Investigations into the Impacts of Prevailing Climate and Size on the Thermal Energy Efficiency of Energy from Waste Plants

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Submitted in fulfillment
of the requirements of the degree of
Masters by Research

August, 2018

ABSTRACT

Energy from Waste (EfW) is increasingly becoming an essential part of the contemporary mix of sustainable energy systems. EfW technologies consist of waste treatment processes that create energy in the form of electricity, heat or transport fuels (e.g. diesel) from a waste source. There exists a global movement towards reduction of dependence on fossil fuels and focus on exploiting renewable energy resources. Waste is available in abundance and recent studies only suggest an increasing tonnage of waste with a growing global population and diverse industries.

Thermal treatment of waste has been around for over a century, with the first incinerator built in Great Britain. The social acceptance of an EfW facility has come a long way since then, with a conscious shift away from a waste landfill as a feasible solution. Generating usable EfW resources, which would otherwise go to landfill, has unquestionable environmental and economic benefits. With a large number of waste disposal operations, establishing itself amongst key solutions as part of waste management in European cities, an efficiency scaling method was developed by the European Commission to incentivize energy recovery operations. This essentially differentiates between waste disposal and energy recovery operation. The efficiency scaling method, known as R1 thermal efficiency, has been adopted by Australian Environment Protection Agencies as well.

The R1 energy-efficiency formula is widely used in the assessment of the thermal energy efficiency of an EfW facility. The R1 metric amongst other efficiency indicators is a means to assess the overall useful energy extraction process from waste. This thesis addresses potential gaps that exist in the R1 formula, particularly addressing a bias in the formula towards EfW plants of larger capacity and located in cooler climate zones. An analysis on the use of the R1 formula is presented to determine the recovery status of some EfW plants. Detailed R1 computations are provided to demonstrate the application of R1 guidelines to specific EfW technologies, incineration and gasification. The study proposes the application of climate and size correction methods in consideration of the disadvantage faced by smaller-sized EfW plants or those located in warmer regions in meeting the set threshold. A key highlight is the case based application of external variants, climate and size correction factors to EfW plants in different locations in Europe, in scaling the R1 value. The proposed size and climate correction factors are compared with the Climate Correction Factor (CCF) defined in the Waste Framework Directive (WFD) of the European Union. The application of the proposed correction factors lead to conservative R1 scaling when compared with the application of the WFD CCF. The introduction of the size correction factor addresses an important gap in the current WFD.

Combined heat and power (CHP) modes of EfW plants have proven to be more efficient, given there is substantial demand of thermal energy. The research analyses CHP modes and relates the outcome to the R1 criterion for the select case studies. The work is novel and the proposed analytical model makes significant contributions to knowledge by demonstrating the impacts of external variants on the outcome of R1 thermal efficiency of EfW plants. The proposed calculation tool would enable engineers, site managers, system auditors with a methodology that can be applied for the initial assessment of R1 thermal efficiency of an EfW. The comparative analysis with European WFD formula and CHP mode provides a broader spectrum to gauge the efficiency of an EfW facility. A follow-on benefit of this work is the fact that it would enable a predictive assessment on a proposed EfW facility and hence assist in addressing concerns of environmental groups.

STUDENT DECLARATION

I, Kazi Mohammed Rayatul Hoque, declare that the Masters by Research thesis entitled “Investigations into the Impacts of Prevailing Climate and Size on the Thermal Energy Efficiency of Energy from Waste Plants” is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature: [redacted]

Date: **18 / 12 / 2018**

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the College of Engineering and Science, Victoria University, for letting me fulfil my quest of being a Masters student here. My deep gratitude goes to my supervisor, Dr. Cagil Ozansoy, for supporting me throughout the course of research, for patiently guiding and encouraging me to conduct high level research, and for pushing my scholarly skills beyond the realm I thought possible.

To Prof. Stephen Collins, Dr. Cagil Ozansoy and Dr. Rudi Van Staden for giving me the opportunity to serve as tutor and lab instructor and thus gain an excellent experience in teaching.

To my parents, Kazi Mozammel Hoque and Nur Mahal Begum and parents-in-law, Jamal Uddin Ahmed and Akhter Begum, for their endless support during my period of working on the thesis. Your love and constant patience have taught me so much about sacrifice, discipline, and compromise.

To my wife, Rozana, for her limitless support, patience and cooperation and my sons, Rayyan and Zabeer. You bring positive chaos to my life which continues to help me grow.

To my sisters, Zuhaina, Tanjina, Tamanna and brothers-in-law, Tanvir, Nahyan and Shabab for their love and positive vibes which felt near always despite the distance.

To my sisters-in-law, Roxana, Fareeha and brothers-in-law, Shabbir, Reza and nieces, Radhwa, Raaya and Raadiya for their remarkable visit from thousands of miles which transformed our house to ‘home’ during their stay. To my nephew, Safiul Azam for that positive drive and presence.

Finally, to my friends, especially Seyed Morteza Alizadeh, Bassam Saleh and Ashraf Ziaur Rahman who helped me to keep my moral on the top.

PUBLICATIONS

[1] Kazi Mohammed Rayatul Hoque, Cagil Ozansoy, and Murat Fahrioglu, "Climate and size correction in European Union's Waste Framework Directive and R1 energy efficiency criteria," *Waste Management & Research,* vol. 36, pp. 670-688, 2018.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

EfW	Energy from Waste
CHP	Combined Heat and Power
CF	Correction Factor
CCF	Climate Correction Factor
SCF	Size Correction Factor
EPA	Environment Protection Authority
EU	European Union
EC	European Commission
ERF	Energy Recovery Facility
WFD	Waste Framework Directive
EF	Equivalence Factors
MSW	Municipal Solid Waste
HDD	Heating Degree Day
NCV	Net Calorific Value
IGCC	Integrated Gasification Combined Cycle
ATT	Advanced Thermal Treatment
FUE	Fuel Utilization Effectiveness
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse Gas

CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

Energy from waste (EfW) by incineration is a well-established thermal treatment technology worldwide. The studies presented by ISWA [1] reported 472 facilities using thermal treatment in Europe. Although, such treatment of waste has been around for over a century, with the first incinerator built in Great Britain in 1876 [2], the technology to this date remains controversial. Many local EfW infrastructures with state-of-the-art design and technology have gained public acceptance. Some of which have been summarised in the report by Whiting [3]. The development and adoption of thermal treatment technologies has been driven by factors that address a fine balance to the following dimensions; technological, environmental, economic and social. A recent report by the European Commission [4] is a testament to the importance of a combined effort in finding the best possible use for waste. The legislations implementation hopes to minimise adverse effects on public health and the environment, while at the same time brings economic benefits to the region.

The focus on extracting useful energy from waste has gained more traction in recent years. A key parameter to assess useful energy from EfW facilities is, efficiency. Essentially, this is the amount of energy coming out (output) over the amount of energy coming in (input) as waste and other added fuels. With the existing number of EfW plants in Europe, it was essential to differentiate between disposal and energy recovery operations of facilities as part of its agenda to manage waste responsibly. The European Commission [5] included this efficiency aspect as part of its Waste Framework Directive (WFD). It introduces the R1 thermal efficiency formula essentially for differentiating EfW operations; energy recovery or disposal. R1 score needs to be equal or greater than 0.65 for classification as an energy recovery facility. Currently, there exist no waste levies on disposal operations, however like the case of waste landfill levies this can be a reality. The implementation and compliance to R1 thermal efficiency could be the starting point to further strict legislation on disposal operations. Consequently, the formula appears to be more of a ‘political’ formula due to integration of political objectives like discouraging the use of primary fuel.

The R1 thermal efficiency formula as per the guidelines [6] firstly defines all the system boundaries for which the energy efficiency is calculated, for example waste pre-processing. Secondly, all energy inputs including additional fuels and energy imported in the form of heat or electricity should be included. Thirdly, any energy circulating back into the system for the EfW operation should be estimated. This specifically refers to energy used for internal processes and can take the load off energy imported. The [6] take into account conversion efficiencies and applies coefficient factors, known as equivalence factors to electrical and thermal energy. Grosso et al. [7] explained this as the average electrical and heat conversion efficiencies considering European conditions. These equivalence factors should vary for other regional conditions as Ozansoy [8] suggests specific to Australia. There is an abundance of land in Australia and it is cheaper to landfill than develop EfW infrastructure in some states. The Environment Protection Agencies (EPA) of New South Wales, Victoria and Western Australia have implemented strategies to enable EfW adoption in favour of environmental and economic benefits that it promises. With the absence of an efficiency criterion, and seeing in practise an existing formula in Europe, the EPAs chose to adopt the R1 parameter for EfW compliance [9-11]. New South Wales leads and encourages smart waste management initiatives. For example, it has the highest landfill levies in Australia [12].

While the formula incentivises and hence encourages efficient ‘energy recovery’ operations, various studies [7, 8, 13, 14] have highlighted shortcomings that exist in the formula. For example, the report by Reimann [14] clearly demonstrates the variance of R1 outcome depending on the location of the EfW facility. Areas where there is significant heat demand and elaborate district heating schemes and consumers, EfW facilities are able to achieve much higher scores. Whereas, warmer regions display very poor R1 efficiency score due to absence of sufficient consumers and significant heat demand.

The inadequacy of the formula was initially floated in the critical review study [15] and with the absence of correction factors to the formula it became tough for various EfW stakeholders to meet the threshold [16, 17]. Plants with lower capacity are less likely to meet the R1 score compared to plants with larger capacity. This has been observed from the analysis presented by [14] and highlighted and refined further in the study by Ozansoy [8]. Ozansoy [8] concludes the use of the R1 formula ‘as-is’ be problematic, with no attention to plant size and geographical location. An evaluation and revision of the R1 formula became necessary to level the field amongst all EfW operators. European Commission [18] later introduced the Climate Correction Factor (CCF) to account for scaling R1 due to location characteristics. While the current R1 formula has been revised, no correction factors exist for taking into account size of the EfW.

The research introduces the EfW thermal efficiency formula, R1. The efficiency parameter is amongst the prime variables used to judge the performance of the EfW thermal treatment process. This chapter also presents a discussion an introductory discussion of the underlying factors for its widespread adoption in Europe and factors that lead to its recent revision. Issues related to choice of EfW technology and impacts will not be treated in this chapter.

This research through case studies aims to bring the different terms of the R1 formula in context through a calculation tool developed in Excel. Essentially aims to demonstrate a working method to calculate the R1 figure and goes further to suggest the correction method for scaling EfW R1 score disadvantaged due to size and/or location. As suggested earlier, wherein European Commission updated the R1 formula, the correction factors for R1 have been developed from data analysis of 3rd CEWEP energy report [14] and focuses on EfW plants of lesser capacity and in different locations. The work has been refined further in [8] wherein the author demonstrates the indirect logarithmic relationship between average R1 values and average plant capacity. Studies have demonstrated plants with larger capacity have benefited from economies of scale and henceforth there is a bias in the R1 formula.

1.2 AIMS OF RESEARCH

Plants compliant with the R1 threshold get recognition as ‘net energy producers’ as opposed to waste disposal facilities, and hence do not pay a levy. Specific aims of the research related to this fundamental purpose of the R1 formula is stated in this section. Primarily, the focus will be on the R1 performance of waste management processes which relies on the legacy combustion process. These combustion-reliant methods are categorically known as, incineration, gasification and pyrolysis. All the three processes are defined in further detail in Chapter 3.

The quantum of output based on input of waste treatment processes is dependent on the climate at that location and size as discussed in [19]. The research aims to explore the impact of such variants and their role in measuring the thermal efficiency of EfW plants. The performance of any energy producing system depends on analysis of input and output values. The input into an EfW plant is essentially the energy required for the start-up, energy required to keep processes running, and the energy required for other secondary needs such as lighting. The output from the plant is usually the electricity generated or the steam produced, and delivered to a third party. These form the system energy boundaries, and in order to analyse and calculate plant performance, it is essential to identify and quantify these factors. As per the original guideline and then the later revision [8, 20], the R1 system boundaries shall comprise only the essential parts of the treatment process and the energy recovery process. Chapter 3 presents a discussion and isolates the system boundaries for incineration and gasification. Classifying the energy inputs and outputs can later be used in advanced equations to derive the overall efficiency of the system, which is presented in Chapter 4.

The research also aims, through the case studies, to explore the application of the European R1 thermal energy efficiency standard in Australia [20]. In doing so, the project aimed to investigate and present answers to the following questions:

- What are the system energy boundaries of EfW technologies, incineration and gasification?
- Which EfW technology is most viable in Australian states? Can the R1 criteria be successfully applied in Australia? Would Australian EfW plants satisfy the R1-criteria?
- Will the plant size, warm Australian climate and choice of EfW operation be a barrier to the deployment of EfW facilities in specific Australian states? Can an EfW operation be technically efficient whilst addressing all guidelines set by the Environment Protection Agency?
- Do the legacy barriers exist in the deployment of EfW facility? Is there sufficient know-how to overcome these barriers and convince stakeholders for its deployment?

The specific aims of the project were to:

- Investigate external factors affecting the performance efficiencies of EfW plants,
- Present case studies of existing plants in operation, identifying their energy system boundaries of gasification and incineration,
- Review the various types of EfW processes and discuss their suitability to Australian states,
- Identify suitable datasets for exemplar incineration and gasification EfW plants demonstrating the application of the R1 criteria,
- Implement an analytical study to demonstrate the impacts of external variants such as climate and size on the thermal efficiency of EfW Plants,
- Identify a range of strategies in waste processing, incineration and energy conversion processes that can be implemented in making plants R1 compliant

1.3 METHODOLOGY

In this research, a step-by-step process has been followed to achieve the objectives mentioned above. These steps are summarized in the following:

Step 1 – Literature review on EfW technologies and Energy system boundaries

Upon review of a broad set of literatures in EfW technologies and particular emphasis to the studies presented in [7, 8, 13] a holistic view of the process was formed. This enabled to map inside-out and develop the system energy boundaries for each waste processing technology. The mapping of the process, in a flow-chart style format was completed in MS Visio. This mapped figure forms the reference point to develop the calculation tool in MS Excel. Moreover, the review of the literature focused on knowledge gaps yet to be addressed and possible future work in this field of Renewable Energy. At this step no data was available from real-life EfW plants.

Step 2 - Application of the R1 Formula and Development of R1 Efficiency Calculator Tool in MS Excel

Following the wide-scoped literature review explained above, research work has been dedicated to investigate the analysis presented in [8] and follow-on with modifications to develop a database wherein the MS Excel R1 Efficiency Calculator tool can be applied. The research targeted specific plants of which data was available to the public and they have been approved for construction. Essentially, this step implemented the R1 formula on the data set compiled on EfW plants. This step was particularly important to analyse the R1 formula parameters, apply the values to each parameter and assess the R1 outcome based on the data available. Essentially this would focus on the R1 assessment without the impact of external variants and thus bringing forward the limitations of applying the formula as is.

Step 3 - Application of the size and climate correction factors to the R1 outcome

The developed R1 Efficiency Calculator tool in MS Excel, thus incorporates the formula to calculate the impact of external variants, such as climate and size to the R1 outcome. The design parameters of the tool involved the selection of the waste processing technology, net calorific value of waste and the system energy boundaries. Consideration of the correction factors for size and climate as mentioned in Equation (1.1) was then designed into the model. Equation (1.1) from [8] is a summary of the correction factors with regards to size and climate as applied to R1 Efficiency Calculator tool for its given conditions.

$$R1 = K_{size} \times \frac{(E_p) - (E_f + E_i)}{0.97 \times (E_w + E_f)} \tag{1.1}$$

$$E_w = \frac{Amount \times NCV_i}{1{,}000{,}000}$$

$$\bullet\ NCV_i\ is\ the\ lower\ net\ calorific\ value\ of\ waste\ in\ kJ/kg$$

$$i \quad 1 \quad NCV_1 \quad 10{,}307\ kJ/kg \quad for\ MSW$$

$$E_P = K_{HDD-elect} \times \begin{bmatrix} e.f_{elec} \times (E_{P-el-\text{int.}used} + E_{P-el-\text{exported}}) \\ +e.f_{heat} \times (E_{P-heat-\text{int.}used} + E_{P-heat-\text{exported}}) \end{bmatrix}$$

$$+e.f_{biochar} \times (E_{P-biochar-\text{exported}}) + e.f_{biofuel} \times (E_{P-biofuel-\text{exported}})$$

$$where$$

$$\bullet e.f_{elec} = 2.8 \qquad for\ black\ coal$$

$$\bullet\ e.f_{elec} = 3.9 \qquad for\ brown\ coal$$

$$\bullet e.f_{heat} = 1.17 \qquad \angle e.f_{biochar} = 1.3 \qquad \angle e.f_{biofuel} = 2.5$$

$$K_{size} = 0.9475 \times \frac{0.77}{0.0692 \times \ln(plant\_capacity) - 0.1303}$$

$$= \quad K_{size} = 3.5207 \times plant\_capacity^{-0.101} \qquad for\ plant\ capacity \le 250{,}000\ Mg$$

$$= \quad K_{size} = 1 \qquad for\ plant\ capacity \ge 250{,}000\ Mg$$

$$where$$

$$\bullet\ plant\_capacity\ is\ in\ Mg\ (1\ Mg = 1\ Tonne)$$

$$\mathrm{K}_{\text{HDD-elect}}\ (HDD) = 1 \quad for \quad HDD \ge 3350$$

$$\mathrm{K}_{\text{HDD-elect}}\ (HDD) = -0.000021 \times HDD + 1.071690 \quad for \quad HDD < 3350$$

$$where$$

- $\mathrm{K}_{\text{HDD-elect}}$ is the climate correction factor on electrcity generation (expressed in %)
- HDD is the heating degree days value for a particular location

Step 4 – EfW Plant Data and Comparative analysis with the EU R1 Formula

Plant data has been compiled into one table for referencing and application into the R1 Efficiency Calculator tool. Once the necessary data applied as concerned into R1 Efficiency Calculator tool, a comparative work with the refined R1 formula was completed. The new R1 formula was presented by the EU in 2015 [18] and to bring this into perspective it was developed into the MS Excel R1 Efficiency Calculator tool. A discussion is presented on these findings in an investigative style, which presents challenging conclusions on the outcome of author proposed correction factors and the EU's climate correction factor.

Step 5 - Realizing process efficiencies and opportunities

At this step, the main idea was to evaluate the impact of combined heat and power operation for EfW. In this regards, the proposed CHP equations were presented in the context of the R1 formula parameters. A case study was used to apply the proposed formulas and compare the outcome. The presented results confirmed the reliability of CHP operation and also the validity of the proposed equations to measure plant performance. In the context of the R1 formula and CHP efficiency formulas, variance in particular to the pressure parameters can have an impact. This utilized MS Excel and simulated scenarios of different thermal power extraction levels. Essentially, the focus was to investigate and elaborate on a range of strategies that can be implemented in making plants more efficient, thus realizing and presenting potential opportunities to optimize performance.

1.4 RESEARCH CONTRIBUTIONS AND SIGNIFICANCE

The main contribution of this research, very informative mathematical equations have been developed into an MS Excel tool to simplify the calculation of R1 thermal efficiency mapped to the energy system boundary of the specific process. The analysis of external variants, like climate and size to the performance of an EfW plant enables engineers to compute a quick overall thermal efficiency assessment without the need to carry out complex and time consuming computational processes or modelling of equipment based energy utilization systems.

In summary, the major contributions of this thesis are:

- **Application of the R1 Efficiency Calculator tool to diverse Case Studies**

This research adopts the R1 efficiency calculator tool presented in [8] and applies it to real life case studies. The use of data from operator and contractor manuals in the calculator tool, which isolates R1 formula parameters gives a clear visibility on the system energy boundaries of the EfW technology. The results are comparable to the independent analysis of the EfW facilities which have similar R1 scores.

- **Application and comparison of different climate and size CF on R1 outcome**

This research addresses issues concerned with the bias in the existing R1 formula. Application of size and climate correction factors developed in [8] and comparative analysis to the EU WFD climate correction factor [18] is novel. The outcome of the proposed formulas in Ozansoy [8] was found to be conservative compared to the recent formula as per European Commission [18] in 2015. The investigation provided a holistic view about the impact of R1 formula correction factors and hence the essence in either to make or break EfW plants 'energy-recovery' status.

- **Analysis of EfW operation in terms of CHP metrics**

The detailed visualization of the mathematical equations for EfW plant in terms of CHP metrics is an important contribution. This assists further developing an analytical model that is comparable to the R1 formula parameters in terms of FUE, FERC, etc. The assessment of the EfW plant in terms of CHP efficiency metrics and comparison to the R1 outcome is valuable. While the parameters do not consider the impact of correction factors, it however does draw out ratios that can be compared to assess the overall performance of the plant. This would assist to better understand the importance of CHP operation and hence pay more importance in identifying suitable ‘heat’ consumers in the early development stages of an EfW project.

1.5 ORGANISATION OF THESIS

Chapter 1 provides an overview of the thesis, its objectives and contribution to the knowledge. It also sheds light on the fundamental definitions of EfW, the processes involved and why R1 thermal efficiency is an important aspect of the EU agenda. The chapter discusses the methodologies used in the research. **Chapter 2**, establishes with facts energy from waste (EfW) by incineration is a well-established thermal treatment technology worldwide.

A comprehensive literature review is presented which introduces background theory to the EfW thermal efficiency formula, R1 and summarizes the existing academic literature and professional works in this space. The efficiency parameter is amongst the prime variables used to judge the performance of the EfW thermal treatment process. The chapter presents a discussion for a deeper understanding of the underlying factors for its widespread adoption in Europe and factors that lead to its recent revision. This chapter also looks at available research for Combined Heat and Power solutions to treat waste. CHP operational efficiency is comparable to R1, thermal efficiency and the basic formula is discussed. Knowledge gaps have been identified and acknowledged in this chapter.

Following this review and upon establishing knowledge gaps, **Chapter 3** focuses on an elaborate overview on the popular EfW technologies and related case studies. The plant operations is described, with emphasis on the process flow and system energy boundaries. The parameters that link to the R1 formula variables mapped to the process flow chart is presented and discussed. Plant operational data is included, which guides to the calculation of R1 thermal efficiency and CHP Efficiency, where applicable. As the primary contribution of this research, in **Chapter 4**, the calculation tool is put into practise.

The focus is on the developed correction factors for size and prevailing climate. The authors R1 excel calculation tool and correction factors herein and is applied to the EfW case studies discussed in Chapter 3. Results are discussed and the influence of the authors proposed correction factors, related to climate and size is compared to that of the European Union Waste Framework Directive climate correction factor. It highlights the importance of climate correction and stresses on the shortcomings that still exist in the R1 formula.

Chapter 5 follows on the theory from Chapter 2 and discusses in further depth Combined Heat and Power (CHP). The efficiency calculations for CHP plants are calculated different in certain operational assumptions and its comparison to R1 formula is analysed. The application of calculating the efficiency through the CHP formulas is applied on the case studies and results in different scenarios are presented. Hypothetical scenarios that can result in unlocking process efficiencies is also discussed, primarily being configurations that can be adopted to improve EfW plants' overall efficiency figure. This chapter establishes the importance of CHP operation and hence its impact on EFW operations. Finally, **Chapter 6** summarises the complete research work, highlights the contributions made and draws the conclusions.

CHAPTER 2 – LITERATURE REVIEW IN EFFICIENCY CONSIDERATIONS OF EFW PLANTS

2.1 INTRODUCTION

Energy from Waste (EfW) by incineration is a well-established thermal treatment technology worldwide. As of 2013, recorded in ISWA [1] report there are a total of 472 facilities using thermal treatment in Europe. Despite many local EfW infrastructures with state-of-the-art design and technology gaining public acceptance in Europe, thermal treatment of waste, specifically incineration still remains controversial. The first incinerator was built in Great Britain in 1876 [2] and since then, capability and frameworks have evolved supporting this technology. Some of the notable EfW infrastructures, both contemporary and old have been summarised in the report by Whiting [3].

The focus on extracting useful energy from waste has gained more traction in recent years. Recent news related to EfW is testament to this, for example EfW plants could be operating in the state of Victoria in Australia by 2025 [21] and this report suggested a group of local councils in the western suburbs combine their waste management contracts to feed a 300,000 tonne per annum incinerator near existing landfill sites. Although, there exists a policy by Victorian EPA [9] the report mentions Victorian Government has not yet formed a position on waste-to-energy technology. Another ambitious project announced in Middle East country of United Arab Emirates, which aims to treat 1.82-million tonnes of solid waste annually, with a total capacity to generate 185 MW of electricity [22]. If realized, this could be the largest waste-to-energy plant operating at one site in the world. The path is clear as nations aim to develop a responsible and cleaner framework to manage waste than diverting to landfill while at the same time bring economic benefits to the region.

