatment costs. High-cost biomass, such as WIL, led to an increase in the COE of 14%, from 26 to 31 c kWh^{-1}. A cheaper, high-energy content biomass, such as MIS, reduced the costs by 5%.
- The associated gate fee for PL decreased the operational costs and led to a reduction of COE by 25%, to 20 c kWh^{-1} when 130 tpd PL was used.

The process economics could be further improved by taking into consideration government aids for renewable energy generation sites and facilities. The REFIT scheme (Renewable Energy Feed in Tariff) in Ireland subsidises electricity sold to the grid, offering tariffs of 15 c kWh^{-1} (≤ 500 kW_{el}) or 13 c kWh^{-1} (> 500 kW_{el}) to plants using AD-CHP and other biomass-based technologies (Department of Communications, Energy & Natural Resources, 2015). It is also important to highlight that the indirect carbon footprint of biomass materials due to land use and market displacement, biomass plantation and harvesting, transport and imports are expected to shift these reductions above the zero carbon footprint limits. These effects were outside of the scope of the present study.

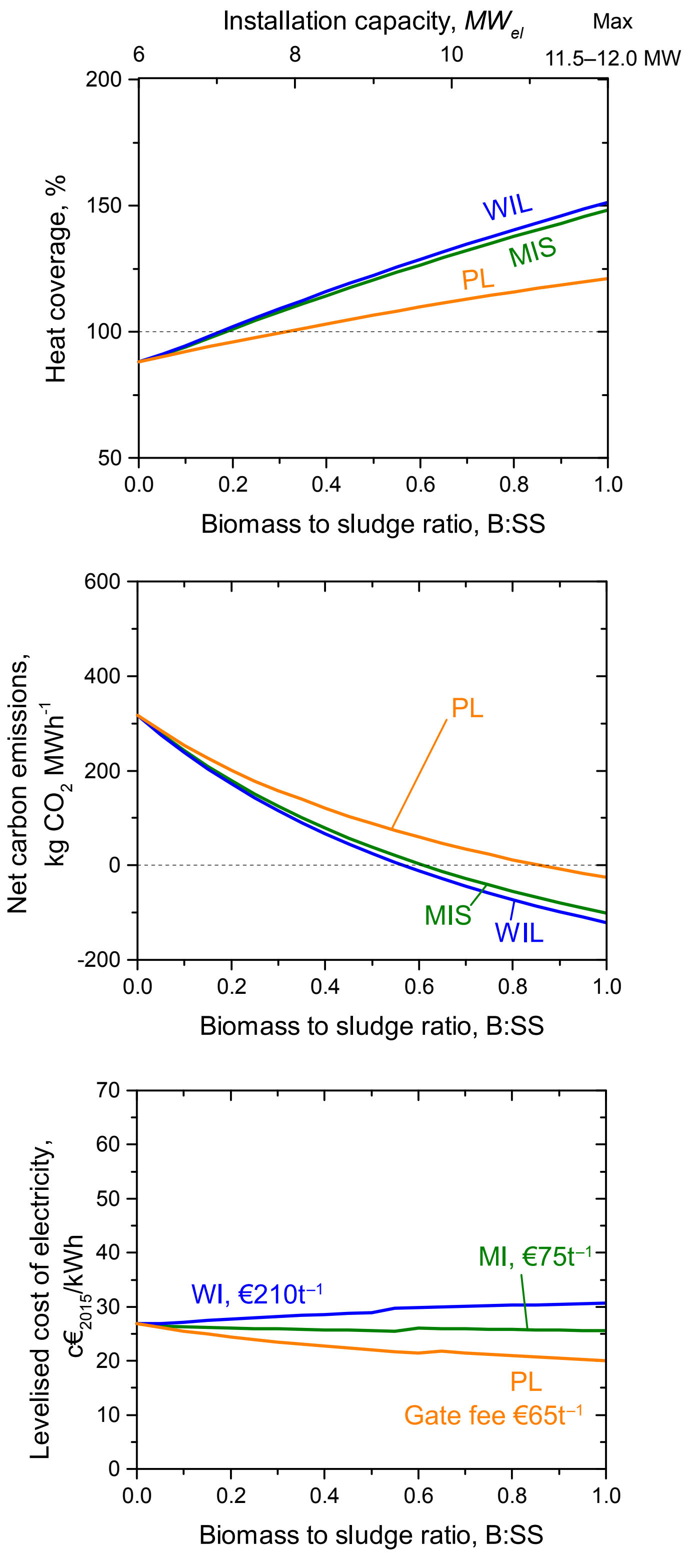

Figure 3.8. Process performance as a function of the biomass to dry sludge mass ratio used in co-processing in a system using gasification and an internal combustion engine.

3.11 Concluding Remarks

- This study undertook a thermodynamic evaluation of sludge and digestate gasification in WWT plants as means of sludge volume reduction and energy recovery.
- The study was extensively supported by empirical data for relevant pilot and full-scale processes, including AD, FB gasification, combustion, solids drying, syngas and flue gas treatment and WWT.
- It was found that integration of energy recovery from sludge through thermal conversion was feasible using conventional CHP generation. In particular, the combination of AD and gasification could theoretically enable a WWT facility to be operated with electricity and heat production in excess of on-site demands.
- ICEs offered sufficient power efficiency and flexibility for adapting them in the process configuration at the plant scale considered in this study (130 tpd dry sludge, 3–6 MW_{el}).
- Through either gasification or combined AD–gasification, treatment costs between €55 and 160 t^{-1} dry sludge were achieved, which are competitive with European landfilling costs and the operational costs of AD plants.
- The LCOE was within reported costs of electricity for AD–CHP plants (23–27 c kWh^{-1}) and offer an opportunity for WWT facilities to implement these sludge treatments.
- These applications reported heavy capital expenditures (>€100 million). One of the potential alternatives to reduce the SCI and improve the energy balance was co-processing of sludge with biomass and other wastes. Feeding similar quantities of biomass with a richer energy content and sludge neutralised the process carbon footprint, increased electricity and heat recovery efficiencies, and reduced the COE by up to 35%.

4 Conclusions and Recommendations

The WWT sector is in constant need of technological and economic advancement to deal with the envisaged increase in the stringency of emission limits, population growth, urbanisation and changes in industrial/agricultural practices. WWT technologies are required to have high pollutant removal efficiencies, to be framed in a sustainable system with minimum impact on the environment and to be economically competitive.

Water management entities are adapting technologies or shifting to new strategies in which self-sufficiency can be guaranteed at all times (Rygaard *et al*., 2011). In this context, this project investigated a series of technologies, i.e. thermal conversion and CHP generation, as new strategies to employ wastewater wastes, i.e. sludge and digestate, for energy recovery on site.

After an evaluation of the current state-of-the-art combustion and gasification, different process configuration scenarios were evaluated to find conditions under which complete coverage of the on-site energy demands could be met or even exceeded.

A modelling tool was built that explored the use of these technologies in WWT facilities, with and without AD. Potential energy generation as power and heat, coverage of on-site demands, COT/power generation and the carbon footprint were considered performance indicators of the feasibility and sustainability of the proposed alternatives.

4.1 Combustion and Gasification Coupled with Steam Turbines

Although combustion (incineration) is a well-established and less expensive approach, process configuration based on this process did not cover on-site electricity demands for WWT treatment and sludge processing. Over 15% of the energy contained in the sludge was required to meet electricity demands. Despite this, a sludge conversion facility of this type (1.6 Mp.e. WWT plant) could provide heat for up to 5000 household units, given proper heat recovery optimisation. The overall carbon footprint was within those observed in WWT treatment facilities undertaking energy recovery using AD ($<500\,kg\,CO_2\,t^{-1}$ dry sludge).

4.2 Gasification Coupled with Gas Turbines

It was feasible to produce electricity and heat in excess of on-site demands using AD, gasification and gas turbines (~5–20% surplus energy in sludge). However, extensive energy use in auxiliary equipment for fuel gas treatment increased COE generation ($>50\,c\,kWh^{-1}$) and the potential carbon footprint of the operation of this plant ($>600\,kg\,CO_2\,t^{-1}$ dry sludge).