With the existing and increasing number of EfW plants in Europe along with forecasted growth of waste [23], a differentiation between disposal and energy recovery operations of facilities was essential. The European Commission [5] as part of its agenda to manage waste responsibly developed the Waste Framework Directive (WFD) and it included the aspect of thermal efficiency assessment. It introduces the R1 thermal efficiency formula essentially stating its differentiation criterion; R1 score needs to be equal or greater than 0.65 for classification as an energy recovery facility. The introduction of R1 and focus toward its implementation and compliance could be the starting point to further strict legislation on disposal operations. This is evident from the results [24] achieved by Europe having built frameworks that created an environment for the EfW industry to grow. For example, the quantity of waste landfilled in 2014 was 16% lower than it had been in 2004.

The R1 thermal efficiency formula as per the guidelines [6] has been briefly described in Section 1.1 along with mention of its energy-system boundaries. The works presented in [7, 8] is crucial to understand the importance of equivalence factors to scale R1 score as applicable. The adoption of this strategy in Europe serves as catalyst to grow the EfW industry. In a continent, like Australia where there is an abundance of land and it is cheaper to landfill than develop EfW infrastructure in some states the adoption of R1 method can be a challenge. Although, strategic policies to enable EfW adoption in favour of environmental and economic benefits have been approved and drafted by Environment Protection Agencies (EPA) of New South Wales, Victoria and Western Australia, the results of R1 adoption is yet to be realized [9-11, 25]. New South Wales currently has in place the highest landfill levies in Australia [12] which is testament to induce an environment to develop more smart waste management practices.

Various studies [7, 8, 13, 14] have highlighted shortcomings that exist in the R1 formula introduced by the European Commission [5]. For example, the report by Reimann [14] clearly demonstrates the variance of R1 outcome depending on the location of the EfW facility. Areas where there is significant heat demand and elaborate district heating schemes and consumers, EfW facilities are able to achieve much higher scores. Whereas, warmer regions display very poor R1 efficiency score due to absence of sufficient consumers and significant heat demand.

The inadequacy of the formula was initially floated in the critical review study [15] and with the absence of correction factors to the formula it became tough for various EfW stakeholders to meet the threshold [16, 26]. Plants with lower capacity are less likely to meet the R1 score compared to plants with larger capacity. This has been observed from the analysis presented by [14] and highlighted and refined further in the study by Ozansoy [8]. Ozansoy [8] concludes the use of the R1 formula ‘as-is’ be problematic, with no attention to plant size and geographical location. An evaluation and revision of the R1 formula became necessary to level the field amongst all EfW operators. European Commission [18] later introduced the Climate Correction Factor (CCF) to account for scaling R1 due to location characteristics. While the current R1 formula has been revised, no correction factors exist for taking into account size of the EfW.

This Chapter introduces the EfW thermal efficiency formula, R1. This efficiency parameter is amongst the prime variables used to judge the performance of the EfW thermal treatment process. This Chapter also presents a discussion for a deeper understanding of the underlying factors for its widespread adoption in Europe and factors that lead to its recent revision. Issues related to choice of EfW technology and impacts will not be treated in this chapter. This Chapter has been structured as follows. Section 2.2 provides an overview of Energy Efficiency in the broader perspective. While Section 2.3 introduces the R1 formula and brings the current R1 formula into light. Section 2.4 and 2.5, discusses existing research literature on the subject matter with relation to waste treatment for energy. Section 2.6 discusses the context of energy from waste and relevance of R1 in Australia. Section 2.7, summarizes the literature review.

2.2 ENERGY EFFICIENCY

The basic definition of energy efficiency is a measure of the amount of useful energy coming out (output) over the amount of energy coming in (input). In simple terms the ratio of useful output and input as mentioned in the study by Gohlke [27]. When applying the principle to EfW facilities, the input is waste and any other added fuels like natural gas, fuel oil etc. while the useful output can be power, heat or even recovered materials. The focus in this study is placed on useful effects in the form of electricity and heat, i.e. electrical energy and thermal heat. The most commonly used efficiencies as highlighted in [27] are gross electric efficiency, net electric efficiency and thermal efficiency.

Gross electric efficiency can be defined by Equation (2.1), wherein it is the ratio of the electricity generated by the generator and the energy content in the waste. The net electrical efficiency is defined by Equation (2.2), wherein the in-plant consumption of electricity is taken into account prior to considering the values for the ratio of power delivered to the grid and the energy content in the waste.

$$\eta_{el\_gross} = \frac{P_{el\ \ gross}}{E_{\mathrm{W}}} \tag{2.1}$$

$$\eta_{el\_net} = \frac{P_{el\ \ net}}{E_{\mathrm{W}}} \tag{2.2}$$

$$\eta_{th} = \frac{P_{th}}{E_{\mathrm{W}}} \tag{2.3}$$

The thermal efficiency is defined by Equation (2.3), which is the ratio of the thermal energy in the form of heat to consumers, such as a district heating network or industries and the energy content in the waste.

An example specific to EfW plants from ISWA [1] describes a plant handling 50000 tpa waste with an average calorific value of 10.4 MJ/kg. The plant produces 3 MW electricity and operates for 7446 hours per year, which is approximately 85% of the year. This translates to 22 GWh, against an input of 125 GWh (calculated from the input of waste considering the net calorific value). The plant and hence its net electrical efficiency is considered to be 22/125 = 17%. The thermal conversion process has resulted in the recovery of 17% of the initial heat value in the form of electricity. EfW efficiency calculations should also include any auxiliary fuel. Although the major part of the total energy input involves energy from the waste, additional energy is often required. This is usually in the form of electricity or primary fuels like coal, oil, wood etc. These are necessary [14] to meet the regulations on combustion of waste and can improve the energy input or the calorific value of the waste. Fuel is used for start-up and for maintaining minimum temperatures, for example in an incinerator furnace this is 850◦C. As per the study by Reimann [14], an average of 2.2% additional energy is imported.

2.3 R1 THERMAL EFFICIENCY FORMULA AND REVISED R1

A theoretical EfW thermal energy efficiency formula, known as R1, was introduced by the European Commission (EC) in the Waste Framework Directive (WFD) 2008/98/EC [5].

It is set out as per Equation (2.4) below:

$$R1 = \frac{E_p - (E_f + E_i)}{0.97 \times (E_w + E_f)} \tag{2.4}$$

where

- E_p is the annual energy produced as heat or electric power. Electric power multiplied by 2.6 and heat multiplied by 1.1 (GJ year^{-1})
- E_f is the annual energy input to the system from fuels impacting steam production (GJ year^{-1})
- E_w is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ year^{-1})
- E_i is the annual energy imported excluding E_w and E_f (GJ year^{-1})
- 0.97 accounts for energy losses due to bottom ash and radiation.

The purpose of the formula was to classify a waste treatment facility utilizing thermal treatment processes, as an energy recovery operation or a disposal operation. At first instance, R1 needs to be equal or greater than 0.65 for classification as a recovery facility. Being able to differentiate between a waste disposal operation and a recovery facility is significant as recovery facilities are not required to pay waste landfill levies. The concise definitions of the various terms of the formula is extracted from the directive [5]. An elaborate discussion on the terms follows.

Energy-produced (E_p) is defined as the amount of energy produced annually in the form of electricity and heat. As per the guidelines [6], two Equivalence Factors (EF) are applied to this value. EF for electricity generated is '2.6' and EF for heat is '1.1'. Equivalence factors compare the heat and electricity produced in EfW plants to primary fuels. For instance, the review presented in [15] explains the equivalency factor of 2.6 for electricity generation provides as estimation of the energy that would have normally been required to produce the same amount of energy externally through for example, a coal fired power plant. The factors take the unavoidable losses of electrical energy production into account allowing processes with different heat and power generation balances to be compared [15]. While the standard formula considers European conditions, it must be noted this EF's will be different for other regions like, Australia. As per [8] given the different conditions in

Australia, EF for electricity generated is proposed to be ‘2.8’ for black coal and ‘3.9’ for brown coal, dependent upon the areas’ dominant fuel source. A sub-formula for E_p can be developed as per Equation (2.5).

$$E_P = 2.6 \times (E_{P-el}) + 1.1 \times (E_{P-heat}) \qquad (2.5)$$

where

- E_{P-el} is electricity produced for internal use and export
- E_{P-heat}*is h*eat produced for internal use and export

$E_{p\text{-}el}$ is the electricity produced annually, i.e. electricity used internally for plant operations, for the incineration process and exported commercially. $E_{p\text{-}heat}$ is the thermal heat used internally for specific plant processes and exported, i.e. district heating purposes. The electricity and heat that is used internally for plant processes are also known as the parasitic loads of the plant.

E_f is defined as the amount of energy imported into the system in the form of conventional fuels to start-up the plant, maintain processes and produce steam. The Net Calorific Value (NCV) of the fuel and the annual consumption, i.e. quantity of the fuel gives the total energy from fuel. Equation (2.6) sets out the parameters.

$$E_f = \sum_{i=1}^{n} m_{f.i} * NCV_i \qquad (2.6)$$

where

- $\sum_{i=1}^{n} m_{f.i}$ is S*um of the quantity of the Fuel type consumed annually*
- NCV_i*is the Net Calorific Value of that specific fuel type*

$i \quad 1 \quad NCV_1 \quad xxx\ kJ/kg \quad for\ that\ fuel\ type$

E_i is defined as the total energy imported into the system in addition to Ef and Ew. This could comprise of electricity or natural gas imported during plant unavailability and plant start-up not contributing to steam production or useful effects as expressed in Equation (2.7). This could also comprise of hot/chilled water input into the system for the efficiency of operational processes of the EfW plant. The measured value is in GJ/y or MWh/y. This would also be considered as parasitic loads of the plant.

$$E_i = E_{i\_el} + E_{i\_th} \tag{2.7}$$

where

- E_{i_el} is electricity imported in MWh/y
- E_{i_th}*is h*eat/steam imported in GJ/y

Energy-waste (E_w) is the annual energy contained in the treated waste calculated using the lower net calorific value of the waste. E_W relation is expressed as in Equation (2.8). The NCV of treated waste influence the final R1 value. NCV can vary from plant to plant due to local waste handling practices and jurisdictions. The identification of waste sources and its proposed NCV has been presented in [8] and has not been repeated in this study.

$$E_w = \frac{Amount \times NCV_i}{1,000,000} \tag{2.8}$$

where

- E_w means annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ)
- *Amount is the amount of waste proccessed in kg*
- *NCV_i is the lower net calorific value of waste in kJ / kg*

$i \quad 1 \quad NCV_1 \quad 10,307\ kJ/kg \quad for\ MSW$

Available resources in this area of R1 research are mostly European Commission (EC) and various EPA guidelines [5, 6, 9, 14]. In recent years in-depth academic research on R1 thermal energy efficiency formula and its application in assessment of EfW plants has gained more attention. While the R1 formula forms a small part of the European Commission strategy implementation to achieve goals linked to a net zero carbon future [4], it would be prudent to analyze the inadequacy that exists in its application. The guidelines [6] had clearly set out the requirements of the efficiency calculations, and equations have been presented inline with the interpretations. However upon application of the formula to a range of plants as per the study in the 3rd CEWEP report [14] and Clerens Consulting report [13] the shortcomings of the formula became transparent.

The study in [8] concludes the use of the R1 formula 'as-is' be problematic, with no attention to plant size and geographical location. An evaluation and revision of the R1 formula became necessary to level the field amongst all EfW operators. The inadequacy of the formula was initially floated in the critical review study [15] and with the absence of correction factors to the formula it became tough for various EfW stakeholders to meet the threshold [16, 26].

The significant shortcomings [15] of the R1 formula were summarised as the need for, a Size Correction Factor (SCF) to account for the impact of size in modular facilities and a Climate Correction Factor (CCF) to compensate for poor heat demand. This prompted the European Commission to conduct a study [28] that explored the consequences of applying a climate correction factor. The European Commission formally released the CCF as a result of the study in the amendment to Annex II of Directive 2008/98/EC [18]. The introduced CCF compensates for the R1 factor to correct the climate impact on electricity production and heat demand. This revised formula aims to avoid any overcompensation for the climate correction and at the same time incentivises the use of heat. In the Climate CF introduced in the revised WFD, there are two potential application methods. For installations in operation and permitted in accordance with applicable Union legislation before 1 September 2015, Equation (2.9) is used. On the other hand, Equation (2.10) is used for those installations permitted after 31 August 2015. Climate CF is applied to the original R1 formula as a multiplicand as given in Equation (2.11).

$$\begin{aligned}
&CCF = 1 \quad if \quad HDD \quad \geq 3350 \\
&CCF = 1.25 \quad if \quad HDD \quad \leq 2150 \\
&CCF = -(0.25/1200) \times HDD + 1.698 \quad when \quad 2150 \leq HDD \leq 3350
\end{aligned} \tag{2.9}$$

$$\begin{aligned}
&CCF = 1 \quad if \quad HDD \quad \geq 3350 \\
&CCF = 1.12 \quad if \quad HDD \quad \leq 2150 \\
&CCF = -(0.12/1200) \times HDD + 1.335 \quad when \quad 2150 \leq HDD \leq 3350
\end{aligned} \tag{2.10}$$

$$R1 = \qquad CCF \quad \times \frac{E_p - (E_f + E_i)}{0.97 \times (E_w + E_f)} \tag{2.11}$$

This is the revised and current R1 formula, since its introduction in 2008 [5]. It incentivises heat use and includes a Heating Degree Day (HDD) categorised application of a multiplicand to compensate for situations, where the heat demand is low, and there are no opportunities to use industrial heat.

2.4 RESEARCH ON R1

Since the introduction of R1, it has gained the more attention of academic research recently. Researchers have focused on the credibility and evaluation of the R1 formula, through various models. Some of the earlier works that included R1, by Van Berlo and De Waart [29], the authors compared variants of landfilling and EfW by using an array of different performance indicators which included the R1 formula amongst others. Performance comparisons of the different methods of evaluation were discussed together with relevance of their results. The study concluded that specific energy conversion indicators related to efficiency can offer a more comprehensive base for development strategies in waste management. Studies by Chromec and Ferraro [30] discusses greenhouse gas emissions (GHG) and went onto conclude the only methods contributing to a CO_2 credit to waste management are recycling and energy recovery in EfW plants. New installations for EfW should be built closer to power and heat consumers, which would then effectively turn waste management from a net source to a net sink regarding GHG emissions. The discussion of R1 in the study [30] focused on the need of an amendment when not in line with the original ecological goals.

Basically, the authors have linked the R1 outcome to GHG goals, suggesting better plant configurations can achieve better R1 figures and thus have a larger impact on the GHG reductions. Gohlke [27] mentions the R1 efficiency parameter, which effectively is an energy balance ratio, is amongst other key efficiency indicators to measure GHG reduction. The work in [27] emphasized on technology upgrades such as increase of steam parameters, implementing strategies towards a reduction of in-plant energy consumption and benefits realized from running EfW plants in combined heat and power (CHP) modes.

The WFD and guidelines report [5, 6] only cover the municipal waste incineration. This is also an aspect of R1 less explored, wherein due to the major availability of incineration plants its application on incineration EfW is apparent. Research by Waldner et al. [31] described combustion modifications to minimize exhaust gas volumes and noxious gases in improving the overall thermal efficiency. This would potentially result in an improvement to the R1 score, yet it is assumed and there was not any demonstration of it. Similarly, more recently Keunecke briefly introduced the ‘R1 scoring’ in [32], and discussed potential increases in steam parameters as a particularly effective option to boosting efficiency. However, the research lacked any evidence of R1 computations and illustrations of a scientific method that shows how R1 scoring would be influenced if steam parameters were increased.

The work presented by Di Maria et al. [33] covered a discussion on the energetic efficiency of an existing EfW plant by introducing modifications to the configuration of saturated steam in the evaporator, but provided no detailed R1 computations. It has demonstrated a potential improvement to the R1 score with that configuration. Researchers from Aston Business School [34] presented an analysis on the efficiency of EfW systems using data envelopment. Lombardi et al. [35] presented a review of technologies and performances of thermal treatment systems for energy recovery from waste. Viganò [36] features a method based on mass and energy balances to determine the energy content of the waste annually treated in a EfW facility. This is crucial in the calculation of the R1 figure achieved by the plant for MSW. The work does present insightful data on the EfW boiler balances, characteristics of the treated waste and relevance of the different terms in the R1 formula.

Except for a handful few of the cited works, there does not exist an exclusive demonstration of the application of R1 utilizing the energy values at system boundaries to a plant or explores the impacts of external factors on the R1 outcome. Others [37-40] published works on different aspects of energetic efficiency in EfW facilities, but did not explore R1 compliance.

The correction factor for size (Size Correction Factor (SCF)) and location aims to level playing field amongst operators of EfW plants. The study by Ozansoy [8] proposes a method of correction based on size and climate. In [8], the author discussed the analysis of data from European EfW plants and presented sub-criteria for use in the unbiased calculation of the R1 value and in scaling the R1 energy efficiency score of EfW plants considering all external factors. One such sub-criterion allowed the calculation of the calorific content of treated waste from different waste streams. Climate Correction Factors (CF) proposed as a function of the Heating Degree Days (HDD) value at a given location. One of the aims of this study was to validate the developed size and climate CFs using three real-life case studies, the plants description and operational data follows in Chapter 3. The research goes onto compare the EC latest formula and presents results in Chapter 4.

As investment in EfW increases [41-43], the significance of the R1 compliance assessment will grow. Many public enquiries and planning appeals [44] into the development of numerous EfW plants are already underway in Europe. These have become battlegrounds between investors trying to secure planning permits for their plants as genuine energy recovery facilities, and opponents of incineration plants trying to appeal against such development. The work presented herein would serve as reference material as it discusses energy system boundaries across EfW plants, and computationally demonstrates the application of the R1 guidelines using three case studies. Finally, the use of climate and size correction methods for scaling the R1 value is explored.

2.5 CHP RESEARCH

Combined Heat and Power (CHP), as the name suggests, is the simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system [45]. It is also known as co-generation. The system consists of a number of individual components, such as the prime mover (heat engine), generator, heat recovery and electrical interconnection which configured into an integrated whole.

The component that drives the overall system is defined as the prime mover. Typically, this identifies the CHP system, since in a CHP system, the prime movers include reciprocating engines, combustion or gas turbines, steam turbines, micro turbines and fuel cells [45]. Prime movers are capable of burning a variety of fuels, including natural gas, coal, oil, alternative fuels to produce mechanical energy. The mechanical energy generated can be applied to diverse processes within a

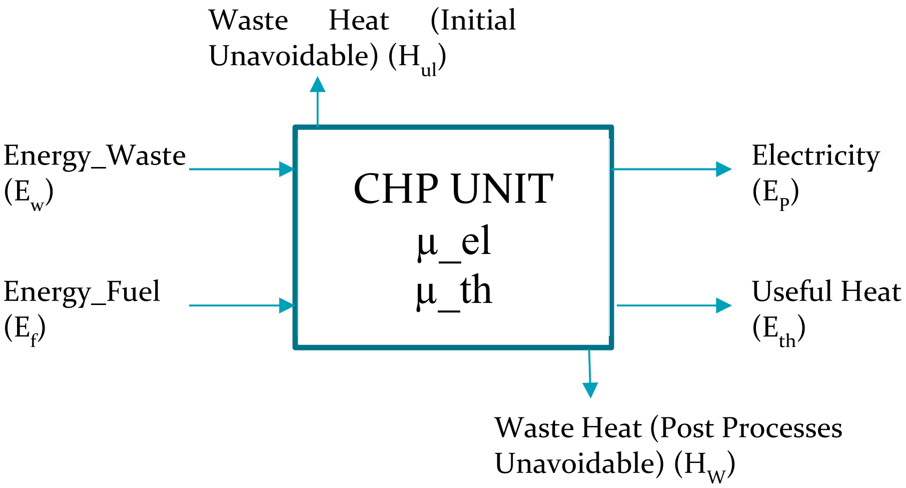


Figure 1 - CHP Unit - Input and Output with heat Losses

plant, i.e. drive a generator for electricity and drive rotating equipment like compressors, pumps and fans.

Thermal energy generated from the system can be applied directly to processes to produce steam, hot water, hot air for drying or chilled water for cooling. Figure 1 highlights an overview of variables for a typical CHP unit. The primary energy is Energy_Waste (E_w) and Energy_Fuel (E_f), goes into the system and initial losses occur to the environment (H_{ul}), which is unavoidable irrespective of the efficiency, when transforming energy introduced to power (E_p) and thermal energy (E_{th}). This is dependent on the state of development of the specific technology. The remaining thermal energy can partly be recovered as (E_{th}) and balance ambient losses occur due to radiation and convection of the steam export processes (H_w).

Effectively speaking, as highlighted in the investigation by [46], any CHP unit designed to generate power and heat would have two parts. In the single mode operation of power only, the system generates power and achieves the maximum technically possible efficiency. However, when operating in the CHP mode, the system is designed for drop in electric power due to useful heat production. Here in the non-CHP part, which generates electricity, would have electric efficiency equal to the system efficiency when operating with no useful heat production. While these principles have been tackled in the studies [46, 47], it is explored in further depth in Chapter 5. Equation (2.12) shows the mathematical representation of the formulae, which can be used for calculating the overall efficiency in a CHP system.

$$EFF_{TOTAL} = \frac{P+Q}{F} \qquad (2.12)$$

where

- $P - Useful \quad Power \quad Generated$
- $Q - Useful \quad Thermal \quad Generated$
- $F - Fuel \quad Consumed \quad (Waste \quad and \quad Start-up \quad Fuel)$
- $EFF_{TOTAL} - Energy\ Efficiency\ in\ a\ CHP\ plant$

2.6 EFW AND R1 IN AUSTRALIA

The demands on the waste management increase with the size of the community and its per capita income [48]. The Waste Management Hierarchy as described in [1, 9] and similar hierarchical figures has gained global acceptance as a tool of reference to prioritise all environmental policies and regulations in this era. Eventually a landfill, although not desirable can be necessary for untreated waste. Australia has taken up key initiatives to encourage and implement EfW model that has been championed in Europe. One recent project is the proposed Kwinana EfW facility by Phoenix Energy, in Western Australia.

The Kwinana projects' Public Environment Review (PER) states that once the location specific process design information is available, then the calculation of R1 efficiency factor shall be meaningful [49]. Phoenix Energy confirms that the EfW plant will satisfy the WA EPA design guidelines and will consider the EC Guidelines [5]. The primary technology at Kwinana facility is a Martin Grate incinerator-based technology and the plant will process MSW from the city of Kwinana designed to a capacity of 80 MW. Once completed, the facility will have a significant 300,000 tonnes per annum capacity, making it able to supply 15% of the city's electricity needs [50]. Direct incineration is an established municipal waste treatment technology. Technologies such as gasification, pyrolysis, plasma gasification and thermal depolymerization has been around, however its application to waste treatment is still in its infancy stages.

The adoption of the European WFD R1 efficiency formulae in Australia proves to be a viable option in the lack of any other concrete alternatives. This considers the body of knowledge and data that already exists with respect to the European WFD [8]. With Australia being a vast nation, there exists a general tendency to opt for landfill. However, proposals for energy recovery facilities are cropping up across Australia [50]. Hence, it is relevant to explore the sensitivity of R1 and the various factors that can impact its outcome. The state of New South Wales (NSW) imposes the highest landfill levy on waste management operators, followed by Victoria, South Australia and Western Australia [12]. It is only prudent to deliver on solutions for sustainable EfW facilities across the nation. Smaller modular sized plants and those located in warmer regions of the world are disadvantaged as the study presented [13] shows. European plants that are located in warmer regions could experience weather patterns similar to Australia and it would be relevant to acknowledge and apply its data. In the state of Victoria by 2025 [21] a report suggests a group of local councils in the western suburbs combine their waste management contracts to feed a 300,000 tonne per annum incinerator near existing landfill sites. Although, there exists a policy by Victorian EPA [9] the report mentions Victorian Government has not yet formed a position on waste-to-energy technology.