Likewise, further technological advances are required in gas turbines to manage low-BTU fuels, such as syngas and combinations of syngas and biogas, with lower installed capacities than the current available units (only $>100\,MW_{el}$).

The use of gas turbines in waste-to-energy facilities may become more suitable in the future for sites in which a high volume of waste is co-processed with other biomass resources (>500 tpd).

4.3 Gasification and AD–Gasification Integrated with Internal Combustion Engines

It was feasible to produce electricity and heat in excess of on-site demands using gasification coupled with ICEs, if all the process configurations were functioning with the highest possible efficiency. An important feature is that AD integrated with gasification gave great flexibility for thermal recovery, leading to conditions in which high surpluses of both electricity and heat were achieved.

These two approaches also offered low operating costs (€150–170 t^{-1} dry sludge) and costs of electricity generation (20–50 $c\,kWh^{-1}$), with competitive carbon footprint levels ($<300\,kg\,CO_2\,t^{-1}$ dry sludge), even lower than that of WWT facilities using only AD energy recovery.

As an additional advantage, ICEs offer flexibility in terms of scalability for energy recovery at scales expected in WWT facilities (> 10 MW_{el}) with competitive power efficiencies.

Co-generation also represented a potential alternative to offset heat demands when gasification alone was used for sludge conversion, requiring biomass rates of 0.2 to 0.3 times that of the sludge feed rate to meet energy demands and give a reduced carbon footprint.

4.4 Recommendations for Future Work

4.4.1 Economies of scale

This report highlights the importance of facility scale in meeting sustainability criteria, especially in terms of operational and capital expenditures. The figures presented here were applied to the scale of the largest WWT facility in Ireland (1.6 Mp.e.), which currently produces about 50 tpd of dry digestate or an estimated 80–100 tpd dry sludge. However, most current WWT facilities using secondary treatment in Ireland have capacities below 10,000 p.e., with potential sludge production that can vary between 0.2 and 3 tpd dry sludge. In contrast, most Irish AD plants process between 26,000 and 400,000 p.e., generating approximately 6–100 tpd dry sludge on site.

Although combustion engines and boilers offer sufficient flexibility to operate with nominal capacities on these scales (100–700 kW_{el}), installation costs would make the implementation of combustion or gasification economically unattractive. Typical sludge incinerators are designed for processing 30 to 700 tpd, depending on the reactor type (FB, 30–200 tpd; moving grate, 120–700 tpd), while gasifiers are restricted to throughputs of between 250 and 500 tpd (EC, 2006). To date, however, incineration and gasification plants have average capacities of between 160 and 1300 tpd in countries including Denmark, Germany, the Netherlands, Norway and the UK.

In addition, this study determined that sludge feed rates of at least 120 tpd raw sludge were required to generate electricity for at least 24 c kWh^{-1}, which is within the range of competitive renewable electricity for Ireland. From the perspective of waste management, feed rates of at least 25 tpd were required to account for treatment costs below €250 t^{-1}. However, this would rely on heavy capital expenditure and fees that would probably be directed to tax-payers.

This issue may be overcome through other approaches that are suggested for future consideration. On-site thermal pretreatment, such as drying and torrefaction, can facilitate sludge transport to a centralised facility. Although these treatments require energy, the electricity and heat recovery produced by a large-scale centralised facility could probably offset the treatment costs in terms of overall energy and carbon footprint. A centralised gasification facility also offers the possibility of implementing biomass or waste co-processing with greater economic and technical feasibilities. Co-processing has the advantage of reducing operational challenges seen in decentralised plants, which arise from seasonal variations in sludge generation and physical/chemical properties of the waste.

Other advantages offered by co-processing include the opportunity for utilising non-recyclable waste, which would facilitate metal and inorganic materials recovery through thermal conversion, using plasma gasification and vitrification. These processes allow the sequestration of toxic heavy metal elements that are present in the waste incineration ash produced by high-temperature treatment that allows the formation of stable and uniform glass products.