Currently the states of NSW, VIC and WA have published EPA guidelines and policies relating to the development of EfW facilities and similarly EPA South Australia [25] have released a discussion paper that presents general information on Energy from Waste processes and national and international experiences, asking questions relating to the role of Energy from Waste within South Australia more broadly. Clearly demonstrating the relevance of EfW in Australia. The paper acknowledges, there are limited examples of EfW facilities currently in operation within Australia, although there are several industrial facilities using anaerobic digestion, refuse derived fuel, or direct combustion technology with some form of waste utilised as a sole or major feedstock. Thermal EfW tends to be discussed to a much larger extent due to its distinctive juxtaposition to landfill disposal and the need to differentiate thermal EfW from thermal waste disposal − a practice which is currently only undertaken on any significant scale for the disposal of medical waste in Australia.

Environment Protection Authority [25] South Australia mentions current absence of legislation in SA to differentiate disposal by incineration from energy recovery. The European R1 indicator is the only generally available criteria that could be applied at present for this purpose and has been adopted by WA and VIC for determining thermal efficiency of such facilities. The NSW EPA has stipulated thermal efficiency criteria where it must be demonstrated that 25% of the energy generated by thermally treating a waste will be captured as electricity. According to EfW policy in VIC, NSW and WA any proposed EfW direct combustion facility that meets the relevant state's energy efficiency criteria would not be considered as a disposal operation and the relevant waste disposal levy would not apply.

Statistical data from waste management in Europe [24] have revealed the following figures which illustrates positive impact of initiatives can be realized when developing an environment for the EfW industry to grow.

- The quantity of waste landfilled in 2014 was 16% lower than it had been in 2004.
- The quantity of waste recovered (excluding energy recovery), in other words recycled or used for backfilling, grew by 20.1% from 890 million tonnes in 2004 to 1,069 million tonnes in 2014; as a result, the share of such recovery in total waste treatment rose from 42.1% in 2004 to 49.9% by 2014.
- Waste incineration (including energy recovery) saw an overall increase between 2004 and 2014 of 29.6% and its share of the total rose from 5.1% to 6.5%.

However, it must be noted while meeting environmental targets and cementing waste as an alternative fuel source is a key driver for widespread EfW adoption, the main challenge would be to study and mitigate the factors that cost the sustainable future of an EfW facility. In [51], the author highlights that while Europe have supported the EfW industry, there are widespread facilities having to shut down due to lack of optimal levels of waste feedstock. Within Europe, exporting waste has become an attractive option in some regions. This is due to low gate fees in countries like Germany, the Netherlands, Sweden and Latvia. Regional gains made in recycling and waste prevention could sabotage a developed EfW infrastructure. In Australia, given its distant location from the rest of the world, it is only logical to develop adequate onshore EfW facilities. The energy recovery option at all times supported and driven by policies and the recognition by people that landfills are a sub-optimal solution at their best and a sanitary disaster at their worst.

2.7 CONCLUSION

This chapter puts forth the basic definition of energy efficiency, which is a ratio of the amount of useful energy coming out (output) over the amount of energy going in (input). In the perspective of thermally treating municipal solid waste, the most commonly used efficiencies as highlighted in [27] are gross electric efficiency, net electric efficiency and thermal efficiency. The thermal efficiency formula, R1, was introduced by the European Commission (EC) in the Waste Framework Directive (WFD) 2008/98/EC [5]. The original equation which currently is not valid was Equation (2.4). The purpose of the formula was to classify a waste treatment facility utilizing thermal treatment processes, as an energy recovery operation or a disposal operation. The study in [8] highlights the use of the R1 formula 'as-is' can be problematic, and attention to plant size and location is required.

Existing research in this aspect has been reviewed in depth and presented in this chapter. Some very notable works have been acknowledged however there does not exist an exclusive demonstration of the application of R1 utilizing the energy values at system boundaries to a plant or work that explores the impacts of external factors on the R1 outcome. Existing literatures like [37-40] published works on different aspects of energetic efficiency in EfW facilities, but did not explore R1 compliance. The research aims to validate the developed size and climate CFs from the study by Ozansoy [8] using three real-life case studies, and thus presenting work on R1 compliance.

This chapter also discusses the relevance of EfW in Australia and how forthcoming projects in waste management consider EfW as a viable option as opposed to landfill. Also the mode of

Combined Heat and Power (CHP), is discussed which is the simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system [45]. It is also known as co-generation. Its relevance becomes obvious when achieving higher R1 figures for CHP operating facilities. The research aims to use data from the case studies to demonstrate the advantages of CHP operation and how optimum operational numbers can be achieved.

CHAPTER 3 – EFW TECHNOLOGIES AND CASE STUDIES

3.1 INTRODUCTION

Waste is available in abundance and recent studies only suggest an increasing tonnage of waste with a growing global population and diverse industries [23]. The previous chapter focused on the efficiency studies and its application in EfW facilities. This chapter details the base EfW technology, presents the operational processes of EfW facilities, and includes plant data of case studies. Thermal treatment of waste has been around for over a century, with the first incinerator built in Great Britain in 1876 [2]. The social acceptance of an EfW facility has come a long way since then, with a gradual shift away from waste landfill as a feasible solution. The development and adoption of thermal treatment technologies has been driven by a balance in addressing technological, environmental, economic and social factors.

A recent report by the European Commission [4] is a testament to the importance of a combined effort in finding the best possible use for waste. The legislations implementation hopes to bring economic benefits to the region and minimise adverse effects on public health and environment. The technologies that are dominant worldwide in thermal treatment of waste is hinged upon combustion of waste. It is a well-established technology and its use as a way to recover energy from waste is gaining increased exposure.

3.2 EFW TECHNOLOGIES

This study primarily focuses on key thermal treatment technologies to extract useful energy from municipal solid waste. Incineration, gasification and pyrolysis technologies are reviewed and its advantages and disadvantages discussed.

3.2.1 Incineration

The process of incineration refers to 'oxidation of the combustible material in the waste to produce heat, water vapour, carbon dioxide and oxygen'[52]. Modern incinerators reduce the volume of the original waste by 95-96 percent, depending upon composition and degree of recovery of materials, such as metals, from the ash for recycling. Incineration plants in development and those built in recent times have developed further from their predecessors, some of which recovered neither energy nor materials.

One particular reason for advancement in this area is the awareness of the health hazard the emissions pose. Nations have designed frameworks for safe operation of incineration plants and set stringent guidelines that include audit and expert reviews on plant emissions and performance. The European Commission Waste Incineration Directive of 2000 is such an example, which sets [5] stringent emission limits to control emissions to the air, water and soil environment and consequent risks associated with human health.

The incineration system boundary in terms of energy inputs and outputs is shown in Figure 1. During start-up, combustion is initiated by auxiliary burners. Auxiliary burners are also required during plant shut-down, and automatically switched on if the incineration chamber temperature falls below 850°C. This prevents thermal NOX generation and ensures complete combustion of MSW [52].

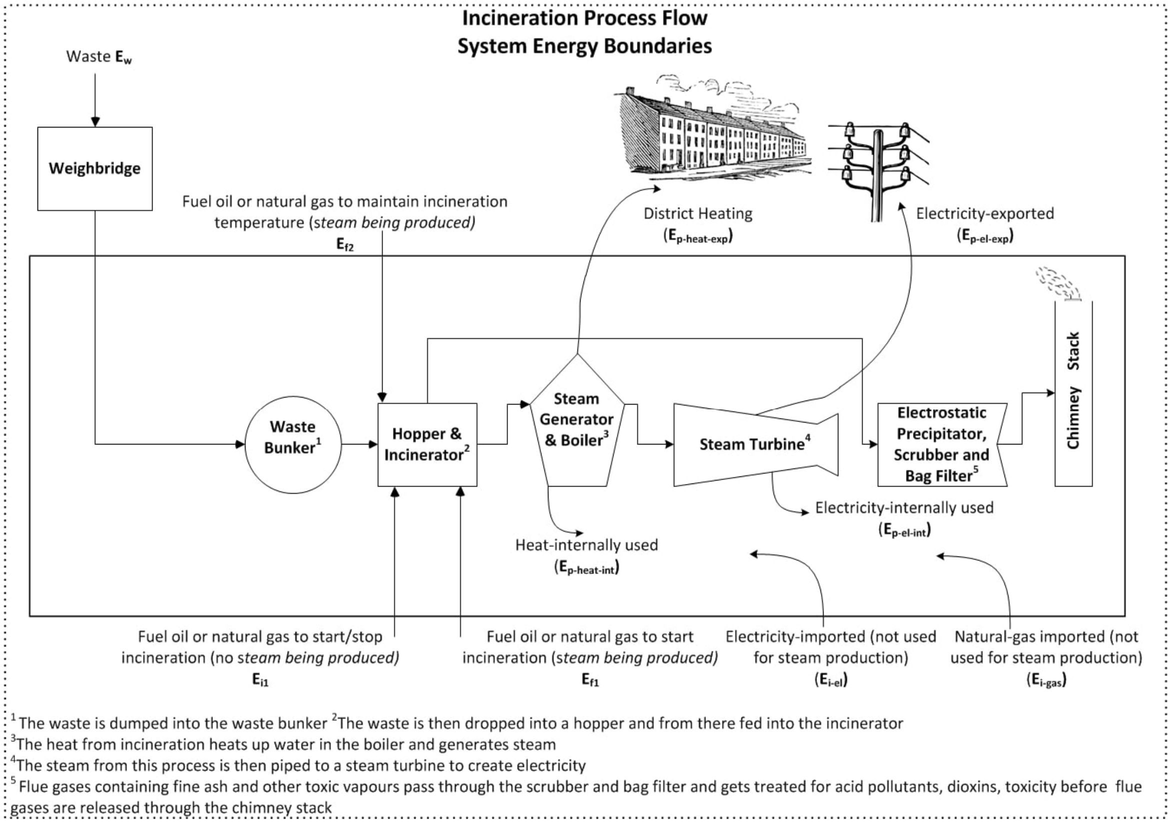
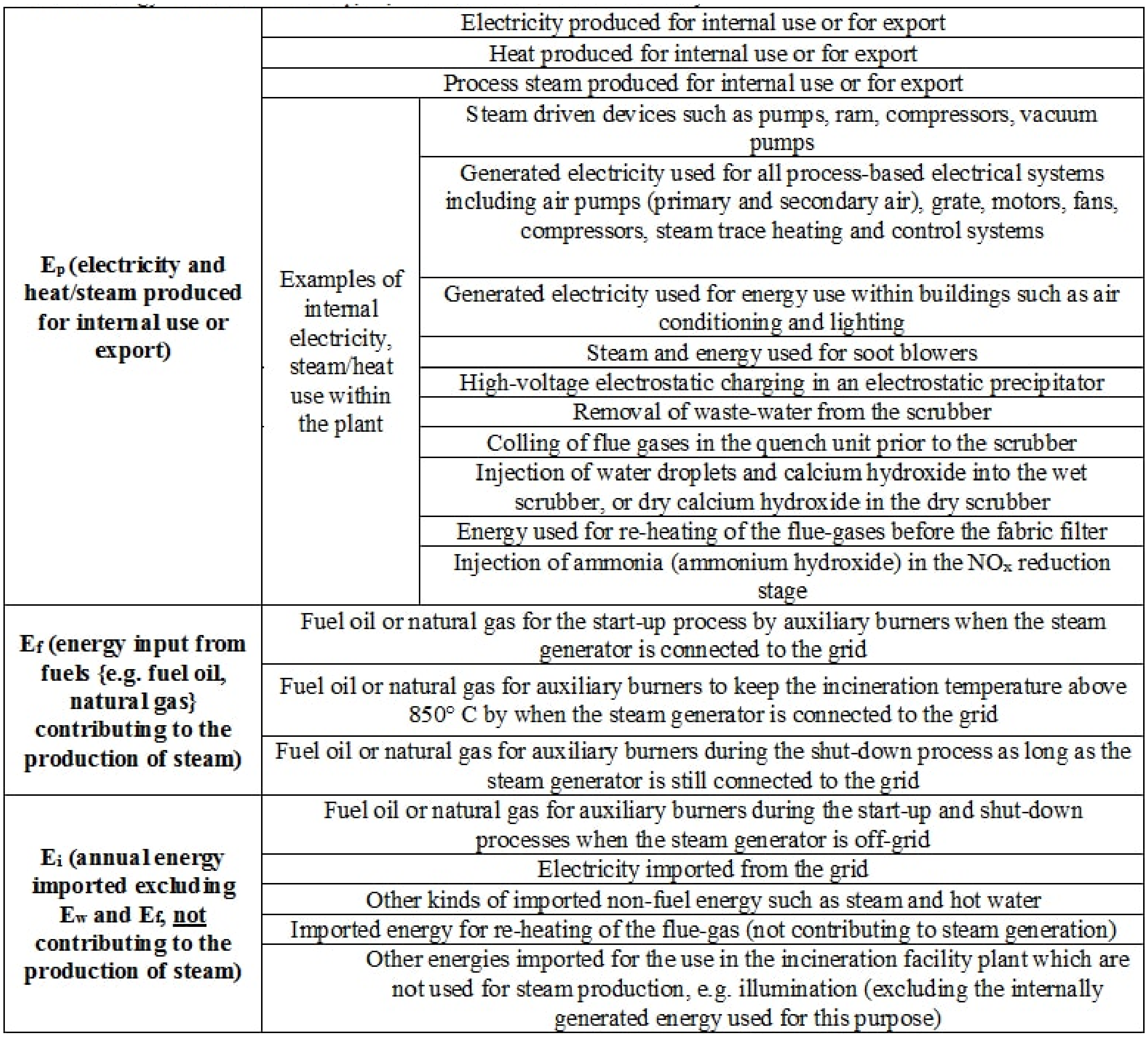


Figure 2 - Incineration EfW Energy System boundaries [65]

Table 1 provides a summary of how the parameters E_p, E_f, or E_i can be categorized in an incineration plant. Chapter 2 elaborates on each of the parameter and hence in this chapter the summary is presented in application to the incineration EfW technology.

Primary air is introduced into the furnace from down under the grate through slits in the grate, which cools off the grate assisting in combustion. The nozzles above the fuel bed and grate are used to blow secondary air into the furnace to provide excess air for combustion ensuring turbulence [52] and thus attaining combustion efficiency through controlled air supply. The majority of generated heat is transferred to the hot flue gases, which must be cooled before entering the flue gas cleaning system as gas temperatures below 250 °C-300 °C are required by the cleaning system processes. This cooling is achieved when the thermal energy of the flue gas is transferred to the water in the boiler tubes to produce steam, which may be used for electrical power generation, and district heating.

Table 1 - Annual Energy to be counted in E_P, E_f and E_i at an incineration facility [65]



E_p (electricity and heat/steam produced for internal use or export)	Electricity produced for internal use or for export	
	Heat produced for internal use or for export	
	Process steam produced for internal use or for export	
	Examples of internal electricity, steam/heat use within the plant	Steam driven devices such as pumps, ram, compressors, vacuum pumps
		Generated electricity used for all process-based electrical systems including air pumps (primary and secondary air), grate, motors, fans, compressors, steam trace heating and control systems
		Generated electricity used for energy use within buildings such as air conditioning and lighting
		Steam and energy used for soot blowers
		High-voltage electrostatic charging in an electrostatic precipitator
		Removal of waste-water from the scrubber
		Colling of flue gases in the quench unit prior to the scrubber
		Injection of water droplets and calcium hydroxide into the wet scrubber, or dry calcium hydroxide in the dry scrubber
		Energy used for re-heating of the flue-gases before the fabric filter
		Injection of ammonia (ammonium hydroxide) in the NO_x reduction stage
E_f (energy input from fuels {e.g. fuel oil, natural gas} contributing to the production of steam)	Fuel oil or natural gas for the start-up process by auxiliary burners when the steam generator is connected to the grid	
	Fuel oil or natural gas for auxiliary burners to keep the incineration temperature above 850° C by when the steam generator is connected to the grid	
	Fuel oil or natural gas for auxiliary burners during the shut-down process as long as the steam generator is still connected to the grid	
E_i (annual energy imported excluding E_w and E_f, not contributing to the production of steam)	Fuel oil or natural gas for auxiliary burners during the start-up and shut-down processes when the steam generator is off-grid	
	Electricity imported from the grid	
	Other kinds of imported non-fuel energy such as steam and hot water	
	Imported energy for re-heating of the flue-gas (not contributing to steam generation)	
	Other energies imported for the use in the incineration facility plant which are not used for steam production, e.g. illumination (excluding the internally generated energy used for this purpose)	

In an incinerator, typical emissions include ‘dust, acidic gases such as hydrogen chloride, hydrogen fluoride and sulphur dioxide, and heavy metals such as mercury, cadmium and lead’ [52]. In a flue gas cleaning system, on particular configuration of processes can be as follows, the gases first enter the Electrostatic Precipitator (EP) for particulate removal, followed by the pre-collector. Typical voltages used in the EPs are about 50 kV. This electrical energy required for the intense electrostatic field is example of $E_{p\text{-int-used}}$. The soluble acid gases in the flue gas are then neutralised and removed by a scrubbing unit, an additional particulate removal process. This unit may be a wet, dry or semidry type. In the wet scrubber, the gases are first cooled to 60° C in the quench unit prior to the scrubber. Energy is utilised in this stage for the injection of water droplets and calcium hydroxide into the wet scrubber. In the dry scrubber, flue gases are first cooled down to 160° C, and dry calcium hydroxide is sprayed onto the incoming gases. After the scrubber, activated carbon and lime is added to the gas flow to adsorb mercury and dioxins and furans before flue gases enter the fabric filter [3, 52]. Flue gases are reheated before gases enter the fabric filter. Fabric filters remove very fine particulates down to the submicron size. In the final stage; NOx are removed by addition of ammonia to form inert nitrogen.

In Australia, the Kwinana EfW facility located in Western Australia is an example of a contemporary incinerator. The facility, when operational, will be able to supply electricity to the National Grid of Western Australia. It is an “Australian-first” project that will use waste disposal to generate a renewable energy supply. The plant is designed to process up to 400,000 tonnes of residual waste a year, which will contribute to its capacity to produce 32 MW (approximately 250,000 MWh energy based on the assumption of 7800 operational hours without considering EF for electricity) of electrical power annually [49]. The advantages of such a facility over solar and wind, is the continuous supply of waste, which Phoenix Energy ensures through supply agreements with the local governments. The agreements ensure that the councils will supply waste (post-recycling) to the plant.

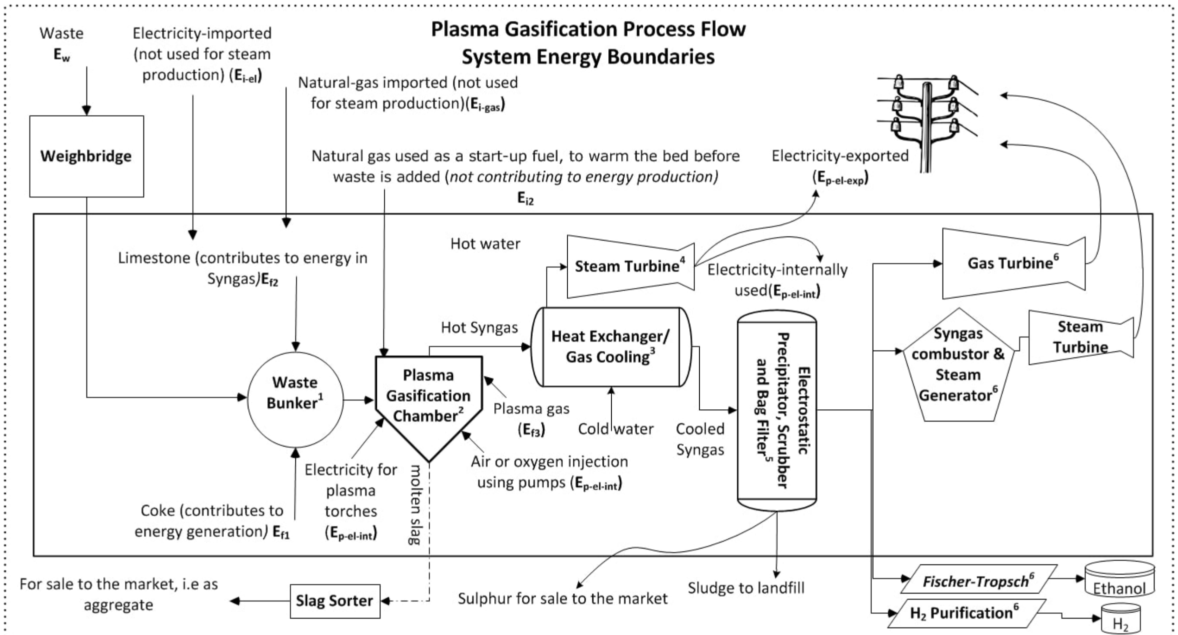
The incineration facility for the case study in Section 3.2 is the Beddington EfW facility, located in Sutton, London, England. The plant is to process (when complete) around 275,000 t of non-hazardous residual waste per annum generating up to 26.17 MW of electricity, and exporting over 22 MW to the UK National Grid. The facility is to process council MSW and commercial and industrial waste in South London [53]. Further operational data of this plant are presented in Section 3.3.

3.2.2 Gasification

Gasification includes Plasma arc gasification or plasma gasification process (PGP). The process comes under Advanced Thermal Treatment (ATT) technology wherein the initial waste collection and combustion is fundamental to produce heat and gases. Gasification of waste occurs at temperatures mostly greater than 900 °C, in the presence of limited oxygen resulting in partial combustion [11]. The process is considered more efficient than direct combustion and converts about 80 per cent of the energy in the waste into synthesis gas (syngas) containing mainly carbon monoxide, hydrogen and methane. This can be further co-processed to produce bio-fuel for transport purposes. It is a well-known technology, although its advanced use with a mixed waste feedstock has not been proven on a commercial scale [54].

A general configuration of the gasification operational process is recorded in WSP International [55]. WSP International [55] describes gasification to primarily convert waste into syngas, which can be cleaned and combusted in gas engines, or further processed to produce secondary fuels such as hydrogen and ethanol. Figure 3 illustrates the energy system boundary for a sample plasma-gasification plant and an overview of the processes. Gasification processes result in a solid residue consisting of inert ash and char [56]. Unlike incineration, gasification is an endothermic process, which means that it requires an external source of heat.

Typical gasification temperatures are 900-1,100 °C with air or 1000-1,400 °C with oxygen. High temperatures, achieved by adding coke or plasma, provide the benefit of melting the ash to produce slag [55]. Plasma gas, generated by the input of electrical energy to a gas, assists in attaining temperatures as high as 1,000-2,000 °C in the reactor though waste is not directly exposed to the plasma arc [55].



[1] The waste is dumped into the waste bunker. Hazardous and non-hazardous wastes, including any combination of solid, liquid and gaseous wastes. Waste pre-treatment for sorting and crushing into smaller pieces to prevent blockages. The prepared waste is blended in a feed hopper with coke and limestone

[2] The pre-treated waste gets fed into the gasification furnace equipped with plasma torches. Air or oxygen is injected above the torches as a source of oxygen for the gasification process. Gasification takes place and combustible syngas is produced in an oxygen starved environment.

[3] The hot syngas from the gasification chamber heat gets cooled by water injection, which prevents the formation of dioxins and furans. The recovered heat (steam) can be utilised in a steam-turbine.

[4] The recovered steam can be utilised in a steam-turbine. [5] The cooled syngas passes through air pollution control (e.g. the scrubber and bag filter) to be filtered of all particulate matter. [6] The treated syngas is used as a fuel source in a gas-turbine or further treated to generate other outputs such as hydrogen or ethanol.

Figure 3 - Gasification EfW Energy System Boundaries [65]

In the bunker, waste is blended with coke and limestone. The plasma gasifier is an insulated, vertical-shaft, air-tight furnace with plasma torches installed at the bottom of the furnace. Heat from plasma torches drives the endothermic gasification process controlled by an Automatic Control System, which adjusts gasification conditions. Waste material does not come in direct contact with the plasma arc, which facilitates operating temperatures in excess of the melting points of metals and inorganic materials. Coke is used as an assistant heating material, which is consumed at a lower rate, forming a bed onto which waste falls and quickly gasified [57].

Prior to filtration, syngas is gas quenched cooled to prevent formation of dioxins and furans. The recovered heat through High Pressure (HP) steam in the exchanger is utilised in a steam-turbine. Generally, in Integrated Gasification Combined Cycle (IGCC) systems, heat is recovered by generating HP steam. This is done as syngas passes through a convective cooler (CSC), i.e. a CSC is usually a shell and tube type heat exchanger/boiler consisting of a set of tubes in a container [58]. Heat is transferred by convection and conduction. The cooled syngas passes through air pollution control units, where it is cleaned off all particulate matter including all acid species, metals etc. Fly ash and acidic gases can be removed using bag filters and wet scrubbers. NOx removal processes such as selective catalytic and non-catalytic reduction can be applicable when syngas is burned with excess air. The specific processes and configurations are selected based on the requirement of the location and economics [3].