It is also important to note that sludge transport and biomass co-processing will have additional direct and indirect energy and costs penalties, as well as increasing the carbon footprint, which must be taken into account in the evaluation of an optimal sludge transport and treatment system. Biomass in particular has direct and indirect carbon emissions linked to harvesting, use of fertilisers, change in land use, imports and transport, which were not considered in the present study but may be significant at larger plant scales and greater biomass-to-sludge co-processing ratios than those evaluated here.

4.4.2 Optimisation of anaerobic digestion for biogas production

An additional aspect to be considered during the integration of AD with thermal conversion for sludge management is the importance of optimising the efficiency of sludge AD. It is possible to increase methane productivity by co-digestion with other readily degradable matter, such as organic fractions of municipal solid wastes, grease, food waste and animal wastes (Davidsson *et al*., 2007; Iacovidou *et al*., 2012). Co-digestion reduces investment expenditure by requiring a greater scale for the digestion stage and a lower scale for thermal conversion, while improving the CHP efficiency in proportion to the increase in biogas production from the addition of other biomass. This was outside of the scope of the present work, but we highly recommend evaluating which wastes in Ireland could be potentially accepted at WWT plants for co-processing with sludge.

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Abbreviations

α_{TC}	Correction factor for total direct and indirect costs
η_B	Overall boiler efficiency
η_{el}	Electrical efficiency
η_{EE}	Electrical efficiency in combustion engine
η_{hr}	Heat recovery efficiency
η_{SC}	Isentropic compressor efficiency
η_{SCP}	Centrifugal pump efficiency
η_{SGT}	Isentropic gas turbine efficiency
η_{SST}	Isentropic steam turbine efficiency
AD	Anaerobic digestion
ADTC	Anaerobic digestion coupled with thermal conversion
B:SS	Biomass to sewage sludge mass ratio
BTU	British thermal unit
C_{el}	Electricity coverage
CGE	Cold gas efficiency
CHP	Combined heat and power
C_{hr}	Heat coverage
COE	Cost of electricity
COT	Cost of treatment
CPI	Consumer price indices
C_{tot}	Total energy coverage
d.b.	Dry basis
DR	Drying stage
ER	Equivalence ratio
FB	Fluidised bed
f_{EI}	Factor of equivalent carbon dioxide emission per unit of output electricity
f_H	Factor of equivalent carbon dioxide emission per unit of heat used
FOB	Free-on-board
f_{PE}	Factor of primary energy consumed per unit of output electricity
f_{PH}	Factor of primary energy consumed per unit of heat used
GS	Gasification
GT	Syngas treatment
H/C	Hydrogen to carbon molar ratio
HE	Heat exchanger
HR	Heat recovery
HRSG	Heat recovery–steam generation
ICE	Internal combustion engine
LCOE	Levelised cost of electricity
LHV	Low heating value
MDEA	Methyldiethanolamine
MIS	*Miscanthus*
MVR	Müllverwertung Rugenberger incineration plant
NO_X	Nitrogen oxide gases
O/H	Oxygen to hydrogen molar ratio
O&M	Operational and maintenance
p.e.	Population equivalent
P_{GS}	Gasification/combustion pressure
P_{IE}	Inlet combustion engine pressure
P_{IGT}	Inlet gas turbine pressure
P_{IS}	Inlet steam pressure
PL	Poultry litter
PR_C	Maximum pressure ratio in compressor
PR_{GT}	Pressure ratio in gas turbine
R_i	Other auxiliary demands
SC	Steam-to-carbon
SCI	Specific capital investment
SO_X	Sulfur oxide gases
SS	Sewage sludge
T_{CA}	Air temperature to combustor
TCC	Total capital cost
T_{DSO}	Temperature of SO_2 scrubbing
T_{ESP}	Maximum gas temperature in electrostatic precipitator
T_{FG}	Flue gas temperature
T_{GA}	Air temperature to gasifier
T_{GS}	Gasification temperature
T_{IGT}	Inlet gas turbine temperature
$T_{max,ST}$	Maximum steam temperature in turbine
tpd	Tonnes per day
T_{SCR}	Temperature of selective catalytic reduction
VS	Volatile solids
WIL	Willow pellets
WWT	Wastewater treatment
x_{GS}	Fraction of syngas
$y_{M,1}$	Moisture content of sludge before drying
$y_{M,2}$	Moisture content of sludge after drying