Major technology types of gasification include fluidised bed gasification, plasma gasification and slagging gasification. A gasification process may also be combined in-line with distinct direct combustion or pyrolysis stages. As per the report compiled by WSP International [55] and European Commission [5] Japan has over a 100 gasification plants from 17 different technology providers. Thus, Japan is broadly considered leaders in this technology space. Considering the objective of this project, in presenting the analysis of R1 thermal efficiency criteria, an example of a UK-based gasification EfW is presented.

The Bilsthorpe Energy Centre, one of the case studies discussed in Section 3.2, was proposed as a dual-purpose facility that recovers recyclable materials from residual waste using separators and magnets. Located in Northern England and serving Nottinghamshire, the plant generates electricity from the plasma gasification of 95,000 t of waste. The produced syngas will be cleaned, compressed, and combusted in a series of high efficiency Internal Combustion Engines (ICE) to generate electricity. It is designed to generate up to 13.77 MW of energy, of which 9.6 MW will be exported to the UK National Grid [59]. Further details of this plant are presented in Section 3.3.

3.2.3 Pyrolysis

This can be defined as thermal breakdown of waste in the absence of air, to produce char, pyrolysis oil and syngas (e.g. the conversion of wood into charcoal) [9]. The process takes place in lower temperatures (around 400^oC) and does not involve any oxygen or air. Waste is placed into an air-free reactor and heated using an external source of energy. The waste is then converted into solid char, pyrolysis oil and syngas through physical and chemical processes. The process can take place at higher temperatures (around 800^oC) and this would change the amount of each produced product. For waste to energy purposes, syngas is the preferred energy product as it is easier to convert into electricity [26].

An example of a pyrolysis EfW is the Scarborough EfW plant, one of the few pyrolysis plants handling MSW in UK. This has been in operation since 2009 having a capacity of 25,000 tonnes of unsorted MSW. The technology has been provided by Graveson Energy Management (GEM), a UK company using flash pyrolysis to convert any carbon based material to syngas. The pyrolyser involves a cylindrical drum rotating within a large vertical steel cylinder heated on its outside surface. The waste reaches 820˚C in a couple of seconds which produces syngas [60]. No case studies presented for this technology and this can be pursued in future works.

3.3 CASE STUDIES

The case studies discussed below as per the base EfW technology. There are two incineration facilities and one gasification facility.

3.3.1 Incineration – Beddington ERF and San Zeno EfW

One of the analysed incineration plants is the Beddington Energy Recovery Facility (ERF) facility, in Sutton, London, England. The plant is to process (when complete) around 275,000 t of non-hazardous residual waste per annum generating up to 26.17 MW of electricity, and exporting over 22 MW to the UK National Grid. The facility is to process council MSW and commercial and industrial waste in South London [53]. The plant is CHP enabled, i.e. it can export heat in the future as part of a district heating scheme. Around 2,517 GJ of electrical energy is imported annually for plant unavailability and 1,097 GJ for plant start-ups. The plant operates for 7796 hours/ year. The plant uses a combustion technology successfully used in the UK and Europe for the combustion of untreated MSW, moving grate furnace. The moving grate comprises of inclined fixed and moving bars (or rollers) that will move the waste from the feed inlet to the residue discharge. The grate movement turns and mixes the waste along the surface of the grate to ensure that all waste is exposed to the combustion process [53].

The second incineration plant analysed herein is the San Zeno EfW facility in central Italy, which is designed to process 42,000 tpa of residual waste [33]. It is a smaller CHP facility, given its capacity and has been in operation since 2000. It is equipped with an adiabatic combustion chamber where temperatures are maintained at above 1,100 °C to avoid the risk of corrosion. This has been possible by introducing excess combustion air. After the combustion chamber, the hot gases enter the heat recovery steam generator. Herein, the first component is the Evaporator that generates steam at about 250 °C and 40 bar. After the Evaporator, the gases enter the Super Heater (SH) increasing the saturated steam temperature to about 380 °C, and eventually exchanging the residual heat in the economizer. The SH steam is expanded in a condensing turbine of 3000 kW electric capacity [33]. Condenser temperatures are maintained at 50 °C by dry cooling towers, after which water is pumped to the degasser feed by a steam bleed from the turbine at 5 bar. In standard operating conditions, the amount of steam generated is 14,000 kg/h and the turbine net electrical output is about 2,400kW. Further discussion on San Zeno plants R1 analysis is provided in Section 4.

3.3.2 Gasification – Bilsthorpe Energy Centre

The Bilsthorpe Energy Centre was proposed as a dual-purpose facility that recovers recyclable materials from residual waste using separators and magnets. Located in Northern England and serving Nottinghamshire, the plant generates electricity from the plasma gasification of 95,000 t of waste. The produced syngas will be cleaned, compressed, and combusted in a series of high efficiency Internal Combustion Engines (ICE) to generate electricity. It is designed to generate up to 13.77 MW of energy, of which 9.6 MW will be exported to the UK National Grid [59]. The plant is being developed to be fuel-cell ready, with plans in place to pilot around 1 MW of Alkaline Fuel Cells in the future. This will generate higher-efficiency electricity from some of the hydrogen contained in the syngas [59].

The plant was approved by the Secretary of State for Communities and Local Government of UK in 2016, once it was confirmed as a recovery facility [61]. This was conditional based on continued R1 compliance post construction [62]. As per its design data, the facility was capable of achieving an R1 efficiency factor above 0.65. Opponents of the scheme claimed that a similar plasma gasification plant failed to overcome the technological difficulties and that drops in the NCV of processed waste would easily make the plant non-R1 compliant [62]. The predicted R1 (without heat export), as part of operators planning submission was 0.68 [63, 64], which exceeded the 0.65 threshold. Further discussion on the plants R1 analysis is provided in Section 4.

3.4 PLANT DATA

This section summarizes the data extracted from sources relevant to the construction, planning approvals and existing operational data of the respective case studies. The Beddington ERF data has been primarily extracted from the planning support documentation of Virodor [53] and the plant is due to be live from late 2018 onwards. Bilsthorpe Energy Centre is due to be in operation from 2019 onwards and data has been extracted from project supporting documentation by Peel Environmental Management Ltd. and Bilsthorpe Waste Limited [64]. The data for the San Zeno combustor was extracted and verified by the author from the study presented in Di Maria et al. [33].

Table 2 - Summary of Plant Data for Case Studies

Sl. No.	Description of Plant Data (In Relation to R1 Formula Parameter)	Plant Data Beddington ERF	Plant Data Bilsthorpe EC	Plant Data San Zeno EfW
1	**Name of Plant**	Beddington Energy Recovery Facility (ERF)	Bilsthorpe Energy Centre	San Zeno EfW
2	**Date Operational**	2018	2019	2000

Sl. No.	Description of Plant Data (In Relation to R1 Formula Parameter)	Plant Data Beddington ERF	Plant Data Bilsthorpe EC	Plant Data San Zeno EfW
3	**Location of Plant**	Sutton, United Kingdom	Nottingham, United Kingdom	Arezzo, Italy
4	**EfW Technology**	Moving Grate Furnace	Gasification	Grid combustor
5	**Heating Degree Days (HDD)**	2474	2953	2104
6	**Annual Throughput/Capacity of Plant (E_Waste) (tpa):**	275000	95000	44,000
7	**Average NCV of Waste (Range_KJ/kg):**	10307	12581	1,800-2,100 kcal/kg
8	**Annual Availability of the plant (Hours):**	7,796	7,600	8,000
9	**Annual amount of fuel consumed contributing to the production of steam (E_fuel), including type of fuel and average NCV**			
i	**Fuel**	Diesel	Coke	Diesel
ii	**Quantity (kg)**	145,780	3800000	48,000
iii	**NCV (kJ/kg)**	42,620	29,384	42,700
10	**Annual amount of fuel consumed not contributing to the production of steam (E_input), including type of fuel and average NCV**			
i	**Fuel**	Diesel	Gas	Diesel
ii	**Quantity**	145,780 kg	36,000 Nm3	6,000 kg
iii	**NCV**	42,620 kJ/kg	35,710 kJ/kg	42700 kJ/kg
11	**Annual amount of electricity imported by the plant for start up (E_input) (MWh):**	792	3773	Negligible
12	**Annual amount of electricity imported by the plant for general use (E_input) (MWh):**	1818	0	0
13	**Energy_Heat (Consumed internally) (MWh):**	0	0	0
14	**Energy_Heat (Exported) (MWh):**	0	0	1,000
15	**Energy_Power (Consumed internally) (MWh):**	29,625	31,700	8,000
16	**Energy_Power (Exported) (MWh):**	164,195	72,960	10,000

3.5 CONCLUSION

This chapter discussed the primary combustion based technologies, i.e incineration, gasification and pyrolysis. The process of incineration refers to ‘oxidation of the combustible material in the waste to produce heat, water vapour, carbon dioxide and oxygen’[52]. Figure 1 illustrates, incineration system boundary in terms of energy inputs and outputs while Table 1 provided a summary of how the R1 formula energy parameters E_p, E_f, or E_i can be categorized in an incineration plant. In Chapter 2 each of the parameter was discussed in detail and in this chapter the summary is presented in application to the incineration EfW technology.

The second combustion based technology, gasification of waste occurs at temperatures mostly greater than 900 °C, in the presence of limited oxygen resulting in partial combustion [11]. The process although considered more efficient than direct combustion, converting about 80 per cent of the energy in the waste into synthesis gas (syngas) has not till date been proven on commercial scale to thermal treatment of MSW. The by-products of gasified MSW can usually be co-processed to produce bio-fuel for transport purposes. A general configuration of the gasification operational process is discussed and an illustration of energy system boundary further validates the discussion.

The third combustion based technology pyrolysis has been discussed, defined as thermal breakdown of waste in the absence of air, to produce char, pyrolysis oil and syngas (e.g. the conversion of wood into charcoal) [9]. The process takes place in lower temperatures (around 400^{o}C) and does not involve any oxygen or air. No case studies presented for this technology and this can be pursued in future works.

Case study plants, Beddington ERF, Bilsthorpe Energy Centre and San Zeno has been introduced and plant process flow discussed. Similarities of the process flow can be drawn to the general configuration discussion in Section 3.2. Operational data of these plants, has been presented in Table 2, Section 3.4 which is later used for the detailed calculations in Chapter 4.

CHAPTER 4 – DEVELOPMENT OF R1 CORRECTION FACTORS

4.1 INTRODUCTION

The R1 formula was discussed in depth in Chapter 2. In this chapter, the prime focus of the research-study is presented and illustrated through results and published article in ISWA [65]. Further to the background research presented in Section 2, it was noted that R1 formula has been referred to in a number of European PhD research thesis [66, 67] but the work in [66, 67] had a specific focus on the evaluation and revision of the European R1 formula. The Confederation of European Energy from Waste Plants (CEWEP) reports [14, 68] and the study by Clerens Consulting [13] are the preliminary work in this field that discusses the inadequacy of the R1 formula and the need to revise in such a way that external factors (that influence its outcome) can be considered. The Clerens Consulting report [13] was the first study available on the worldwide web that had a key focus on the development of such climate and size correction factors. The work discussed in this chapter follows the methodology in [8, 13] and independently carries out a comparison to investigate the impact of the amendment of applying the European Commission Climate Correction Factor.

Ozansoy [8] points out that the adoption of the R1 formula ‘as is’ could be problematic in Australia (as compared to plants in northern Europe), where there is limited or virtually inexistent heat demand, and the presence of smaller-sized plants may result in R1 values lower than the current threshold set by EU for consideration as a genuine energy recovery facility. The European Commission (EC) recognized this shortcoming of the R1 formula. The Joint Research Centre of the EC commissioned a study [13] to quantify the impact of similar conditions on the value of the R1 thus ensuring a level playing field within the EU. The study [13] conducted for the EC has concluded that correction factors for climate should be applied to the R1 formula to level the playing field as much as possible within the EU. This is also significant in Australia, because it may mean the difference between whether a facility pays waste-levy or not. This may in the future be a key factor driving or inhibiting investment in EfW facilities. Currently, most landfill operators in Europe have to pay waste-levy if their operations fail classification as energy recovery and/or D10 facility.

This chapter discusses the analysis of data from European EfW plants and development of sub-criteria (as mathematical relations) to be used in the unbiased calculation of thermal energy efficiency thresholds. As stated earlier, EC has already completed similar works in Europe to consider the impact of external variants on the determination of thermal efficiency indicators in a more equitable fashion. This research has followed the methods taken by the European studies and used the body of knowledge created in this area as a starting point to further validate the work and results obtained to draw out some probing questions on the current state of affairs. The chapter presents the following:

- Review of the ‘equivalence factors’ for heat and electricity
- Review of size and climate correction factors from [8] developed as a function of the plant capacity and Heating Degree Days (HDD) value at a location consecutively
- Development of sub-criteria to be used in conjunction with the original R1 formula to calculate the thermal energy efficiency of EfW plants considering all external factors
- Development of an Excel calculation tool for the modified R1 value calculation process and presentation of results on its application to real-life case studies
- Demonstrate the application of the sub-criteria and draw comparisons to the current R1 formula as per the European Commission

4.2 PROPOSED CORRECTION FACTORS

Correction factors devised by Ozansoy [8] can be applied to minimize handicap on facilities located in regions where there is lack of heat demand. In the following sub-sections the equivalence factors, proposed corrections factors and the latest European Commission, amended R1 formula that includes the Climate Correction Factor is discussed.

4.2.1 Energy in the Waste and Equivalence Factors (EFs)

E_w is the annual energy in the treated waste given by Eq. (4.1) using the NCV of the processed waste [15]. Eq. (4.2) shows the two EFs (for electricity and heat) defined in the WFD [5, 6] to be applied in the calculation of the produced energy, E_p (GJ year-1), E_i and E_f. The EF for electricity and heat is applied irrespective whether produced, imported, self-consumed or taken back into the system as return flow or backflow [5, 6]. No EF applies for fuels (fuel-oil, gas …), i.e. the factor is 1. The equivalence factor for electricity is 2.6. The equivalence factor for heat (steam or hot water) is 1.1.

$$E_w = \frac{Amount \times NCV_{Waste}}{1,000,000} \qquad (4.1)$$

where

- E_w means annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ)
- *Amount is the amount of waste proccessed in kg*
- NCV_{Waste} *is the lower net calorific value of waste in* $kJkg^{-1}$

$E_{p\_el\_int}$ in Eq. (4.2) constitutes electricity used internally for office lighting or similar without any direct impact on the production of any useful effects. Similarly, $E_{p\_ht\_int}$ is the heat used for office heating or similar and does not contribute to the production of steam. Where $E_{p\_el\_int}$ or $E_{p\_ht\_int}$ contribute to useful effects, then they are assumed to replace heat or electricity import that would have otherwise contributed to useful effects of the same extent.

$$E_p = e.f_{elec} \times (E_{p-el-\text{int}} + E_{p-el-\text{exp}}) \qquad (4.2)$$
$$+ e.f_{heat} \times (E_{p-ht-\text{int}} + E_{p-ht-\text{exp}})$$

where

$e.f_{elec} = 2.6$ *and* $e.f_{heat} = 1.1$

- $E_{p-el-\text{int}}$ is electricity produced and used internally
- $E_{p-el-\text{exp}}$ is electricity delivered to a third party
- $E_{p-ht-\text{int}}$ *is h*eat produced and used internally
- $E_{p-ht-\text{exp}}$ *is* steam delivered to a third party

4.2.2 Size Correction Factor (SCF)

In developing the SCF, an analysis of data from the 3rd CEWEP energy report [14] allowed to categorize average R1 values as a function of the average plant capacity. Using this data, average R1 values vs. average plant capacity was plotted which showed an indirect logarithmic relationship. Then, a mathematical relationship was developed for K_{size} with $K_{size} = 1$ when plant_capacity ≥ 250,000 t. A “Power” type regression line fit was obtained to express K_{size} as a mathematical function. K_{size} is applied as a size multiplicative factor to the R1 value. The SCF aims to bring a level playing field amongst the operators of EfW plants removing the bias towards larger plants that benefit from economies of scale. Eq. (4.3) gives the sub-criteria to be applied to the R1 energy efficiency formula for size scaling.

$$K_{size} = 0.947 \times \frac{0.77}{0.069 \times \ln(plant\_capacity) - 0.130} \qquad (4.3)$$
$$= \quad K_{size} = 3.520 \times plant\_capacity^{-0.101}$$
$$for\ \ plant\ capacity \leq 250,000\ Mg$$
$$= \quad K_{size} = 1 \quad for\ \ plant\ capacity \geq 250,000\ Mg$$
$$where \quad \angle\ plant\_capacity\ is\ in\ Mg\ (1\ Mg = 1\ Tonne)$$

4.2.3 Climate correction factor (CF)

The climate correction factor addresses technical constraints impacting the R1 values both in terms of the reduction in electricity production efficiency and the lack of heat demand. The methodology to be used relies on the examination of a location's Heating Degree Days (HDD), a tool that can be used to assess heating needs to determine the lack of heat demand and electric handicap. The impact of warm temperatures on electricity production efficiency, referred to as the 'handicap', and heat demand will be identified through the use of mathematical correlated functions that rely on easy to obtain yearly averages and HDD data. An analysis of HDD data vs. calculated electric handicaps will lead to the development of a relationship for the climate correction factors. The HDD method is widely used for the assessment of climatic conditions in academic studies [69, 70]. HDD for a day is computed from the following formulae given in equations (4.4-4.5). If the mean daily outdoor temperature is greater than or equal 15, then the HDD will be zero for that particular day. If the mean daily outdoor temperature is smaller than 15, then HDD_{day} is computed from equation (4.4). The HDD for the year is calculated from a summation of the daily HDDs as in equation (4.6).

$$HDD_{day} = T_{base} - \left(\frac{T_{\min} + T_{\max}}{2} \right) \quad (4.4) \quad if\ T_{mean} = \left(\frac{T_{\min} + T_{\max}}{2} \right) < 15$$

$$HDD_{day} = 0 \quad (4.5) \quad if\ T_{mean} = \left(\frac{T_{\min} + T_{\max}}{2} \right) \geq 15$$

$$HDD_{year} = \sum_{i=1}^{365} HDD_{i_{th}-day} \quad (4.6)$$

where

$\angle T_{base} = 18°C$ *in Europe* $\angle T_{\min}$ is the min temperature at a location in a particular day

$\angle T_{\max}$ is the maximum temperature at a location in a particular day

An indirect linear relationship was developed between a location's yearly HDD average, and the handicap this causes on electricity generation efficiency and heat demand. A high HDD value signifies a higher heat demand, and a smaller negative 'handicap' on the electricity production efficiency. In warmer climates (small HDD value), the heat demand would be less and the negative 'handicap' higher. Using this knowledge, the K_{HDD} factor was developed to neutralize the impact of the handicap on the overall energy-efficiency of an EfW facility. $K_{HDD} = 1$ for regions with an annual average HDD > 3350, since these regions are already experiencing favourable conditions and do not require any correction. The 3rd CEWEP energy report [14] assigns an HDD of 3350 as the threshold below which EfW plants experience unfavourable handicaps. Eq. (4.7) was derived to accurately estimate K_{HDD} for regions with an HDD < 3350 with the worst-case correlation factor of 98.23 %.

$$\mathrm{K}_{\mathrm{HDD}} = 1 \quad \mathit{for} \quad HDD \geq 3350 \qquad (4.7)$$

$$\mathrm{K}_{\mathrm{HDD}} = \left(-2.1\times10^{-5} \times HDD\right) + 1.071690 \ \mathit{for}\ HDD < 3350$$

where

- $\mathrm{K}_{\mathrm{HDD}}$ is the climate correction factor (in %)
- HDD is the heating degree days value for a location

4.2.4 Summary of the revised R1 guidelines

Eq. (4.8) summarises the mathematical sub-criteria developed in [8]. The size and climate CFs enable the overall value to be scaled up minimising the handicap on facilities with smaller modular sizes and those located in warmer regions.

$$R1 = K_{size} \times \frac{(E_p) - (E_f + E_i)}{0.97 \times (E_w + E_f)} \qquad (4.8)$$

$$E_w = \frac{Amount \times NCV_i}{1,000,000}$$

$$E_p = K_{HDD} \times \begin{bmatrix} e.f_{elec} \times (E_{p-el-\mathrm{int}} + E_{p-el-\mathrm{exp}}) \\ +e.f_{heat} \times (E_{p-ht-\mathrm{int}} + E_{p-ht-\mathrm{exp}}) \end{bmatrix}$$

where

$$e.f_{elec} = 2.6 \ \ \mathit{and} \ \ e.f_{heat} = 1.1$$

$$K_{size} = 3.5207 \times capacity^{-0.101} \ \ \mathit{for\ capacity} \leq 250,000\ Mg$$

$$K_{size} = 1 \quad \mathit{for\ capacity} \geq 250,000\ Mg$$

$$\mathrm{K}_{\mathrm{HDD}} = 1 \ \ \mathit{for} \quad HDD \geq 3350$$

$$\mathrm{K}_{\mathrm{HDD}} = (-2.1\times10^{-5} \times HDD\,) + 1.071690 \ \ \mathit{for} \ \ HDD < 3350$$

4.2.5 Climate Correction Factor (CCF) in the European Union's WFD

A CCF was proposed in Annex II of the revised Directive 2008/98/EC [18] to consider the impact of climate on electricity production and heat demand. This amendment was proposed as a result of a study by the European Commission [28] that explored the consequences of applying a climate correction factor. This revised formula aims to avoid any overcompensation for the climate correction and at the same time incentivises the use of heat. In the CCF introduced in the revised WFD, there are two potential application methods. For installations in operation and permitted in accordance with applicable Union legislation before 1 September 2015, Eq. (4.9) is used. On the other hand, Eq. (4.10) is used for those installations permitted after 31 August 2015. CCF is applied to the original R1 formula as a multiplicand as given in Eq. (4.11). Herein, the authors will compare the application of Eq. (4.9-4.11) with proposed Eq. (4.7) in Section 4.2.3.

$$\begin{aligned} &CCF = 1 \quad if \quad HDD \geq 3350 \\ &CCF = 1.25 \quad if \quad HDD \leq 2150 \\ &CCF = -(0.25/1200) \times HDD + 1.698 \quad when \quad 2150 \leq HDD \leq 3350 \end{aligned} \tag{4.9}$$

$$\begin{aligned} &CCF = 1 \quad if \quad HDD \geq 3350 \\ &CCF = 1.12 \quad if \quad HDD \leq 2150 \\ &CCF = -(0.12/1200) \times HDD + 1.335 \quad when \quad 2150 \leq HDD \leq 3350 \end{aligned} \tag{4.10}$$

$$R1 = CCF \times \frac{E_p - (E_f + E_i)}{0.97 \times (E_w + E_f)} \tag{4.11}$$

4.3 R1 CALCULATION TOOL IN EXCEL

This calculation tool has been adopted from the study in [8] and has been modified to accommodate the data extracted for the case studies. The calculation table is available in Appendix A.

4.4 RESULTS

This section provides computations to show how to interpret and apply the R1 policy. Computational R1 analysis, based on design data, is presented and application of CFs in R1 scaling is demonstrated. Analytical examples are presented to demonstrate the application of R1 guidelines to the Beddington, Bilsthorpe and San Zeno EfW facilities. The following subsections present comparative analysis using the authors' proposed size and climate factors against the CCF detailed in the revised WFD.

4.4.1 R1 Assessment of the Beddington EfW facility

The following subsections presents R1 policy application to the plant data for Beddington ERF. The outcome is then corrected through the applicable size and climate correction factors as proposed in the study by Ozansoy [8]. This is then compared to the EU WFD climate correction factor for the current R1 formula.

4.4.1.1 Assessment using the proposed correction factors

Table 3 and Table 4 from Hoque et al. [65] presents the implemented R1 assessment for this plant as 0.65, which is equal to the 0.65 threshold justifying the 'recovery' status of the plant. Fig. 4 shows the R1 computations. When heat export becomes available, the R1 ratio is expected to increase since this would allow the generated steam to be partially supplied to nearby customers. When operated in the CHP-mode, this would increase the overall efficiency of the system (hence the R1 score) as a portion of the generated steam would escape the inefficient generator stage, where the heat to power ratio would be 4:1 or similar. This as explained in [53] as the amount of useful heat to be utilized in the generation of electrical power. In the case of the Beddington plant, 250 kW of electric power displaces 1000 kW useful heat, i.e. thermal.