Appendix 1 Estimation of Costs for Thermal and AD Conversion Systems of Sludge/Digestate

System	Estimation of costs				
	Investment, M€	Labour[a]	Maintenance	Utilities[b]	Chemicals
Combustion	$FOB = 0.464 \times MW_{fuel}^{0.769}$	Workers per shift $= MW_{fuel} \times (0.3 - 0.049 \ln MW_{fuel})$	3% TCC per year	Estimated air blower power	n/a
Gasification	$FOB = 0.034 \times m_{fuel}^{0.698}\ (m_{fuel}$: kg h$^{-1})$	Workers per shift $= 0.04 \times m_{fuel}^{0.475}$	5% TCC per year	Estimated air blower power and heat required to maintain T_{GS}; electricity, heat and water used for ESP and H_2S removal; ~0.06 m^3 water t^{-1} syngas treated	Dolomite: 0.032 kg kg^{-1} dry fuel at €75.8 t^{-1}; costs of chemicals for H_2S removal: €209 t^{-1} S removed
Anaerobic digestion	$FOB = 3.667 \times m_{fuel}^{1.053}\ (m_{fuel}$: ton d$^{-1})$	Hours year^{-1} kW^{-1} $= 140.8 \times kW_{el}^{-0.6}$	–	~1 MW as heat ~185 kW as electricity	–
ICE	$FOB = 2.0598 \times MW_{el}^{0.836}$	Workers per shift $= 0.485 \times MW_{fuel}^{0.483}$	M€ year^{-1} $= 0.14 \times MW_{el}^{0.782}$	4% of generated electricity, diesel consumption: ~65 g diesel Nm^{-3} biogas	–
Gas turbine	$FOB = 0.7172 \times MW_{el}^{0.795}$	O&M, M€ year^{-1} $= 0.13 \times MW_{el}^{0.855}$		Estimated by power requirement in compressors	–
Steam turbine	$FOB = 0.9013 \times MW_{el}^{0.719}$	For $MW_{el} < 35$ MW: Workers per shift $= MW_{el} \times (0.93 - 0.19 \ln MW_{el})$ For $MW_{el} \geq 35$ MW: Workers per shift $= 1.69 \times MW_{el}^{0.446}$	€0.0055 kWh^{-1}	Power for pressurising water; water use: ~6.5 t MWh^{-1}	–
Combined cycle	$FOB = 1.821 \times MW_{el}^{0.798}$	Combined from above			
Flue gas treatment	De-SO_X: €595 kW^{-1} De-NO_X: €350 kW^{-1}	O&M and chemicals for de-SO_X: €2.5 kg^{-1} removed SO_2 O&M de-NO_X: €3.5 kW^{-1} year^{-1}		Estimated for heating and flue gas blowers to stack	De-NO_X chemicals: €3.1 kW^{-1} year^{-1}

[a]The number of shifts per day was assumed to be three. The average salary for a process engineer in Ireland corresponds to €45,300 or approximately €23.6 per working hour.

[b]The Irish business electricity price for band IA is 21 c kWh^{-1}. The Irish business gas price for band I1 is 5.2 c kWh^{-1}. The average national water charge for industry and businesses is €2.35 m^{-3}.

ESP, electrostatic precipitator.

Appendix 2 Economy of Scale: Effect of Sludge Feed Rate on Costs of Treatment and Levelised Cost of Electricity Generation