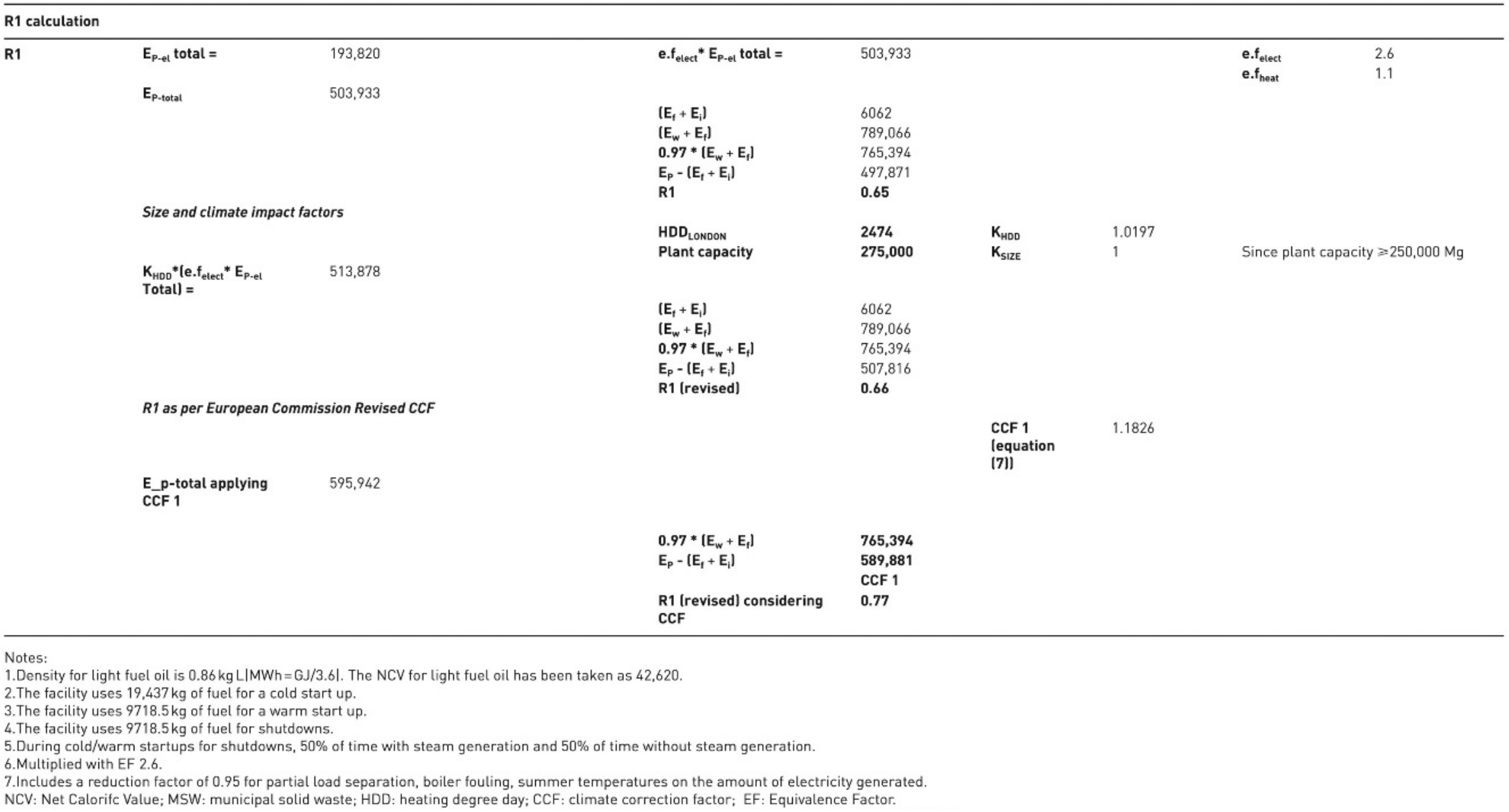
In conducting the analysis, 275,000 t of MSW per annum with an NCV 10,307 kJ kg^{-1} (i.e. the weighted mean NCV value of 314 European MSW plants) was chosen. Then, the annual energy contained in the waste fed into the incineration system (E_w) was calculated as 787,340 MWh. The plant meets the R1 threshold even with such a NCV_{Waste} assumption. The average NCV_{Waste} is likely to be higher than 10,307 (kJ kg^{-1}), which signifies that a reduction in the throughput below 275,000 t of MSW may even be possible whilst still satisfying the R1 threshold. If the NCV_{Waste} increases beyond 10,307 (kJ kg^{-1}), then the waste throughput will be reduced in order to achieve the nominal efficiency of the furnace-boiler system. This can be achieved because the facility was designed with a 10% NCV_{Waste} tolerance [53]. Due to this design specification, the control system is also able to cater an increase in waste throughput up to a maximum of 302,500 tpa to compensate for a reduction in NCV_{Waste}. In case of an NCV_{Waste} increase, the system can reduce throughput down to a minimum of 247,500 tpa as per the planning supporting statement [53]. The power output (E_p) does therefore not depend on the NCV and will be kept constant through throughput variations in response to NCV fluctuations.

Table 3 – R1 Calculation for the Beddington EFW Facility – Plant Data and R1 Parameters* [65]

Type of energy	Explanation	Type of waste	Amount (t)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)		
E_W	Annual energy input to the system by waste	MSW	275,000	10,307	2,834,425	787,340		
		E_W total				**787,340**		
		Type of fuel	Amount (L)	Amount (kg)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)	
E_f	Annual energy input to the system from fuels contributing to the production of steam	Light fuel oil (start-up) – 3 cold start-ups pa (2 boilers)	22,601	19,437	42,620	2485	690	
		Light fuel oil (start-up) – 3 warm start-ups pa (2 boilers)	11,301	9719	42,620	1243	345	
		Light fuel oil – 6 shutdowns (2 boilers)	11,301	9719	42,620	2485	690	
		E_f total				6213	**1726**	
		Type of fuel	Amount (L)	Amount (kg)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)	
E_i	Annual energy input to the system from fuels not contributing to the production of steam	Light fuel oil (start-up) – 3 cold start-ups pa (2 boilers)	22,601	19,437	42,620	2485	690	
		Light fuel oil (start-up) – 3 warm start-ups pa (2 boilers)	11,301	9719	42,620	1243	345	
		Light fuel oil – 6 shutdowns (2 boilers)	11,301	9719	42,620	2485	690	
			(MW)	(h)				
		Electricity imported for plant unavailability	0.7252	964		2517	1818	
		Electric power imported for plant start-ups				1097	792	
		E_i total				9827	**4336**	
		Type	Description	Capacity (MW)	Availability (h)		Energy (MWh)	Reduction factor
E_P	Annual generated energy	$E_{P\text{-el-int.used}}$	Used internally	4	7796		29,625	0.95
		$E_{P\text{-el-exported}}$	Delivered to a third party	22.17	7796		164,195	0.95
		$E_{P\text{-el}}$ total	Total	**26.17**			**193,820**	

*All entries in bold are results of Summations, Steps in Equation Calculations and should be read in conjunction with the computations provided in Figure 4.

Table 4 – R1 Calculation for the Beddington EFW Facility – R1, Size and Climate Correction and EU CCF * [65]



R1 calculation								
R1	**$E_{P\text{-}el}$ total =**	193,820	**$e.f_{elect}$* $E_{P\text{-}el}$ total =**	503,933			**$e.f_{elect}$**	2.6
							$e.f_{heat}$	1.1
	$E_{P\text{-}total}$	503,933						
			(E_f + E_i)	6062				
			(E_w + E_f)	789,066				
			0.97 * (E_w + E_f)	765,394				
			E_P - (E_f + E_i)	497,871				
			R1	**0.65**				
	Size and climate impact factors							
			HDD_{LONDON}	**2474**	**K_{HDD}**	1.0197		
			Plant capacity	**275,000**	**K_{SIZE}**	1	Since plant capacity ≥250,000 Mg	
	K_{HDD}*($e.f_{elect}$* $E_{P\text{-}el}$ Total) =	513,878						
			(E_f + E_i)	6062				
			(E_w + E_f)	789,066				
			0.97 * (E_w + E_f)	765,394				
			E_P - (E_f + E_i)	507,816				
			R1 (revised)	**0.66**				
	R1 as per European Commission Revised CCF							
					CCF 1 (equation (7))	1.1826		
	E_p-total applying CCF 1	595,942						
			0.97 * (E_w + E_f)	**765,394**				
			E_P - (E_f + E_i)	**589,881** **CCF 1**				
			R1 (revised) considering CCF	**0.77**				

Notes:
1.Density for light fuel oil is 0.86 kg L|MWh = GJ/3.6|. The NCV for light fuel oil has been taken as 42,620.
2.The facility uses 19,437 kg of fuel for a cold start up.
3.The facility uses 9718.5 kg of fuel for a warm start up.
4.The facility uses 9718.5 kg of fuel for shutdowns.
5.During cold/warm startups for shutdowns, 50% of time with steam generation and 50% of time without steam generation.
6.Multiplied with EF 2.6.
7.Includes a reduction factor of 0.95 for partial load separation, boiler fouling, summer temperatures on the amount of electricity generated.
NCV: Net Calorifc Value; MSW: municipal solid waste; HDD: heating degree day; CCF: climate correction factor; EF: Equivalence Factor.

*All entries in bold are results of Summations, Steps in Equation Calculations and should be read in conjunction with the computations provided in Figure 4.

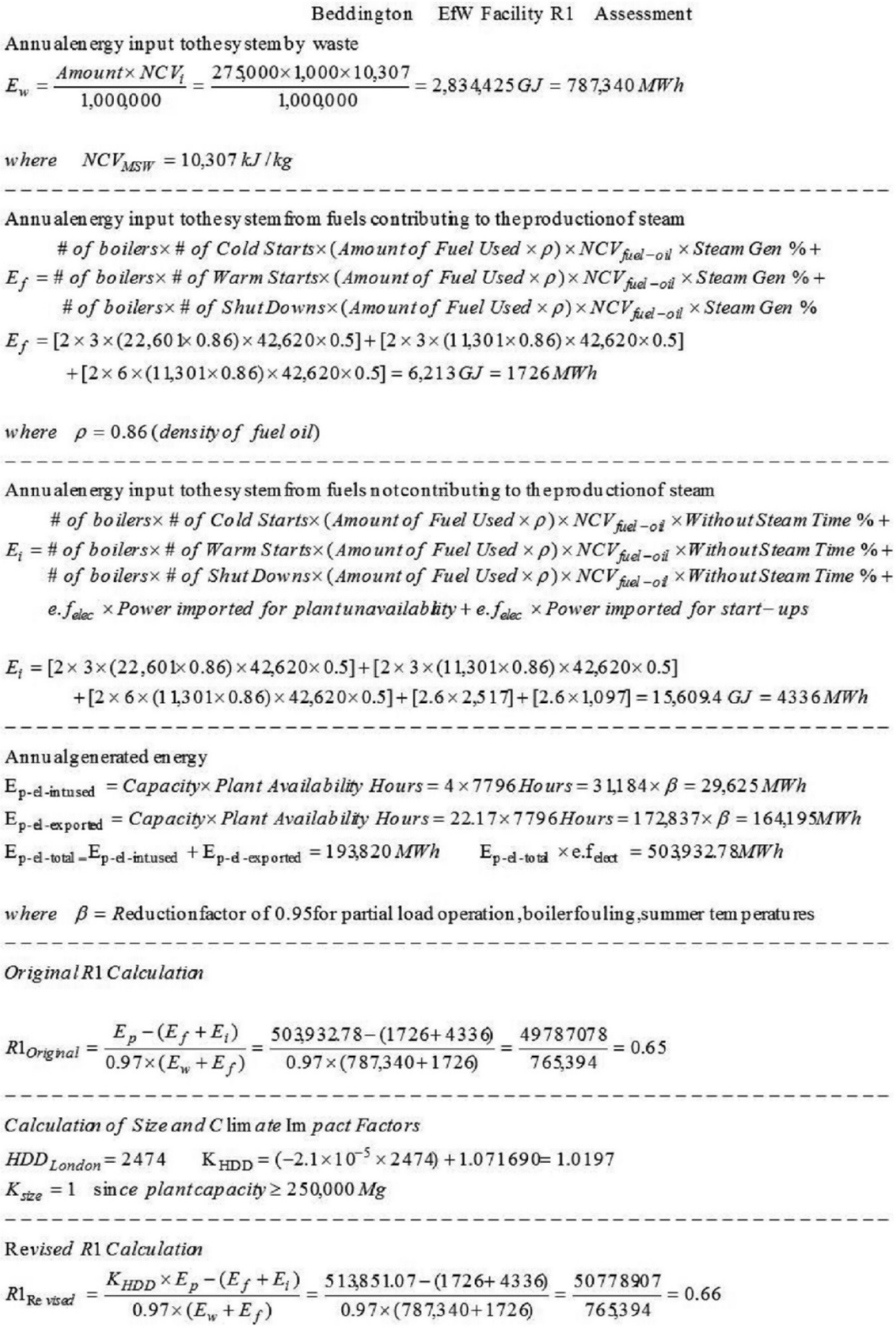
In accordance with the information in [53], it has been assumed that the plant will make three cold start-ups, three warm start-ups and six shut-downs per annum. It is known that 19,437 kg of fuel is required for a cold start-up and half of this amount (9718.5 kg) is required in a warm start-up or shut-down. In accordance with [6], during cold/warm start-ups and shut-downs, consumption at the burner is roughly 50% of the time with steam generation (useful effects) and 50% of the time without steam generation (without useful effects). In simpler terms, 50% of the light fuel-oil imported for cold/warm start-ups and shut-downs is taken to contribute to the production of steam, and hence E_f accordingly estimated as demonstrated in Table 2. Given this scenario, E_f was calculated as 1726 MWh.

E_i is calculated from the remaining 50% of the light fuel-oil used during cold/warm start-ups and shut-downs plus the electricity imported during plant unavailability and start-ups. The plant is estimated to require around 0.725 MW of electrical power when offline (964 hours) from which the total electrical energy import requirement can be estimated as 1818 MWh. It is known that 1,097 GJ of electrical energy is required for start-ups. Given all these facts, E_i was determined as 4,336 MWh.

The predicted electricity import for plant unavailability and start-ups needs to be multiplied by the '×2.6' EF as EFs are to be applied to imported electricity and heat. Another correction in the assessment conducted by the author was by not applying the '×1.1' EF to the fuel-oil usage of the auxiliary burners during the plant start-up. This correction addresses a gap in the report [53] wherein the R1 value was calculated by applying the '×1.1' EF to the fuel used for plant start-ups, and shut downs. As per EU guidelines [6], the EF for electricity and heat is applied irrespective whether produced, imported, self-consumed or taken back into the system as return flow or backflow. No EF applies for fuels (fuel-oil, gas …), i.e. the factor is 1. The equivalence factor for electricity is 2.6. The equivalence factor for heat (steam or hot water) is 1.1. The plant is expected to generate a total

26.17 MW, 4 MW of which is used internally and 22.17 MW exported. Given that the plant operates for 7796 hours, the E_p was calculated as 193,820 MWh. The scaled E_p becomes 503,933 MWh when multiplied by the '×2.6' EF. In calculating the E_p term, a reduction factor of 0.95 has been assumed to take into account partial load separation, boiler fouling, radiation, convection losses and summer temperatures on the electrical power output. All these factors contribute to and impact the annual output of a generator [71]. The use of such a factor would enable a better assessment of the annual output considering that at times of high air temperature and partial loading, the power output would be less than nominal. Such a practice was applied in the original R1 analysis (at the time of planning submission) and was kept unchanged for consistency. Having calculated all the variables, the unscaled R1 score was calculated as 0.65 for this plant.

The assessment given in Fig. 4 also shows the scaled R1 score taking into account the developed K_{size} and K_{HDD} factors. K_{size} is 1 for this plant as its capacity is greater than 250,000 t per annum, and K_{HDD} becomes 1.0197 for London with an HDD of 2474 [72]. The new revised value for R1 was then computed as 0.66. For this case study plant, the CCF and SCF have not made a significant impact on R1 since the plant is already enjoying economies of scale due to its large size and location in a relatively cool climate.



Beddington EfW Facility R1 Assessment

Annual energy input to the system by waste

$$E_w = \frac{Amount \times NCV_i}{1,000,000} = \frac{275,000 \times 1,000 \times 10,307}{1,000,000} = 2,834,425\,GJ = 787,340\,MWh$$

where $NCV_{MSW} = 10,307\,kJ/kg$

- -

Annual energy input to the system from fuels contributing to the production of steam

$$\begin{aligned} & \#\ of\ boilers \times \#\ of\ Cold\ Starts \times (Amount\ of\ Fuel\ Used \times \rho) \times NCV_{fuel-oil} \times Steam\ Gen\ \% + \\ E_f = & \#\ of\ boilers \times \#\ of\ Warm\ Starts \times (Amount\ of\ Fuel\ Used \times \rho) \times NCV_{fuel-oil} \times Steam\ Gen\ \% + \\ & \#\ of\ boilers \times \#\ of\ Shut\ Downs \times (Amount\ of\ Fuel\ Used \times \rho) \times NCV_{fuel-oil} \times Steam\ Gen\ \% \end{aligned}$$

$$\begin{aligned} E_f = & [2 \times 3 \times (22,601 \times 0.86) \times 42,620 \times 0.5] + [2 \times 3 \times (11,301 \times 0.86) \times 42,620 \times 0.5] \\ & + [2 \times 6 \times (11,301 \times 0.86) \times 42,620 \times 0.5] = 6,213\,GJ = 1726\,MWh \end{aligned}$$

where $\rho = 0.86\,(density\ of\ fuel\ oil)$

- -

Annual energy input to the system from fuels not contributing to the production of steam

$$\begin{aligned} & \#\ of\ boilers \times \#\ of\ Cold\ Starts \times (Amount\ of\ Fuel\ Used \times \rho) \times NCV_{fuel-oil} \times Without\ Steam\ Time\ \% + \\ E_i = & \#\ of\ boilers \times \#\ of\ Warm\ Starts \times (Amount\ of\ Fuel\ Used \times \rho) \times NCV_{fuel-oil} \times Without\ Steam\ Time\ \% + \\ & \#\ of\ boilers \times \#\ of\ Shut\ Downs \times (Amount\ of\ Fuel\ Used \times \rho) \times NCV_{fuel-oil} \times Without\ Steam\ Time\ \% + \\ & e.f_{elec} \times Power\ imported\ for\ plant\ unavailability + e.f_{elec} \times Power\ imported\ for\ start-ups \end{aligned}$$

$$\begin{aligned} E_i = & [2 \times 3 \times (22,601 \times 0.86) \times 42,620 \times 0.5] + [2 \times 3 \times (11,301 \times 0.86) \times 42,620 \times 0.5] \\ & + [2 \times 6 \times (11,301 \times 0.86) \times 42,620 \times 0.5] + [2.6 \times 2,517] + [2.6 \times 1,097] = 15,609.4\,GJ = 4336\,MWh \end{aligned}$$

- -

Annual generated energy

$E_{\text{p-el-intused}} = Capacity \times Plant\ Availability\ Hours = 4 \times 7796\,Hours = 31,184 \times \beta = 29,625\,MWh$

$E_{\text{p-el-exported}} = Capacity \times Plant\ Availability\ Hours = 22.17 \times 7796\,Hours = 172,837 \times \beta = 164,195\,MWh$

$E_{\text{p-el-total}} = E_{\text{p-el-intused}} + E_{\text{p-el-exported}} = 193,820\,MWh \qquad E_{\text{p-el-total}} \times e.f_{\text{elect}} = 503,932.78\,MWh$

where β = Reduction factor of 0.95 for partial load operation, boiler fouling, summer temperatures

- -

Original R1 Calculation

$$R1_{Original} = \frac{E_p - (E_f + E_i)}{0.97 \times (E_w + E_f)} = \frac{503,932.78 - (1726 + 4336)}{0.97 \times (787,340 + 1726)} = \frac{49787078}{765,394} = 0.65$$

- -

Calculation of Size and Climate Impact Factors

$HDD_{London} = 2474 \qquad K_{HDD} = (-2.1 \times 10^{-5} \times 2474) + 1.071690 = 1.0197$

$K_{size} = 1$ since $plant\ capacity \geq 250,000\,Mg$

- -

Revised *R1 Calculation*

$$R1_{Revised} = \frac{K_{HDD} \times E_p - (E_f + E_i)}{0.97 \times (E_w + E_f)} = \frac{513,851.07 - (1726 + 4336)}{0.97 \times (787,340 + 1726)} = \frac{507789.07}{765,394} = 0.66$$

Figure 4 – R1 Computations for Beddington EFW Facility [65]

4.4.1.2 Assessment using the WFD CCF and comparative analysis

The application of the CCF introduced in the revised WFD can be seen from Table 3. The application of the WFD CCF scaled the R1 value to 0.77, significantly higher than the 0.66 value obtained using the correction factors proposed by the authors. The reason is primarily due to a higher CCF factor of 1.18, when computed as per the WFD guidelines, to compensate for situations where the heat demand is low.

R1 formula is an incentive for operators to increase the overall efficiency of plants and, in particular, to increase the heat export where possible. As the plant, is not in operation and received permission for installation prior to 1 September 2015, the applicable WFD CCF formula is Eq. (4.9). The WFD CCF scaled the R1 value to 0.77, which is a significant increase in comparison to the 0.66 corrected R1 figure by the proposed correction factors. Hence it is observed the WFD CCF overcompensates the R1 threshold value of 0.65. The higher multiplicands given by the WFD CCF would bring most plants of similar capacities and technology closer to the required R1 ratio to be categorised as ‘recovery’. This is also demonstrated in a study by the European Commission [28] wherein a range of consequences were analysed for a set of revised correction factors for climate. Despite the selection of a well-balanced correction factor, it still appears to overcompensate the R1 outcome for lack of heat demand.

The authors’ correction factor for climate on the other hand is conservative and does not affect the outcome by a large margin. R1 was computed as 0.66, as compared to the 0.77 achieved from the application of the WFD CCF. Being located in UK, the Beddington EfW facility is already in a relatively cool climate and hence the large scaling (0.77 from 0.65) provided by the WFD CCF is unjustifiable.

4.4.2 R1 Assessment of the Bilsthorpe gasification plant

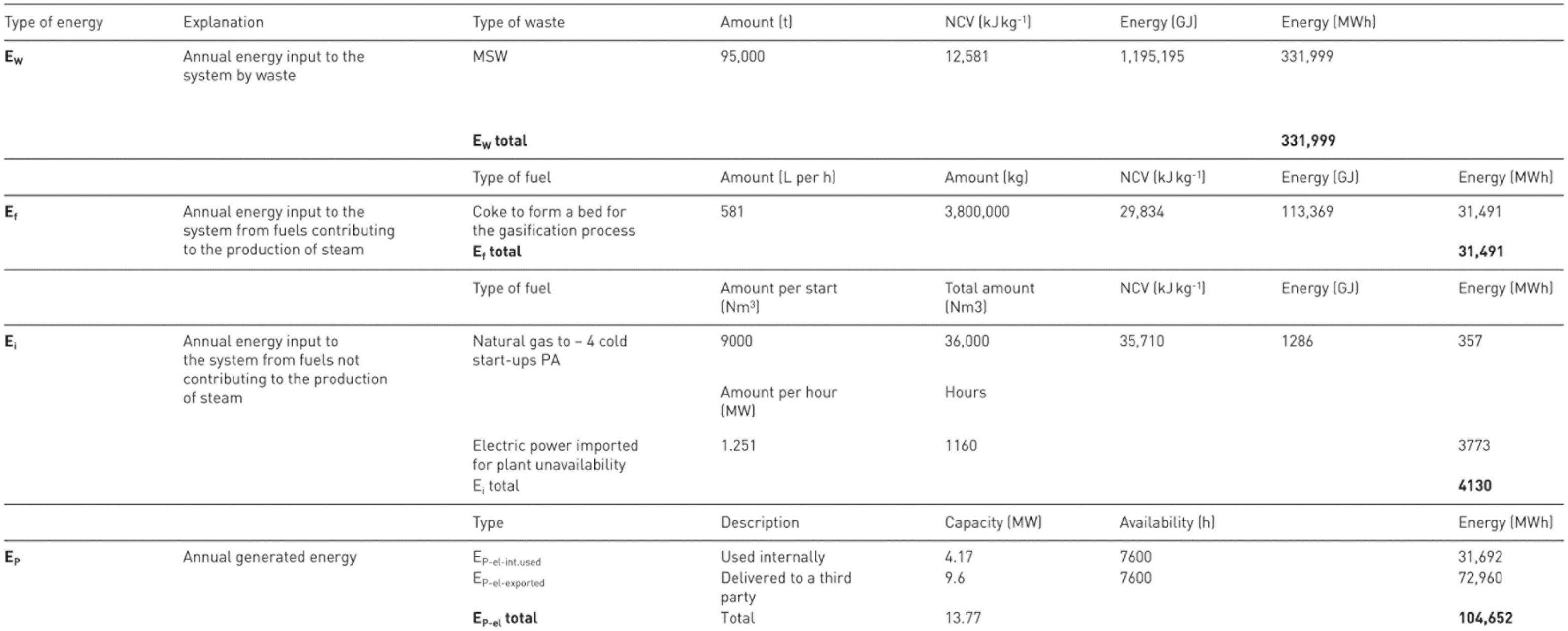
The following subsections presents R1 policy application to the plant data for Bilsthorpe Energy Centre. The outcome is then corrected through the applicable size and climate correction factors as proposed in the study by Ozansoy [8]. This is then compared to the EU WFD climate correction factor for the current R1 formula.