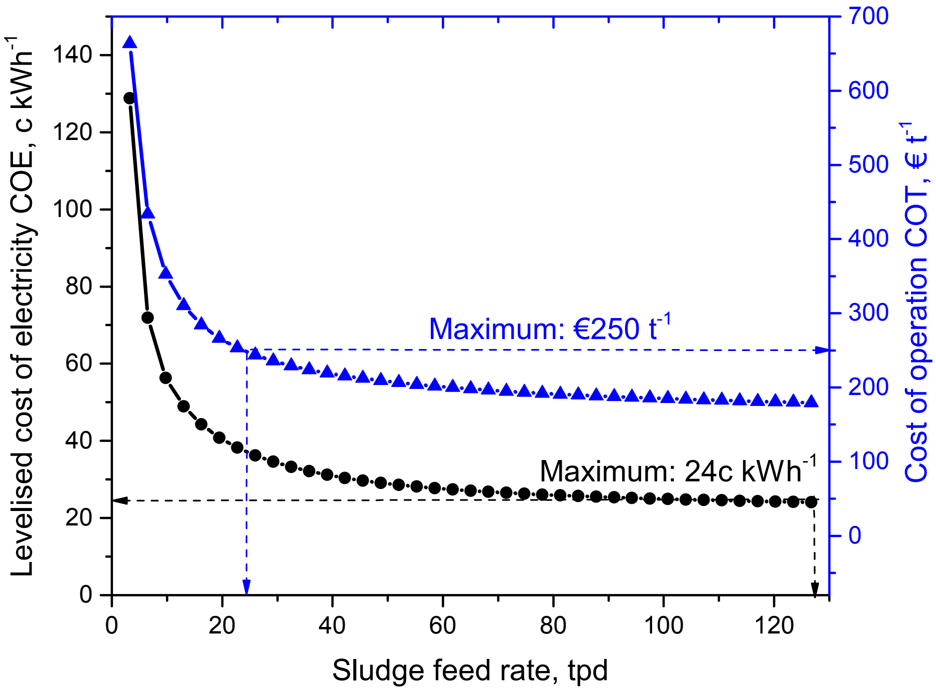

Figure A2.1. Levelised costs of electricity and costs of operation of a sludge gasification plant as functions of the sewage sludge feeding rate.

These two economic performance factors are affected exponentially by the capacity of the sludge management facility in the WWT plant. Currently, in Ireland, electricity costs vary between 9 and 21 c kWh^{-1} (Howley and Holland, 2015). Sludge feeding rates greater than 120 tpd were required to reach a COE of 24 c kWh^{-1}, near to the electricity prices described above. In contrast, if the sludge management facility is considered as a waste treatment site, COT were maintained below €250 t^{-1} with sludge feeding rates above 25 tpd, which gives more flexibility to the implementation of the technology in terms of the waste management scheme.

Appendix 3 Sensitivity Analysis of Gasification Performance

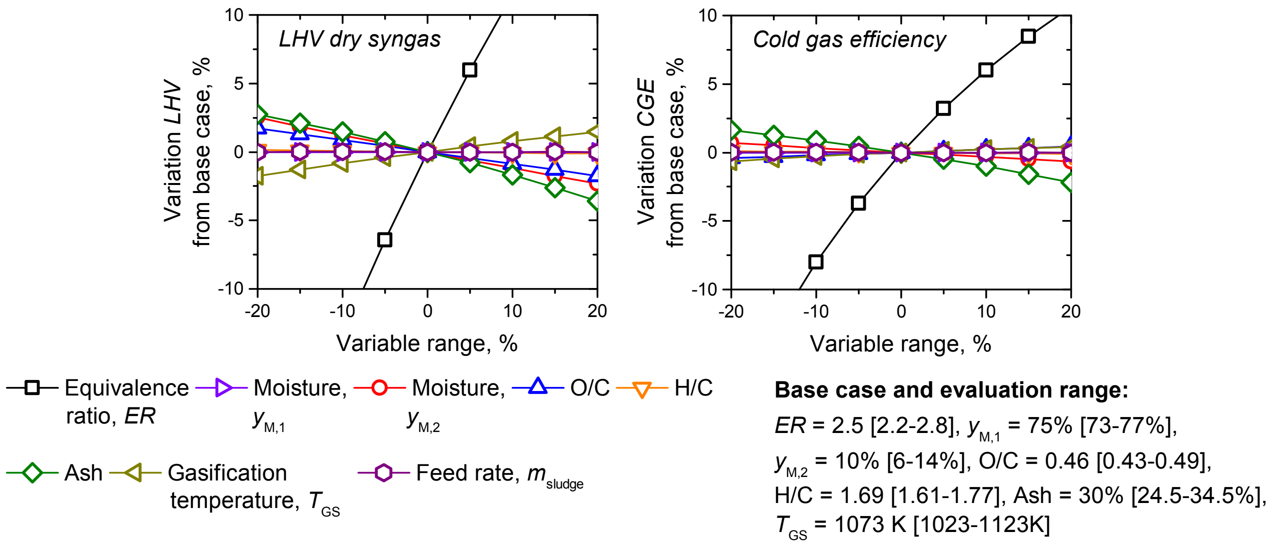

Figure A3.1. Sensitivity of the lower heating value of syngas and the cold gas efficiency from gasification as functions of the following process parameters: equivalence ratio (*ER*), sludge moisture contents ($y_{M,1}$ and $y_{M,2}$), gasification temperature (T_{GS}), sludge feed rate, and sludge properties (O/C, H/C and ash content). The strongest correlation of syngas LHV and CGE was to the ER, since this defined the extent of the fuel oxidation and, therefore, the energy content of the gas product. Increases of 11% in the dry syngas LHV and of 6% in the CGE were observed when increasing ER by 10% within the evaluated range.

Appendix 4 Sensitivity Analysis of Costs of Operation, Levelised Costs of Electricity and Carbon Emissions of the Gasification and Combustion Engine Process

- COT was mainly affected by the extent of sludge drying, represented by the initial moisture content ($y_{M,1}$). When $y_{M,1}$ was increased from 75% to 77%, COT increased by 5% in relation to the reference case.
- As with electrical efficiency, ER and ash content had the most significant influence on the costs of electricity generation. Decreasing the ER to 2.2 led to an increase in the COE of 6.9%, while a 10% increase of the ash content raised COE by 7.8%.
- The increase of the associated heat duty for sludge drying did not affect COE to a significant extent ($<2.9\%$). Similarly, other variations in the sludge properties, other than ash content, had minor effects on this economic indicator.
- Implicit to the increase in electricity generation, a greater sludge feed rate led to reductions in COE of up to 3% and in COT of up to 2%. This improvement in the electricity balance illustrates the effect that the capacity of the thermal conversion facility can have on the techno-economic performance of the plant. Greater scales are linked to higher efficiencies and better economy of scales.
- The process parameters had opposite effects on the carbon footprint compared with the CHP coverage in the plant configuration. Decreasing the amount of oxidising agent (higher ER) increased net carbon emissions by only 1%; however, reducing the ER to 2.2 led to an overall increase in the carbon footprint of 8.4%.
- A higher gasification temperature ($T_{GS} = 1123\,K$) allowed further heat savings that decreased the carbon footprint of the process by 4% in relation to the reference case.
- Both ash and initial moisture content ($y_{M,1}$) of the sludge affected the carbon footprint significantly because of the effects on electricity and heat coverage. When the treated sludge had an ash content of 34.5%, the wastewater and sludge treatment plant emissions increased by 12% from the reference case (ash = 29.5%). Similarly, $y_{M,1} = 77\%$, only 2% higher than in the original scenario, led to carbon emissions that were 15% greater than in the reference case.
- Other sludge properties had minor effects on the carbon footprint (a change of less than 5%).
- The effect of the sludge feed rate on the electricity coverage was also reflected in carbon emissions: greenhouse gases associated with operation were reduced by more than 5%.