4.4.2.1 Assessment using the proposed correction factors

Table 5 and Table 6 from Hoque et al. [65] presents author's own R1 assessment for the Bilsthorpe facility and Fig. 5 shows author's own R1 computations, demonstrating the application of Climate CF and SCF in scaling the R1 value. The plant is designed to process 95,000 t of waste with a design-stage anticipated Calorific Value (CV) of waste being 12.58 MJ kg^{-1} as given in [73]. Using this knowledge, it is possible to calculate E_w as 331,999 MWh. Coke is added to form the gasification bed structure. This energy input contributes to the production of syngas, and must therefore be counted in E_f. It is known that 3800 t of coke is to be used annually contributing to around 31,419 MWh of energy input into the system, which must be counted in E_f. The higher the CV of waste, the less coke would ideally be required. It is possible to increase the amount of syngas generated per tonne of waste by increasing the amount of coke input to the system. Further research in this area should investigate the process efficiency of coke as an additive, and identify the economic feasibility of using coke as opposed to the R1 efficiency gains that can be attained.

Natural gas is used during the gasification process as a start-up fuel to warm the gasification bed. As it was in the case of fuel-oil for incineration, this does not directly contribute to the formation of syngas, but establishes stable syngas generation. Therefore, the amount of natural gas used must count towards E_i. It is expected that there will be four start-ups a year, with 9,000 Nm^3 of natural gas used for each start-up. In this study, the NCV for natural gas has been taken as 35.71 MJ (Nm^3)$^{-1}$ in contrast to the 34.2 MJ $(Nm^3)^{-1}$ used in [63]. This is an estimated average calorific value of natural gas in the UK [74].

Table 5 – R1 Calculation for the Bilsthorpe EfW – Plant Data and R1 Parameters* [65]



Type of energy	Explanation	Type of waste	Amount (t)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)	
E_W	Annual energy input to the system by waste	MSW	95,000	12,581	1,195,195	331,999	
		E_W total				**331,999**	
		Type of fuel	Amount (L per h)	Amount (kg)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)
E_f	Annual energy input to the system from fuels contributing to the production of steam	Coke to form a bed for the gasification process	581	3,800,000	29,834	113,369	31,491
		E_f total					**31,491**
		Type of fuel	Amount per start (Nm^3)	Total amount (Nm3)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)
E_i	Annual energy input to the system from fuels not contributing to the production of steam	Natural gas to – 4 cold start-ups PA	9000	36,000	35,710	1286	357
			Amount per hour (MW)	Hours			
		Electric power imported for plant unavailability	1.251	1160			3773
		E_i total					**4130**
		Type	Description	Capacity (MW)	Availability (h)		Energy (MWh)
E_P	Annual generated energy	$E_{P\text{-el-int.used}}$	Used internally	4.17	7600		31,692
		$E_{P\text{-el-exported}}$	Delivered to a third party	9.6	7600		72,960
		$E_{P\text{-el}}$ total	Total	13.77			**104,652**

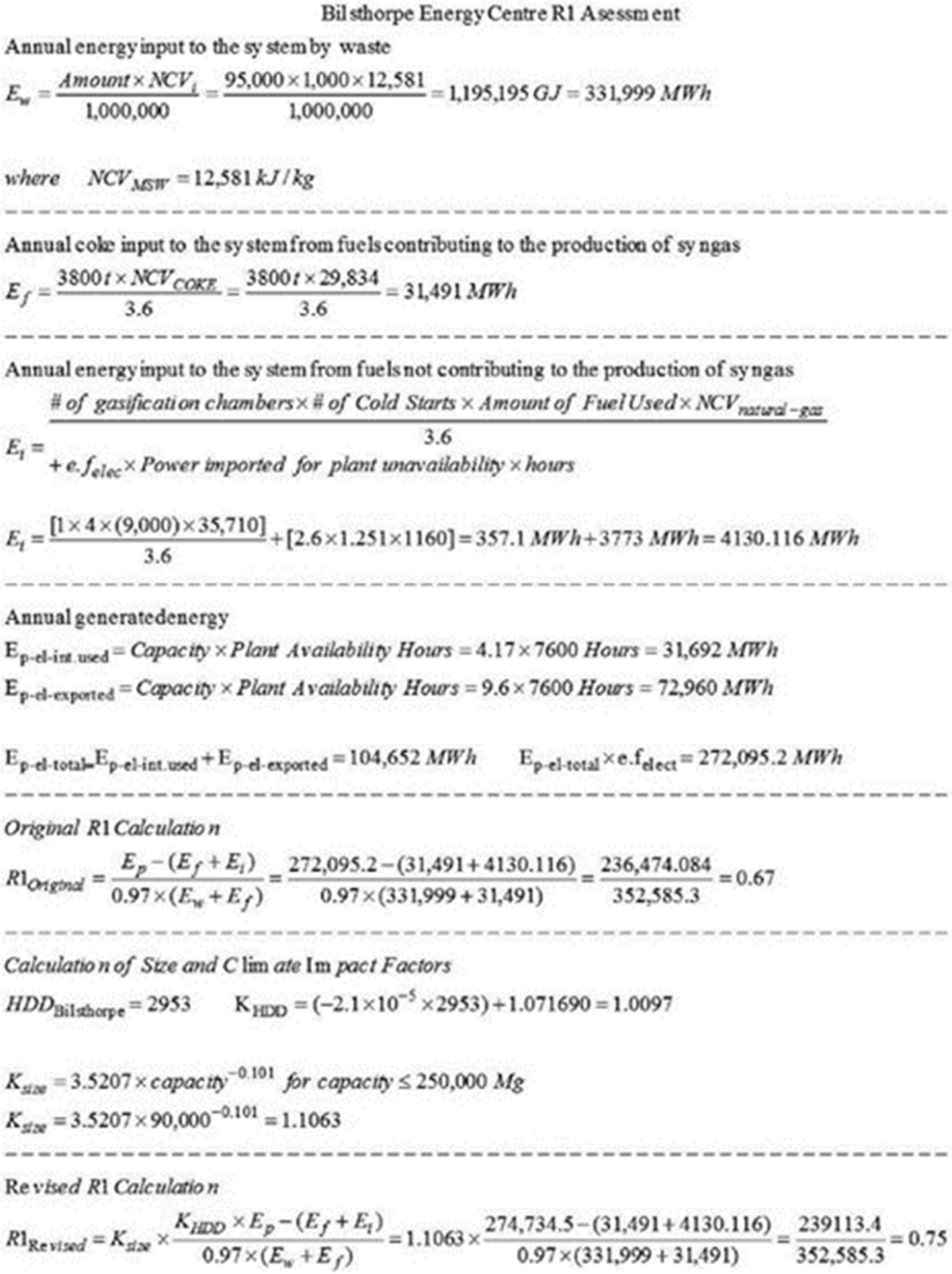
*All entries in bold are results of Summations, Steps in Equation Calculations and should be read in conjunction with the computations provided in Figure 5.

Table 6 – R1 Calculation for the Bilsthorpe EFW – R1, Size and Climate Correction and EU CCF* [65]

R1 calculation							
R1	**E_{P-el} total =**	104,652	**$e.f_{elect}$* E_{P-el} total =**	272,095		**$e.f_{elect}$**	2.6
						$e.f_{heat}$	1.1
	$E_{P-total}$	272,095					
			$(E_f + E_i)$	35,622			
			$(E_w + E_f)$	363,490			
			$0.97 * (E_w + E_f)$	352,585			
			$E_P - (E_f + E_i)$	236,474			
	Size and Climate Impact factors		**R1**	**0.67**			
		$HDD_{NOTTINGHAM}$	**2953**		**K_{HDD} =**	1.0097	
		Plant capacity	**95,000**		**K_{SIZE} =**	1.1063	
	$E_{p-total} = K_{HDD-elect}*(e.f_{elect}* E_{P-el\ total})$	274,728					
			$(E_f + E_i)$	35,622			
			$(E_w + E_f)$	363,490			
			$0.97 * (E_w + E_f)$	352,585			
			$E_P - (E_f + E_i)$	239,107			
			R1 (revised) considering K_{HDD} & K_{SIZE}	**0.75**			
			R1 (revised) considering K_{HDD}	**0.68**			
	R1 as per European Commission Revised CCF						
	$E_{p-total}$	282,897			**CCF**	1.0397	
			$0.97 * (E_w + E_f)$	352,585			
			$E_P - (E_f + E_i)$	247,276			
			R1 (revised) considering CCF only	**0.70**			

NCV: Net Calorifc Value; MSW: municipal solid waste; HDD: heating degree day; CCF: climate correction factor; EF: Equivalence Factor.
Note: *All the entries in* bold *are results of Summations, Steps in Equation Calculations and should draw a reference point to the calculations shown in Figure 4.*

*All entries in bold are results of Summations, Steps in Equation Calculations and should be read in conjunction with the computations provided in Figure 5.



Bilsthorpe Energy Centre R1 Asessment

Annual energy input to the system by waste

$$E_w = \frac{Amount \times NCV_i}{1{,}000{,}000} = \frac{95{,}000 \times 1{,}000 \times 12{,}581}{1{,}000{,}000} = 1{,}195{,}195\ GJ = 331{,}999\ MWh$$

where $NCV_{MSW} = 12{,}581\ kJ/kg$

Annual coke input to the system from fuels contributing to the production of syngas

$$E_f = \frac{3800t \times NCV_{COKE}}{3.6} = \frac{3800t \times 29{,}834}{3.6} = 31{,}491\ MWh$$

Annual energy input to the system from fuels not contributing to the production of syngas

$$E_I = \frac{\#\ of\ gasification\ chambers \times \#\ of\ Cold\ Starts \times Amount\ of\ Fuel\ Used \times NCV_{natural-gas}}{3.6} + e.f_{elec} \times Power\ imported\ for\ plant\ unavailability \times hours$$

$$E_I = \frac{[1 \times 4 \times (9{,}000) \times 35{,}710]}{3.6} + [2.6 \times 1.251 \times 1160] = 357.1\ MWh + 3773\ MWh = 4130.116\ MWh$$

Annual generated energy

$E_{p\text{-}el\text{-}int.used} = Capacity \times Plant\ Availability\ Hours = 4.17 \times 7600\ Hours = 31{,}692\ MWh$

$E_{p\text{-}el\text{-}exported} = Capacity \times Plant\ Availability\ Hours = 9.6 \times 7600\ Hours = 72{,}960\ MWh$

$E_{p\text{-}el\text{-}total} = E_{p\text{-}el\text{-}int.used} + E_{p\text{-}el\text{-}exported} = 104{,}652\ MWh$ $\quad E_{p\text{-}el\text{-}total} \times e.f_{elect} = 272{,}095.2\ MWh$

Original R1 Calculation

$$R1_{Original} = \frac{E_p - (E_f + E_I)}{0.97 \times (E_w + E_f)} = \frac{272{,}095.2 - (31{,}491 + 4130.116)}{0.97 \times (331{,}999 + 31{,}491)} = \frac{236{,}474.084}{352{,}585.3} = 0.67$$

Calculation of Size and Climate Impact Factors

$HDD_{Bilsthorpe} = 2953$ $\quad K_{HDD} = (-2.1 \times 10^{-5} \times 2953) + 1.071690 = 1.0097$

$K_{size} = 3.5207 \times capacity^{-0.101}$ for capacity $\leq 250{,}000\ Mg$

$K_{size} = 3.5207 \times 90{,}000^{-0.101} = 1.1063$

Revised R1 Calculation

$$R1_{Revised} = K_{size} \times \frac{K_{HDD} \times E_p - (E_f + E_I)}{0.97 \times (E_w + E_f)} = 1.1063 \times \frac{274{,}734.5 - (31{,}491 + 4130.116)}{0.97 \times (331{,}999 + 31{,}491)} = \frac{239113.4}{352{,}585.3} = 0.75$$

Figure 5 - R1 Computations for the Bilsthorpe EFW plant [65]

The facility uses 4.17 MW of electrical energy during its operation (7600 hours per year) and this energy is supplied by the gas turbines. During the cold start, electricity imported (E_i) is used to power the plasma torches. When plant starts producing useful effects, i.e. power, $E_{p\_el\_int}$ is used for this purpose. This is permissible and must be considered in the $E_{p\_el\_int}$ because it replaces electric power that the plant would have otherwise imported to influence the production of useful effects. Assuming that the facility would use 30% of 4.17 MW (1.251 MW) during offline periods (1160 hours per year), and multiplying it by '×2.6' EF, the amount of electricity imported for the offline periods was calculated as ~ 3773 MWh.

The EF was considered for the computation of E_i as recommended in [6]. The total E_i equals to the annual energy input from the start-up natural gas plus the annual energy imported as electricity during offline periods.

In calculating the annual energy generated, it is known that the facility will use eight gas engine sets rated at 1950 kWe with a total output of 14.6 MWe [64]. The expected full-load figure is to be around 94% of the nameplate rating, which equates to a maximum output of around 13.77 MWe. 9.6 MW of 13.77 MWe will be exported to the UK National Grid, and 4.17 MW will be used internally. Knowing that the plant will be operational for 7600 hours, E_p can be calculated as ~272,095 MWh as shown in Fig. 5.

Having calculated all the components, the unscaled R1 score for this plant was calculated as 0.67. The assessment was later revised taking into account the K_{size} (SCF) and K_{HDD} (Climate CF) factors. K_{size} was calculated from Eq. (4.3) as 1.1063 for this plant as its capacity is relatively small at 95,000 t per annum. This is a relatively high SCF, which would allow R1 value for this plant to be scaled up reducing the handicap it incurs as a smaller, modular sized facility. Bilsthorpe has a relatively higher HDD of 2953 [13, 72] which signifies that Bilsthorpe is in a cooler climate as compared to London. As expected, K_{HDD} for this plant is lower and was calculated as 1.0097. The new scaled value of R1 was then computed as 0.75. Overall, the R1 value was scaled up by a factor of 1.12.

4.4.2.2 Using the WFD CCF and comparative analysis

The application of the CCF in the revised WFD can be seen from Table 6. The R1 value was scaled to 0.70, using the WFD CCF. This indicates a lower scaling from the one calculated using the correction factors proposed by the authors. This is due to the fact that WFD only has climate based correction, whereas authors are proposing a SCF to be applied in conjunction with the Climate CF. The absence of a size correction factor is still a serious shortcoming in the WFD. Since this facility was constructed after September 2015, the applicable EC's CCF formula is Equation (4.10). R1 formula is an incentive for operators to increase the overall efficiency of plants, and in particular, to increase the heat export where possible. In this case, it can be observed that it does not overcompensate for the plant and in effect brings it to an equal footing to the incineration technology despite capacity and technology type. This is also demonstrated in the study by the European Commission [28] wherein a range of consequences were analysed for a revised correction factors for climate. Hence, from a policy perspective, there is no distinction between an unscaled and scaled R1 value as EU policies have been frame worked to encourage development of EfW facilities even in smaller capacity, different technology and/or in warmer regional areas. The literature however acknowledges that incineration technology is dominant in Europe and the formula has been developed with available data from operational EfW plants.

Even though the correction factors proposed by the authors resulted in an R1 score of 0.75 against 0.70 (by the WFD CCF), it should be noted that the factors proposed by authors corrects for both modular size as well as lack of heat demand. Such size-based correction is yet to be considered in the WFD. Therefore, a difference of 0.05 is justifiable.

4.4.3 R1 Assessment of the San Zeno Incineration facility

The following subsections presents R1 policy application to the plant data for San Zeno EfW. The outcome is then corrected through the applicable size and climate correction factors as proposed in the study by Ozansoy [8]. This is then compared to the EU WFD climate correction factor for the current R1 formula.

4.4.3.1 Assessment using the proposed correction factors

Table 7 from Hoque et al. [65] presents authors' own unscaled R1 assessment for the plant as 0.40, which is significantly lower than the 0.65 threshold justifying the 'disposal' operation of the plant. The system at the plant measures the NCV in real time which can vary in the range of 10,500 kJ kg-1 to 12,000 kJ kg-1. For the purposes of the calculation, it was assumed to be 10,500 kJ kg-1 , which is approximately equal to the weighted mean NCV value of 314 European MSW plants [14]. Then, the annual energy contained in the waste fed into the incineration system (Ew) was calculated as 122,500 MWh. From the information available in [33], it can be concluded that the plant will consume 48,000 kg of diesel per annum which contributes to the production of steam. It is also known that 6,000 kg of fuel is required in a warm start-up or shut-down. Given this scenario, E_f was calculated as 569 MWh.

E_i is calculated from the remaining 50% of the diesel used during cold/warm start-ups and shutdowns plus the electricity imported during plant unavailability and start-ups. Required electrical power for the plant is negligible and E_i was determined as 71 MWh. The predicted electricity import for plant unavailability and start-ups needs to be multiplied by the '×2.6' EF. The plant generates a total 2.366 MW, 1.05 MW of which is used internally and 1.32 MW exported. Given that the plant operates for 8000 hours, the E_p was calculated as 17,982 MWh. The scaled E_p becomes 46,752 MWh when multiplied by the '×2.6' EF. Having calculated all the variables, the unscaled R1 was calculated as 0.40 for this plant. The plant also generates, through steam bleed at turbine, 1104 MWh of heat upon application of the 1.1 EF.

The assessment given in Table 4 also shows the scaled R1 score taking into account the developed K_{size} and K_{HDD} factors. K_{size} is 1.2014 for this plant as its capacity is less than 250,000 t per annum, and K_{HDD} becomes 1.0275 for central Italy with an HDD of 2104 [13]. The new revised value for R1 was then computed as 0.49. For this case study plant, the Climate CF and SCF have made a significant impact on R1 since the plant is small and in a climate zone, where the heat demand is relatively less or does not exist. This impact is justified considering the essence of applying the correction factors, which is aligned with the objectives of the EU policy and WFD. A prime objective being to support and develop EfW facilities in warmer regions or in smaller capacities.

Table 7 - R1 Calculation for the San Zeno EFW plant – Plant Data, R1 Parameters, R1, Size and Climate Correction and EU CCF [65]

Type of energy	Explanation	Type of waste	Amount (t)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)	
E_W	Annual energy input to the system by waste	MSW **E_W total**	42,000	10,500	441,000	122,500 **122,500**	
		Type of fuel	Amount (L per h)	Amount (kg)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)
E_f	Annual energy input to the system from fuels contributing to the production of steam	Diesel consumed **E_f total**	0.006	48,000	42,700	2050	569 **569**
		Type of fuel	Amount per start (L per h)	Total amount (kg)	NCV (kJ kg^{-1})	Energy (GJ)	Energy (MWh)
E_i	Annual energy input to the system from fuels not contributing to the production of steam	Diesel- start-ups PA	0.75	6000	42,700	256	71
			Amount per hour (MW)	Hours			
		Electric power imported for plant unavailability	Negligible				
		E_i total					**71**
		Type	Description	Capacity (MW)	Availability (h)		Energy (MWh)
E_P	Annual generated energy	$E_{P-el-int.used}$	Used internally	1.05	8000		7980
		$E_{P-el-exported}$	delivered to a third party	1.32	8000		10,002
		E_{P-el} total	Total	2.366			**17,982**
		E_{p-heat}	Total	0.13	8000		**1003**
R1 calculation							
R1	**E_{P-el} total =**	17,982	**$e.f_{elect}$* E_{P-el} total =**	46,752		**$e.f_{elect}$**	2.6
	E_{p-heat} total	1003	**$e.f_{heat}$* E_{P-heat} total =**	1104		**$e.f_{heat}$**	1.1
	$E_{P-total}$	47,856					
			$(E_f + E_i)$	641			
			$(E_w + E_f)$	123,069			
			0.97 * $(E_w + E_f)$	119,377			
			E_P - $(E_f + E_i)$	47,215			
	Size and Climate Impact factors		**R1**	**0.40**			
		HDD_{ITALY}	**2104**		**K_{HDD} =**	1.0275	
		Plant capacity	**42,000**		**K_{SIZE} =**	1.2014	
	$E_{p-total}$ = $K_{HDD-elect}$*($e.f_{elect}$* $E_{P-el\ Total}$)	49,172					
			$(E_f + E_i)$	641			
			$(E_w + E_f)$	123,069			
			0.97 * $(E_w + E_f)$	119,377			
			E_P - $(E_f + E_i)$	48,531			
			R1 (revised) considering K_{HDD} & K_{SIZE}	**0.49**			
			R1 (revised) considering K_{HDD}	**0.41**			
	R1 as per European Commission Revised CCF						
	$E_{p-total}$	59,820			**CCF**	1.2500	
			0.97 * $(E_w + E_f)$	119,377			
			E_p - $(E_f + E_i)$	59,179			
			R1 (revised) considering CCF only	**0.50**			

NCV: Net Calorifc Value; MSW: municipal solid waste; CCF: climate correction factor; EF: Equivalence Factor.

Note: *All the entries in* bold *are results of Summations, Steps in Equation Calculations.*

4.4.3.2 Application of the WFD CCF and comparative analysis

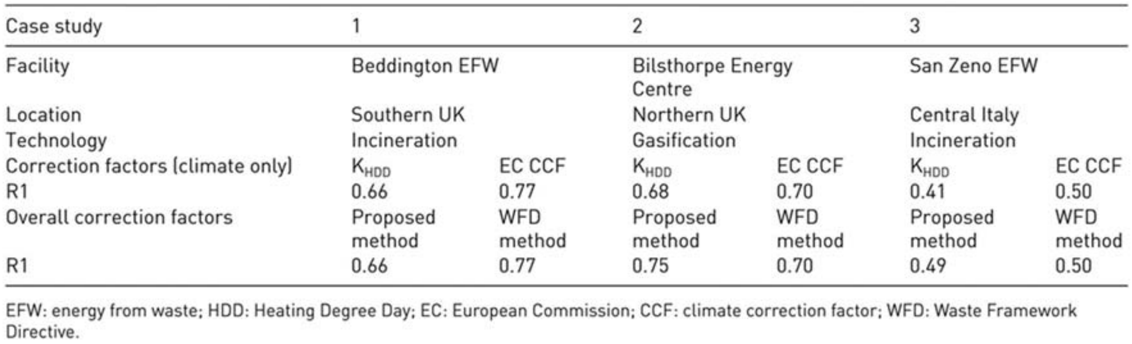
The application of the CCF given by the WFD can be seen from Table 7. The R1 value was scaled to 0.50, using the WFD CCF, which is slightly higher than the scaled value (0.49) calculated using the correction factors proposed by the authors. Despite applying two correction factors, the scaled value by authors' method is still lower than 0.50, predicted by the WFD CCF. The 0.41 correction achieved by the authors proposed climate correction factor, which scaled the R1 value from 0.40 just as WFD CCF, which gives a value of 0.50. As the plant was installed prior to September 2015, the applicable WFD CCF formula is Equation (4.9). With a CCF of 1.25 being applied, due to HDD being less than 2150, the WFD CCF overcompensates for the inefficiencies in comparison to the authors outcome using proposed correction method. The correction factor aims to compensate the effect of lack of heat demand and makes the R1 formula workable in warmer areas. However, in this case study the plant is still considered a 'disposal' facility.

Ozansoy [8] correction factor for climate is comparatively conservative giving an R1 value of 0.41 (when only K_{HDD} is applied), compared to the 0.50 achieved from the application of the WFD CCF.

4.4.4 R1 Comparative Analysis without application of Size Correction Factor

This section analyses R1 scaling when not taking into consideration the Size Correction Factor of Eq. (4.3). The previous sections have taken into consideration a comprehensive calculation, demonstrating the impact of all correction factors as applied. It would also be prudent to isolate and view R1 outcomes without considering the correction for size, proposed by the author. Table 8 presents the R1 score for each one of the case studies when not taking into account author's SCF. Although the changes are not significant, it can be seen that WFD CCF has a greater impact on the R1 outcome. Application of the WFD CCF to Beddington facility gives an R1 score of 0.77, Bilsthorpe energy centre an R1 score of 0.70 and San Zeno an R1 score of 0.50. All these WFD scaled R1 scores are greater than R1 scaling by author's proposed K_{HDD} formula for climate. The San Zeno facility would be categorised as a disposal operation as opposed to energy recovery, irrespective of which method is used.

Table 8 – Comparative summary of proposed method versus EU WFD method [65]



Case study	1		2		3	
Facility	Beddington EFW		Bilsthorpe Energy Centre		San Zeno EFW	
Location	Southern UK		Northern UK		Central Italy	
Technology	Incineration		Gasification		Incineration	
Correction factors (climate only)	K_{HDD}	EC CCF	K_{HDD}	EC CCF	K_{HDD}	EC CCF
R1	0.66	0.77	0.68	0.70	0.41	0.50
Overall correction factors	Proposed method	WFD method	Proposed method	WFD method	Proposed method	WFD method
R1	0.66	0.77	0.75	0.70	0.49	0.50

EFW: energy from waste; HDD: Heating Degree Day; EC: European Commission; CCF: climate correction factor; WFD: Waste Framework Directive.

4.5 CONCLUSION

This chapter explored application of the R1 energy-efficiency guidelines in the assessment of the thermal energy efficiency of three EfW facilities. Detailed computations were given to demonstrate the calculation of the R1 value using datasets from real-life case studies presented in Chapter 3. Climate and size CFs were then applied to the datasets in demonstrating how the overall

R1 value can be scaled minimizing the handicap on facilities with smaller modular sizes and those located in warmer regions of the world.

The first case study is an incineration plant, which processes 275,000 t of non-hazardous residual waste a year generating up to 26.17 MW of electricity. The R1 efficiency for the Beddington EfW facility was calculated as 0.65, justifying the ‘recovery’ status of the plant. The scaled R1 value for the Beddington EfW facility was computed as 0.66 after applying the CFs to consider the impacts of size and climate. For this case study plant, the CFs had small impact as the plant is already enjoying economies of scale due to its large size and high electrical efficiency due to its location in a relatively cool climate. Application of the WFD CCF resulted in an R1 value of 0.77. This demonstrates the accuracy of the factors proposed by the authors as it is unjustifiable for the R1 value of a plant located in an already cool climate just as UK to increase by almost 20% as given by the WFD CCF. In the WFD CCF there exists no distinction to which plants correction factor must be applied to. It covers the full spectrum of plants in EfW. Ideally the correction factor should not make a big impact on the R1 score in such circumstances. This is demonstrated in the application of authors’ CCF because it only led to an overshoot of 0.01. This equates to a justifiable scaling of less than 2% of the original unscaled value. A justifiable correction factor outcome for an already good performing plant should be approximately around the R1 threshold, 0.65 or near its original calculated figure prior to application of correction factor.

The second case study is a plasma gasification plant for processing 95,000 t of waste per annum to generate up to 13.77 MW of electrical energy. The unscaled R1 efficiency indicator for Bilsthorpe plasma gasification plant was calculated as 0.68, and the scaled R1 value was computed to be 0.75 scaled up in consideration of the handicap it incurs as a smaller-sized facility. Application of the EU CCF resulted in an R1 value of 0.70. When Eq. (4.10) of the WFD CCF is applied, very similar outcomes were achieved, which not only demonstrates the validity of the factors proposed by the authors, but also the fact that Eq. (4.10) does not overshoot like Eq. (4.9). The outcome of Eq. (4.9) which is 0.73, is higher due to the use of a higher multiplicand.

The third case study is an incineration plant for processing 42,000 t of waste per annum to generate up to 1.32 MW of electrical energy. The unscaled R1 efficiency indicator for the San Zeno incineration plant was calculated as 0.40, and the scaled R1 value was computed as 0.49 scaled up in consideration of the handicap it incurs as a smaller-sized facility and as a plant located in a region with less heat demand. Application of the WFD CCF resulted in an R1 value of 0.50. The scaling by the proposed correction factors was once again more conservative. The San Zeno facility is particularly handicapped due to size and location, as the computations suggest only when corrected for both does it come closer to the R1 requirement.

A detailed analysis through mass and energy balance will have to be done in future works to assess the overall impact on environment. It is however apparent to state that the net impact of an efficiency requirement will have significant environmental benefits when adopted as a standard. This has been emphasized in the study presented by [27, 30]. Further demonstration of the conservative approach by the author can be seen from the R1 outcome when correcting for climate only. Impact of scaling R1 only by the WFD CCF is apparent, with higher values of R1 compared to author's proposed Climate CF formula for every case study.

A critical analysis of EU's WFD and in particular the policy on the assessment of the energy recovery status of EfW plants has been presented in this chapter. The significance of R1 compliance assessment will ever grow as investment in incineration and gasification plants increases. Many public enquiries and planning appeals are already underway between investors trying to secure planning permits for their plants as genuine energy recovery facilities, and opponents of incineration plants trying to appeal against such development. Discussions in this chapter are substantial and will have implications on the R1 policy by highlighting the need to recognise plants, disadvantaged in terms of size or location, and the need to apply correction factors to scale the calculated R1 scores for such facilities.

CHAPTER 5 – CHP ANALYSIS OF EFW OPERATIONS

5.1 INTRODUCTION

Preceding chapters have analysed the R1 formula and highlighted some shortcomings of the formula. Analysing the formula since its introduction and its significance in the EU's WFD [18], one can understand that it is politically motivated. However, there are other efficiency formulae that can be applied to EfW facilities. These have been summarised by Gohlke [27], wherein countries like Switzerland, Netherlands, Austria and Japan are listed to have their own formulae as per their own regulations. Not all of them are specific to EfW facilities. For example, that of Austria is a general efficiency requirement for combined heat and power generation, which includes the production of heat and power in EfW plants [27].

With reference to the processes described in Chapter 3, a conventional combustion system incinerates waste. The energy content or caloric value of the waste is transferred to hot flue gases escaping the furnace. Flue gases are created during the combustion of waste. These gases contain the majority of the available fuel as heat. This heating potential is used in the boiler for the necessary heat transfers and recovery. Steam is formed and is used to either generate electricity via a steam turbine, or heat, or both via a Combined Heat and Power (CHP) configuration. The statistics, available from various European Commission reports on thermal treatment of waste, and provide evidence on the operational popularity of Combined Heat and Power (CHP) plants. This is in large partly due to substantial demand of thermal energy in very cool climate zones or demand of heat from dense, close-knitted industrial zones or district heating networks.

CHP, as the name suggests, is the simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system [45]. This form of 'useful-energy' production is also known as co-generation. The overall processes and infrastructure related to production of electricity is complicated and is considered an expensive form of energy. Electricity production generates thermal losses, which if not recovered by CHP, demonstrates a poor utilization of fuel resources [32]. Heat is comparatively cheaper to produce. However, its supply is largely dependent on the availability and proximity of site to the consumers. The infrastructure quality of the heat distribution network is vital to keep heat losses to a minimum and maintain an overall optimum net efficiency figure. CHP systems consist of a number of individual components, such as the prime mover (heat engine), generator, heat recovery and electrical interconnection which can be configured into an integrated whole [75].

The objective of this Chapter is to present a comparison of results between the more general CHP efficiency formula and the EU R1 formula. The data is extracted from the case studies covered in Chapter 3. The impact of variance in operating conditions on the overall efficiency outcome is analysed. A theoretical analysis is then presented to demonstrate the influence on the R1 outcome. Section (5.2) covers the CHP efficiency conventions and presents the formulas in R1 parameter terms. Section (5.3) applies the CHP formulas to the case study, Beddington EfW and San Zeno EfW and discusses the results. Section (5.4) discussed hypothetical scenarios that can result in unlocking process efficiencies, primarily focused to configurations that can be adopted to improve EfW plant's overall efficiency scores.

This Chapter contributes to body of knowledge by analysing the efficiency of EfW plants using CHP conventions, but with R1 terms such as E_w, E_p, and E_f. This chapter has investigated an efficiency formula that can be generally used for CHP applications and compares this to the R1 outcome. It considers the figures based on thermodynamic principles such as energy efficiency (η) and power loss coefficient.

5.2 CHP EFFICIENCY

Separate Heat and Power (SHP) is a conventional method of generation and distribution of electricity and heat. Power is generated at a power station and added to the network. Heat on the other hand is generated at a heating station and added to a district heating network. Co-generation; a simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) has advantages over SHP. The key advantage is that higher efficiencies can be achieved for the same output. As highlighted by Thomas et al. [45], CHP typically requires only ¾ of the primary energy SHP systems require. CHP systems typically consume less fuel than SHP to generate the same output. Figure 6, from Energy Solutions Centre [75], shows that a typical CHP system can reduce energy requirements by 40 percent compared to separate production of heat and power.

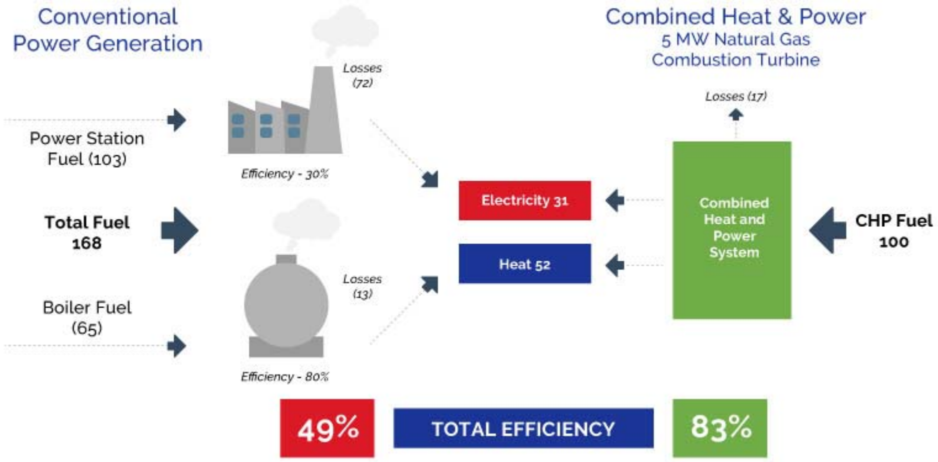


Figure 6 - Combined Heat and Power vs. Conventional Power Generation [75]

For 100 units of input fuel, CHP converts 83 units to useful energy. 31 units of this total constitutes the electricity output and 52 units are for useful thermal energy, i.e. hot water or steam. Traditional separate heat and power components require 168 units of energy to accomplish the same outcome. This also has a net beneficial impact on emissions. Efficiency formula in CHP systems captures energy content of both electricity and usable steam. The efficiency of a CHP system is given by the net electrical output added to the net useful thermal output divided by the total fuel consumed in the production of electricity and steam. This was given as Equation (2.12) in Chapter 2. Equation (2.12), when expressed using the terms used in the R1 formula, can be represented using Equation (5.1).

$$EFF_{TOTAL} = \frac{E_{p-el-\mathrm{int}} + E_{p-el-\mathrm{exp}} + E_{p-ht-\mathrm{int}} + E_{p-ht-\mathrm{exp}}}{E_w + E_f} \tag{5.1}$$

where

- $E_{p-el-\mathrm{int}}$ is electricity produced and used internally
- $E_{p-el-\mathrm{exp}}$ is electricity delivered to a third party
- $E_{p-ht-\mathrm{int}}$ *is h*eat produced and used internally
- $E_{p-ht-\mathrm{exp}}$ *is* steam delivered to a third party
- $\mathrm{E_w}$ is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ year^{-1})
- $\mathrm{E_f}$ is the annual energy input to the system from fuels impacting steam production (GJ year^{-1})
- $\mathrm{EFF_{Total}}$ *is the Energy Efficiency in an EfW plant*

5.2.1 Federal Energy Regulatory Commission (FERC) efficiency value for EfW plants

A critical factor needs to be highlighted here. Although the CHP formula of Equation (5.1) provides a means to capture the energy content of electricity and steam (heat), it however does not reflect the qualities of each. Studies have historically evidenced that the useful application of electricity is higher relative to steam, and hence the use of the equivalence factors in R1 for electricity and heat respectively.

Further it should be noted that while the R1 formula captures the loss of energy from the input fuel, due to equipment efficiencies, within the CHP formula, that is not accounted for. As per [45], in order to account for the differences in the quality of two energy forms, the Public Utilities Regulatory Policies Act of 1978 (PURPA) discounts half of the thermal energy in its efficiency calculation referred to as the FERC methodology. The FERC methodology considers the values of different forms of energy in the calculation of the CHP efficiency. The FERC efficiency value for CHP applications EFF_{FERC} is given by Equation (5.2).

$$EFF_{FERC} = \frac{P + \frac{Q}{2}}{F} \tag{5.2}$$

Where

- $P - Net \quad Power \quad Output \quad from \quad CHP \quad system$
- $Q - Net \quad Thermal \quad Output \quad from \quad CHP \quad system$
- $F - Fuel \quad Consumed \quad (Waste \quad and \quad Start-up \quad Fuel)$
- $\mathrm{EFF_{FERC}}$ *is the Energy Efficiency as per PURPA of EfW plant*

The FERC efficiency value of Equation (5.2) when expressed using the R1 terms can be represented using Equation (5.3). Although it is not proven whether the standard, EFF_{FERC} was arbitrarily set, this methodology reduces the thermal energy by half, i.e Q/2 and hence applies a weightage in comparison to generated power. Equation (5.3) is a contribution of this Thesis and has been developed to present the FERC efficiency value of EfW plants using R1 terms for its constituents.

$$EFF_{FERC} = \frac{(E_{p-el-\mathrm{int}} + E_{p-el-\exp}) + \frac{(E_{p-ht-\mathrm{int}} + E_{p-ht-\exp})}{2}}{E_w + E_f} \tag{5.3}$$

where

- $E_{p-el-\mathrm{int}}$ is electricity produced and used internally
- $E_{p-el-\exp}$ is electricity delivered to a third party
- $E_{p-ht-\mathrm{int}}$ *is h*eat produced and used internally
- $E_{p-ht-\exp}$ *is* steam delivered to a third party
- $\mathrm{E_w}$ is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)
- $\mathrm{E_f}$ is the annual energy input to the system from fuels impacting steam production (GJ/year)

$\mathrm{EFF_{FERC}}$ *is the Energy Efficiency as per PURPA of EfW plant*

5.2.2 Fuel Utilization Effectiveness (FUE) of an EfW plant

CHP efficiency can also be gauged as effective electrical efficiency, also known as the Fuel Utilization Effectiveness (FUE). The CHP efficiency in this scenario is the ratio of net electrical output to net fuel consumption, where the net fuel consumption excludes the portion of fuel that goes to producing useful heat output. The fuel used to produce useful heat is calculated assuming a typical boiler efficiency of 80%. The formula for the FUE is shown by Equation (5.4). The formula specifically measures the efficiency of generating power through the incremental fuel consumption of the CHP system.

$$FUE = \frac{P}{F - Q / EFF_Q} \tag{5.4}$$

Where

- P – *Net Power Output from CHP system*
- Q – *Net Thermal Output from CHP system*
- F – *Fuel Consumed (Waste and Start-up Fuel)*
- EFF_Q – *Efficiency of displaced thermal generation*
- FUE – *Fuel Utilization Effectiveness*

FUE, in R1 terms can be represented as in Equation (5.5).

$$FUE = \frac{E_{p-el-\text{int}} + E_{p-el-\exp}}{(E_w + E_f) - \left(\frac{E_{p-ht-\text{int}} + E_{p-ht-\exp}}{EFF_Q}\right)} \tag{5.5}$$

where

- $E_{p-el-\text{int}}$ is electricity produced and used internally (GJ/year)
- $E_{p-el-\exp}$ is electricity delivered to a third party (GJ/year)
- $E_{p-ht-\text{int}}$ *is h*eat produced and used internally
- $E_{p-ht-\exp}$ *is* steam delivered to a third party
- $\mathrm{E_f}$ is the annual energy input to the system from fuels impacting steam production (GJ/year)
- $\mathrm{E_w}$ is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)
- EFF_Q is the efficiency of the displaced thermal generation/heat
- FUE is the Fuel Utilization Effectiveness

5.2.3 Electric, thermal and total efficiencies of EfW plants

Inspired by the work given in Frangopoulos [46], three new efficiency measures can be derived for EfW plants. Equation (5.6) and Equation (5.7) enables the calculation of electric; thermal efficiencies of an EfW plant consecutively. Equation (5.8) provides the calculation for the total CHP efficiency. Equations (5.6 to 5.8) are applicable to CHP-enabled EfW systems.

$$\mu_{el} = \frac{E_{P\_el}}{E_w + E_f} \tag{5.6}$$

where

- E_{P-el} is total electricity produced by the unit in a certain period of time, used internally and delivered to a third party (GJ/year)
- E_f is the annual energy input to the system from fuels impacting steam production (GJ/year)
- E_w is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)

$$\mu_{th} = \frac{E_{P\_Heat}}{E_w + E_f} \tag{5.7}$$

where

- E_{P-Heat} is total useful heat produced by the unit in a same period of time as E_{P_el}, used internally and delivered to a third party (GJ/year)
- E_f is the annual energy input to the system from fuels impacting steam production (GJ/year)
- E_w is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)

$$\mu_{CHP} = \mu_{el} + \mu_{th} \tag{5.8}$$

where

- μ_{el} is electric efficiency
- μ_{th} is t*hermal* efficiency

5.2.4 EfW power-to-heat ratio

An essential concept related to the CHP efficiency is the power-to-heat ratio. This ratio indicates the proportion of power (electrical or mechanical energy) to heat energy (steam or hot water) produced in the CHP system, as expressed by R1 terms of Equation (5.9). The power-to-heat ratio is a variable and this study attempts to utilize this factor to draw a set of comparisons and quantify the findings. Efficiencies of power and steam generation systems vary as per their configurations, makes or models of boiler, turbine and generator systems used. Hence, they have an important bearing on the overall CHP efficiency of a system. This can be considered in 'full cogeneration mode' when there is no waste heat as mentioned in [46]. In full cogeneration mode, $E_{P\text{-}heat}$ equals to the overall heat in a CHP system (H) which includes the heat output as well as waste heat ($H_{CHP} + H_{Waste}$) and $E_{P\_el} = E$. Equation (5.9) provides the power to heat ratio in full cogeneration mode.

$$C_{CHP} = \frac{E_{P\_el}}{E_{P\_Heat}} \tag{5.9}$$

where

- E_{P_el} is total electricity produced by the unit in a certain period of time, used internally and delivered to a third party (GJ/year)
- E_{P_Heat} is total useful heat produced by the unit in a same period of time as E_{P_el}, used internally and delivered to a third party (GJ/year)
- C_{CHP} is power to heat ratio when in full cogeneration mode

In the full cogeneration scenario, the 'power station' is now being operated as a 'CHP facility' and this scenario differs, since the configuration now directs 'useful heat' instead of heat being wasted or rejected by the system. The steam condensing turbine continues to generate electricity. However, it is lesser than when in complete 'power' mode due to steam bleed at the turbine. Ideal system efficiency calculations, based on heat and mass balance principles, can be used to determine the overall energy transfer process and hence lead to a better understanding of useful work done.

For this study, as mentioned by Frangopoulos [46], this is achieved by splitting the cogeneration unit in CHP and non-CHP parts leading us to determine the electricity production, the fuel consumption, and the efficiencies of each part. By incorporating heat balance assumptions and coupling it with the equations presented, this method also provides an understanding of the overall CHP system efficiency. The study assumes unavoidable losses in each part, and useful heat that gets wasted is considered only for the non-CHP part attributable to the losses associated with continuous electricity generation. Consequently, this leads to an understanding that in cogeneration units there is loss of total electric power generated due to 'useful heat' production, thus a fundamental assumption is made wherein the non-CHP part operates with electric efficiency equal to the efficiency of the complete system when in the 'Power' only operation, i.e. no useful heat production.

5.2.5 EfW power loss coefficient

CHP efficiency is a composite measure of the CHP fuel conversion capability and is expressed as the ratio of net output to fuel consumed. Overall CHP efficiency will vary depending on size (capacity) and power-to-heat ratio. Combustion turbines achieve higher efficiencies at greater size and with higher power-to-heat ratios [45]. Hence, in effect a power loss coefficient can be defined, whereby the production of useful heat results in loss of electrical or mechanical power [46]. This phenomenon is mainly associated with condensing extraction steam turbines which features as the prime mover in a CHP system. Equation (5.10) represents the power loss coefficient.

$$\beta = \frac{E_{MAX} - E}{E_{P\_Heat}} \tag{5.10}$$

where

•E_{MAX} is maximum electricity produced by the unit when E_{P_Heat}=0 in (GJ/year)

•E is e*lectricity* produced by the unit in a specific period of time as E_{P_Heat}, used internally and delivered to a third party (GJ/year)

•E_{P-Heat} is useful heat produced by the unit in a same period of time as E , used internally and delivered to a third party (GJ/year)

•β is *power loss coefficient*

The power loss coefficient; β, is not a constant and can be seen as a function of E_{P_Heat}. E_{MAX} is the maximum electricity produced, which in a CHP plant, would be the operating point when it is in 'power only' mode or when the mode of operation is fully condensed turbine. At that mode, there is no E_{P_heat} and β = 0. When the flow of extracted steam is zero, all input energy is used for power generation. In that case, the plant is not a cogeneration plant as it is not cogenerating both heat and power. It is a power station and therefore, in cogeneration mode, there is dependence between increase in the heat output and decrease in the electrical power output. When useful heat is being produced, E_{MAX} can be represented using Equation (5.11). As mentioned in [47], the power loss coefficient (β) should be determined on the basis of measurements in the CHP plant under consideration, or in the absence of physical data, on the basis of calculations. Power loss coefficient (β) depends upon technical parameters related to extracted steam pressure and temperature, efficiency of all turbine stages and the vacuum in the condenser.

$$E_{MAX} = \beta \times E_{P\_Heat} + E \tag{5.11}$$

where

- E_{MAX} is maximum electricity produced by the unit when E_{P_Heat}=0 in (GJ/year)
- E is e*lectricity* produced by the unit in a specific period of time as E_{P_Heat}, used internally and delivered to a third party (GJ/year)
- E_{P-Heat} is useful heat produced by the unit in a same period of time as E , used internally and delivered to a third party (GJ/year)

For reliable calculations, all parameters must be known. Experimentally, it can be deduced without interference to the production process and must be done taking a log of measurements over the duration of an hour. One of the case studies to be discussed in this Chapter, the Beddington facility assumed a constant figure of β = 1/4, for its estimation purposes in the plant's planning support documentation Virodor [53]. Hence, in effect Equation 5.12 also holds true when in CHP mode.

$$E = E_{MAX} - \beta \times E_{P\_Heat} \tag{5.12}$$

where

- E_{MAX} is maximum electricity produced by the unit when E_{P_Heat}=0 in (GJ/year)
- E is e*lectricity* produced by the unit in a specific period of time as E_{P_Heat}, used internally and delivered to a third party (GJ/year)
- E_{P-Heat} is useful heat produced by the unit in a same period of time as E , used internally and delivered to a third party (GJ/year)

However, the β value is likely to change during the actual CHP operation. This is supported by Urošević et al. [47], where it is stated that in real conditions, the pressure and temperatures in well-guided processes can deviate up to around 1%, affecting the power loss coefficient by some 5%. This is one basis, for calculating the upper and lower performance levels of a CHP enabled EfW plant for power loss coefficient in the range $0.95\beta < \beta < 1.05\beta$. Hence, it can further be deduced that the electrical efficiency measure given by Equation (5.6) can be represented as in Equation (5.13).

$$\mu_{el\_MAX} = \frac{E_{MAX}}{E_w + E_f} \tag{5.13}$$

where

- E_{MAX} is total electricity produced by the unit in a certain period of time, used internally and delivered to a third party (GJ $year^{-1}$)
- E_f is the annual energy input to the system from fuels impacting steam production (GJ $year^{-1}$)
- E_w is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ $year^{-1}$)

The power loss coefficient can be compared to the plants heat to power ratio, as they are linked by principle. It is a number that as mentioned by Urošević et al. [47] represents the balance between increasing useful heat energy and reducing the electrical energy generated.