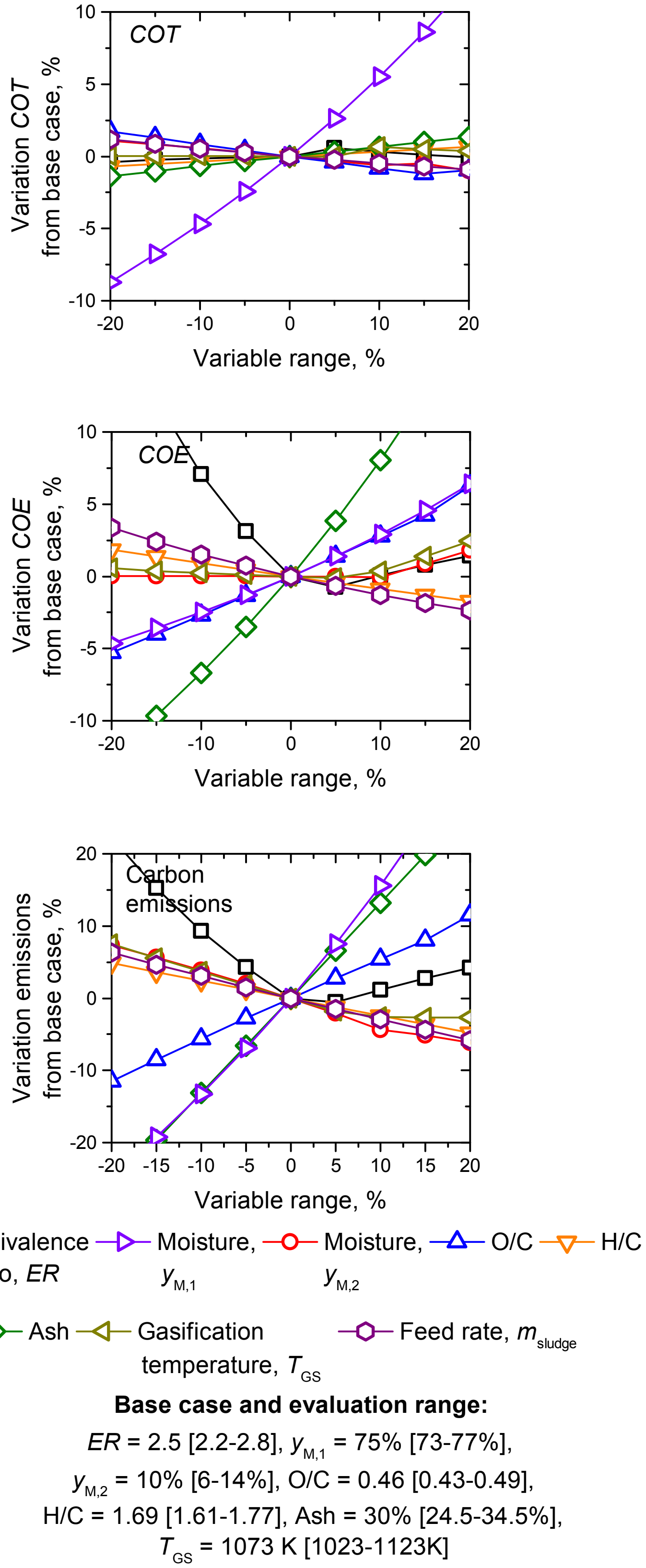

Figure A4.1. Sensitivity of cost of operation, levelised costs of electricity and carbon emissions in the system using gasification and combustion engine as functions of the following process parameters: equivalence ratio (*ER*), sludge moisture contents ($y_{M,1}$ and $y_{M,2}$), gasification temperature (T_{GS}), sludge feed rate, and sludge properties (O/C, H/C and ash content).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Thermodynamic Modelling of Energy Recovery Options from Digestate at Wastewater Treatment Plants

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Karla Dussan and Rory Monaghan

Identify Pressures

It is vitally important to evaluate alternative means of sludge disposal in order to avoid pollution of agricultural land. Thermal conversion technologies can address the problem of surplus sludge while also providing a means to support the consolidation of a secure and indigenous energy market in Ireland.

Plant scale and poor fuel properties of sludge were identified as some of the technical challenges facing the implementation of thermal conversion plants; however, a number of potential solutions, including centralised plants and waste/biomass co-processing, have also been identified which may assist in overcoming these challenges.

Inform policy

This techno-economic performance study offers valuable information with respect to the potential of on-site and centralised thermal conversion of sewage sludge. The information generated will inform and assist stakeholders and local and government authorities in their consideration of the establishment of these alternatives in the future.

The recognised challenges with regard to implementation of gasification and combustion as waste management techniques will also inform and direct future focused research and technological development activities in areas of greatest need.

Develop solutions

This study created inexpensive computational tools which will be available for process modelling and techno-economic evaluation of the thermal conversion of sewage sludge, and of any characterised organic waste, intended for power and heat generation. These alternatives offer sustainable means of waste management and renewable energy production that can significantly reduce the carbon footprint of waste disposal practices and improve the energy security of Ireland.

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