5.3 CHP APPLICATION ON CASE STUDY

The following subsections evaluates the application of the formulas on the case studies discussed in Chapter 3. These include the power-to-heat ratio, power loss coefficient, FERC and FUE analysis. The work given below demonstrates the application of these newly developed measures as applied to EfW plants.

5.3.1 Beddington EfW – CHP Analysis

Beddington EfW incineration facility, introduced in Chapter 3, is a plant that is CHP enabled. The plant can export heat in the future as part of a district heating scheme. It is designed to export 20 MW thermal power and 17 MW electric power when in CHP mode [53]. Around 2,517 GJ of electrical energy is imported annually for plant unavailability and 1,097 GJ for plant start-ups. The plant operates for 7796 hours/year.

As part of the operator's planning submission, an estimation of the plant's predicted R1 efficiency (without heat export) was conducted and presented to the Waste Planning Authority [53]. Appendix 2 in [53] provides a brief review of the plant's R1 assessment. R1 predicted was 0.686 [53], classifying the facility as a 'recovery' plant. This section presents the investigation on plant performance when considering heat export. Further performance investigation is carried out by applying the overall CHP efficiency formula. Upon compilation of the data for overall CHP efficiency, this is put into context with the R1 outcome. Steam turbine configurations are explored, essentially referring to the Virodor report [53] where it states that a drop in electrical export by up to 20% can be experienced when switching to CHP mode. As per the report, the maximum 'useful' heat that can be extracted from the turbine is 20 MW. Heat to power ratio has been reported as 4:1, i.e. for each 1000 kW of heat generated there is a decrease of 250 kW of electricity production. Effectively this is the 'power loss coefficient' associated with generation of useful heat which results in loss of power. Plants equipped with back-pressure steam turbine (i.e. gas turbines or internal combustion engines) electricity generation remains stable even if useful heat energy is increased or decreased. Essentially because input energy is first transformed into electrical energy and afterwards into useful heat energy through the steam bleed from the turbine. The processes are carried out one after the other [47]. In such plants, for increasing useful heat energy, one has to increase the surface area of the heat exchanger in order to generate more useful heat after the back-pressure turbine, but without changing the levels of power generation.

In the CHP mode, the turbine used can be a back-pressure turbine, condensing turbine or an extracting condensing turbine. The power generation is dependent upon the extracted quantity of steam and its pressure, i.e. location where the steam has been extracted. The Beddington facility uses an extracting condensing turbine. It is assumed that the extracted steam is useful heat and the energy at the inlet of the steam turbine is unchanged, which is being generated by the incineration of waste as primary fuel. Essentially, a simultaneous operation with the generation of heat and power. Since, it is a two part process, the formulas suggest the amount of energy generated as electrical energy when in power only mode must be equivalent to the amount of heat and power produced in the CHP mode. Effectively, the energy balance suggests that the maximum electrical power from the turbine in power only mode must be equivalent to the 'electrical' and 'useful' heat produced from the CHP operation. This is in reference to equation 5.11. As mentioned in [47], power loss is dependent upon extracted steam pressure and temperature, the efficiency of all turbine stages, and the vacuum in the condenser. For accurate calculation, it is important to know all the variables.

For this case study, some fundamental assumptions are necessary to have an accurate understanding of the energy balance and overall improvement in system efficiency. This is also necessary in order to work through without temperature and pressure values.

The electric efficiency of the turbine from the ‘power’ only mode to the ‘CHP’ mode remains unchanged. The decrease in heat utilized for power generation, when switching to ‘CHP’ mode from Power-only mode, is due to ‘steam bleed’ at the turbine and is directed to the boiler contributing to the overall ‘useful-heat’ production. When in CHP mode, the maximum electricity that can be extracted from the turbine is not equal to the electricity produced when in Power-only mode. In optimum CHP mode, the turbine and other equipments related to power generation is not loaded 100%. Based on these assumptions, herein a comparison can be drawn with two possible CHP operations in addition to the R1 calculations presented in Section 4.

$$Power\ Only\ \left(E_{P\_el}\right)$$

$$= 193{,}820\ MWh\ (equivalent\ to\ 26.17\ MW\ and\ 503{,}933\ MWh\ equivalent)$$

$$CHP = \ Power\ \left(E_{P\_el}\right) + Thermal\ \left(E_{P\_th}\right) = 156{,}789\ MWh + 148{,}124\ MWh$$

$$= 304{,}913\ MWh\ (equivalent\ to\ 21.17\ MW\ electrical\ and\ 20\ MW\ Thermal)$$

When equivalency for heat and electricity is considered this is equal to sum of 570,588 MWh.

$$Power\ Lost\ in\ Energy\ Produced\ (in\ moving\ to\ CHP\ from\ Power\ Only)$$

$$= 37{,}031\ MWh\ (equivalent\ to\ 5\ MW\ electrical\ loss\ and\ 20\ MW\ Thermal\ gain)$$

The values are extracted from the plant data presented in Chapter 3 and calculations presented in Chapter 4. This suggests that the electric efficiency in CHP mode decreases, while the thermal efficiency increases. Figure 7 is a summarized table, of the Power-only and CHP mode as inferred from the Virodor [53] documents and complements the equations presented in Section 4.

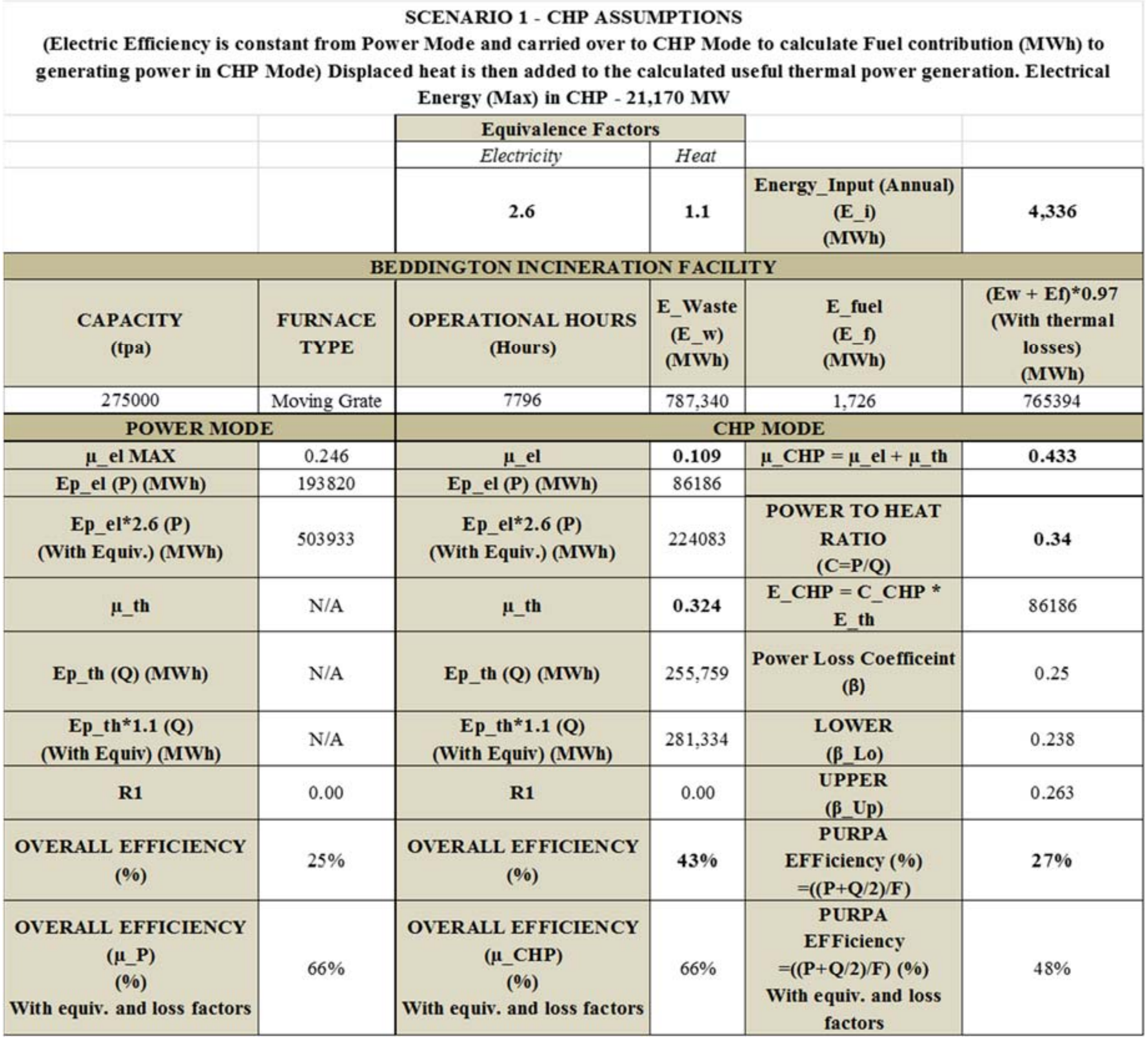
BASE SCENARIO - With reference to the Existing R1 Calculations of Power-Only and CHP Mode					
		Equivalence Factors			
		Electricity	*Heat*		
		2.6	1.1	Energy_Input (Annual) (E_i) (MWh)	4,336
BEDDINGTON INCINERATION FACILITY					
CAPACITY (tpa)	FURNACE TYPE	OPERATIONAL HOURS (hours)	E_Waste (E_w) (MWh)	E_fuel (E_f) (MWh)	(Ew + Ef)*0.97 (With thermal losses) (MWh)
275000	Moving Grate	7796	787,340	1,726	765394
POWER MODE		CHP MODE			
µ_el MAX	0.246	µ_el	**0.199**	µ_CHP = µ_el + µ_th	**0.386**
Ep_el (P) (MWh)	193820	Ep_el (P) (MWh)	156789		
Ep_el*2.6 (P) (With Equiv.) (MWh)	503933	Ep_el*2.6 (P) (With Equiv.) (MWh)	407652	POWER TO HEAT RATIO (C=P/Q)	1.059
µ_th	N/A	µ_th	**0.188**	E_CHP = C_CHP * E_th	156789
Ep_th (Q) (MWh)	N/A	Ep_th (Q) (MWh)	148,124	Power Loss Coefficeint (β)	0.25
Ep_th*1.1 (Q) (With Equiv) (MWh)	N/A	Ep_th*1.1 (Q) (With Equiv) (MWh)	162,936	LOWER (β_Lo)	0.238
R1	0.65	R1	0.74	UPPER (β_Up)	0.263
OVERALL EFFICIENCY (%)	25%	OVERALL EFFICIENCY (%)	**39%**	PURPA EFFiciency =((P+Q/2)/F) (%)	**29%**
OVERALL EFFICIENCY (µ_P) (%) With equiv. and loss factors	66%	OVERALL EFFICIENCY (µ_CHP) (%) With equiv. and loss factors	75%	PURPA EFFiciency =((P+Q/2)/F) (%) With equiv. and loss factors	64%

Figure 7 - R1 Calculation and CHP Calculation based on the plant data in Section 3 and calculations in Section 4

There can be a fundamental flaw in this understanding, as the difference in energy loss between power only mode and CHP mode to produce electricity is 37,031 MWh. This lost or diverted energy in theory translates to the 5 MW power ‘drop’ due to useful heat production in CHP mode. However, for the useful heat production, the calculations gave us a result of 148,124 MWh and this seems erroneous as its too low. The subsequent tables justify a higher figure and this should inturn balance out the total heat produced which has useful affects.

The calculation of the heat to power ratio using Equation 5.9 gives a result of 1.06, which seems erroneous as ideally the power to heat ratio should be lesser than 1 as more energy, i.e. heat is lost in producing electricity and not vice versa. This ratio of generated power over useful heat forms the foundation of extracting and presenting data on the energy balance in the subsequent tables and thus the efficiency figures. The value of the useful heat production seems erroneous and too low as per the Virodor documents and subsequent tables Figure 8 and Figure 9 have been introduced as possible scenarios on what the actual figure should be based on an understanding of energy balance. The FERC efficiency value as per Equation 5.3 is 29% and overall efficiency as per equation 5.8, μ_{CHP} stands at 39%.

Figure 8 is the first comparative scenario which takes into consideration the electric efficiency from the power-only mode to calculate the fuel, i.e. generated power in order to determine the maximum power available from the turbine in CHP mode.



SCENARIO 1 - CHP ASSUMPTIONS
(Electric Efficiency is constant from Power Mode and carried over to CHP Mode to calculate Fuel contribution (MWh) to generating power in CHP Mode) Displaced heat is then added to the calculated useful thermal power generation. Electrical Energy (Max) in CHP - 21,170 MW

		Equivalence Factors			
		Electricity	*Heat*		
		2.6	**1.1**	**Energy_Input (Annual) (E_i) (MWh)**	**4,336**
BEDDINGTON INCINERATION FACILITY					
CAPACITY (tpa)	**FURNACE TYPE**	**OPERATIONAL HOURS (Hours)**	**E_Waste (E_w) (MWh)**	**E_fuel (E_f) (MWh)**	**(Ew + Ef)*0.97 (With thermal losses) (MWh)**
275000	Moving Grate	7796	787,340	1,726	765394
POWER MODE		**CHP MODE**			
µ_el MAX	0.246	**µ_el**	**0.109**	**µ_CHP = µ_el + µ_th**	**0.433**
Ep_el (P) (MWh)	193820	**Ep_el (P) (MWh)**	86186		
Ep_el*2.6 (P) (With Equiv.) (MWh)	503933	**Ep_el*2.6 (P) (With Equiv.) (MWh)**	224083	**POWER TO HEAT RATIO (C=P/Q)**	**0.34**
µ_th	N/A	**µ_th**	**0.324**	**E_CHP = C_CHP * E_th**	86186
Ep_th (Q) (MWh)	N/A	**Ep_th (Q) (MWh)**	255,759	**Power Loss Coefficeint (β)**	0.25
Ep_th*1.1 (Q) (With Equiv) (MWh)	N/A	**Ep_th*1.1 (Q) (With Equiv) (MWh)**	281,334	**LOWER (β_Lo)**	0.238
R1	0.00	**R1**	0.00	**UPPER (β_Up)**	0.263
OVERALL EFFICIENCY (%)	25%	**OVERALL EFFICIENCY (%)**	**43%**	**PURPA EFFiciency (%) =((P+Q/2)/F)**	**27%**
OVERALL EFFICIENCY (µ_P) (%) With equiv. and loss factors	66%	**OVERALL EFFICIENCY (µ_CHP) (%) With equiv. and loss factors**	66%	**PURPA EFFiciency =((P+Q/2)/F) (%) With equiv. and loss factors**	48%

Figure 8 - R1 Calculation and CHP Calculation based on the plant data in Section 3 and calculations in Section 4, with focus on heat balance for power generation and μ_{el_MAX} is constant

Numercially when compared, it appears as though the electric efficiency is lower, however this is only due to less heat contributing to the generation of electricity, whereas balance is being diverted through steam bleed from the turbine for ‘useful-heat’. In the CHP operation, the electric efficiency, Equation 5.6 is used to determine the fuel consumed that contributes to the reported maximum power available in CHP mode, i.e. 21.17 MW. The difference in energy loss between the power only mode and CHP mode to produce electricity is 107,850 MWh. This energy is assumed to contribute to useful heat production in CHP mode. Hence the total energy available towards useful heat production is 255,974 MWh. This is the maximum thermal power available from CHP system and is equivalent to 5 MW electrical power.

$$CHP = \ Power\ (E_{P\_el}) + Thermal\ (E_{P\_th}) = 86{,}186\ MWh + 255{,}759\ MWh$$

$$= 341{,}945\ MWh\ (equivalent\ to\ 21.17\ MW\ electrical\ and\ 20\ MW\ Thermal)$$

The total useful power from the system to generate power and heat is 341,945 MWh (505,417 MWh with equivalency factors). İt is then approximately equal to the equivalent figure of 503,933 MWh in the Power-only mode. The power to heat ratio as per Equation 5.9 gives a result of 0.3, which is closer to the reported power loss coefficient of the system 0.25. The FERC efficiency value as per Equation 5.3 is 27% and overall efficiency as per Equation 5.8, Overall Efficiency which represents the ratio (μ_{CHP}) stands at 43%.

Figure 9 is the second comparative scenario which takes into consideration the conventional calculation of electric efficiency in CHP mode and adds to useful thermal energy production the difference in energy loss between the power only and CHP modes to produce electricity of 37,031 MWh. This energy is assumed to also contribute to useful heat production in the CHP mode. Hence, the total energy available towards useful heat production is 185,155 MWh. This is the maximum thermal power available from CHP system and is equivalent to 5 MW electrical power. The power to heat ratio as per equation 5.9 gives a result of 0.8468, which is lower than 1, yet on the upper end and not closer to the power loss coefficient value of the system, 0.25. The FERC efficiency value as per Equation 5.3 is 32% and overall efficiency which represents the ratio as per Equation 5.8, μ_{CHP} at 0.4334 which is 43% Overall Efficiency.

SCENARIO 2 - CHP ASSUMPTIONS **(Electric efficiency is not constant and calculation of energy utilised as per convention, however adding displaced heat to useful thermal power generation) - Electrical Energy (Max) in CHP - 21,170 MW**					
		Equivalence Factors			
		Electricity	*Heat*		
		2.6	**1.1**	**Energy_Input (Annual) (E_i) (MWh)**	**4,336**
BEDDINGTON INCINERATION FACILITY					
CAPACITY (tpa)	**FURNACE TYPE**	**OPERATIONAL HOURS (hours)**	**E_Waste (E_w)**	**E_fuel (E_f) (MWh)**	**(Ew + Ef)*0.97 (With thermal losses) (MWh)**
275000	Moving Grate	7796	787,340	1,726	765394
POWER MODE		**CHP MODE**			
µ_el MAX	0.246	**µ_el**	**0.199**	**µ_CHP = µ_el + µ_th**	**0.4334**
Ep_el (P) (MWh)	193820	**Ep_el (P) (MWh)**	156789		
Ep_el*2.6 (P) (With Equiv.) (MWh)	503933	**Ep_el*2.6 (P) (With Equiv.) (MWh)**	407652	**POWER TO HEAT RATIO (C=P/Q)**	**0.847**
µ_th	N/A	**µ_th**	**0.235**	**E_CHP = C_CHP * E_th**	156789
Ep_th (Q) (MWh)	N/A	**Ep_th (Q) (MWh)**	185,155	**Power Loss Coefficeint (β)**	0.25
Ep_th*1.1 (Q) (With Equiv) (MWh)	N/A	**Ep_th*1.1 (Q) (With Equiv) (MWh)**	203,671	**LOWER (β_Lo)**	0.238
R1	0.72	**R1**	0.00	**UPPER (β_Up)**	0.263
OVERALL EFFICIENCY (%)	25%	**OVERALL EFFICIENCY (%)**	**43%**	**PURPA EFFiciency =((P+Q/2)/F) (%)**	**32%**
OVERALL EFFICIENCY (µ_P) (%) With equiv. and loss factors	66%	**OVERALL EFFICIENCY (µ_CHP) (%) With equiv. and loss factors**	80%	**PURPA EFFiciency =((P+Q/2)/F) (%) With equiv. and loss factors**	67%

Figure 9 - R1 Calculation and CHP Calculation based on the plant data in Section 3 and calculations in Section 4, not considering constant electric efficiency from Power only mode and adding displaced thermal to useful thermal energy production

Given the principles of heat balance and understanding a significant amount of heat is wasted in the electrical energy conversion process, it is Scenario 1 (Figure 8) that holds true in terms of CHP analysis and considering the equivalent energy output balance scenario.

In actual CHP operation, the work in [47] states that in real conditions, the power loss coefficient can vary by 5% with differences in pressure and temperature by 1%. This is applied to the study herein and results in the range $0.2375 < \beta < 0.2625$. The objective herein is to analyse the maximum useful energy that can be extracted from the system with application of varying heat balance operational modes. Figure 10 represents R1 improvement with the variance in the power loss coefficient over the range possible by varying the temperature and pressure parameters. This only depicts the potential optimum improvement that is possible in R1 by extracting the maximum useful heat from the turbine based on the values presented in base case.

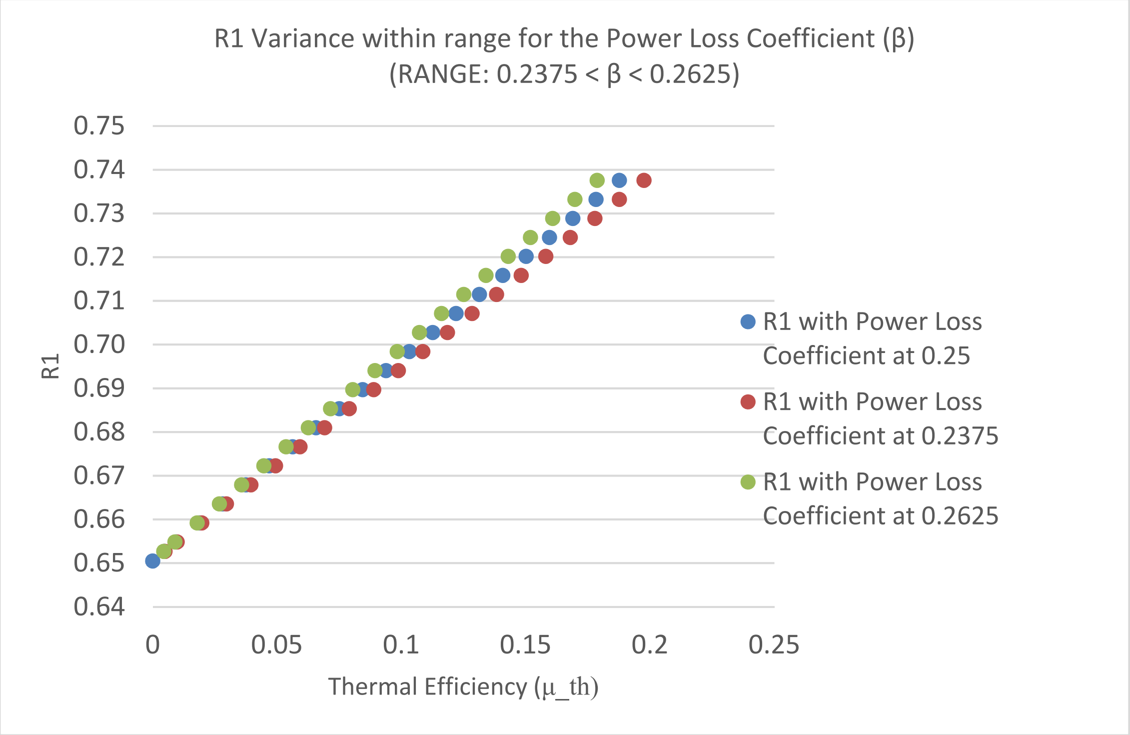


Figure 10 - R1 Variance within the range of +/-5% Power Loss Coefficient (β)

The overall efficiency of the system, μ_{CHP} given by Equation (5.8), is the sum of electrical and thermal efficiencies in the CHP mode. For the Beddington plant, μ_{CHP} is 39% with $\mu_{el} + \mu_{th}$. It must be noted that equivalence factors have not been accounted in these calculations. When equivalence factors are accounted for, the CHP efficiency figures are higher and closer to the R1 ratio. With reference to cell blocks in Figure 7, please note the last two columns which list the Overall Efficiency (%) figures with and without equivalence and loss factors under the respective operating conditions.

It is evident that in the power-only mode, the overall efficiency figure is about 25% in comparison to the CHP mode when it is approximately 40%. Effectively, this proves the effectiveness of CHP-mode operation in terms of extracting optimum benefit from the facility. When the outcomes of these equations are compared to the R1 and the equivalence factors are applied, the calculated overall efficiency figure comes close to the R1 value. When in the power-only mode, the overall efficiency figure of 66% is comparative to the R1 outcome of 0.65. Similarly, in the CHP-mode; the efficiency outcome when considering with the equivalence factors is 75% and is comparative to the R1 outcome of 0.74. Figure 11 is a representation of varying β conditions applied to the data in Figure 7, the base scenario.

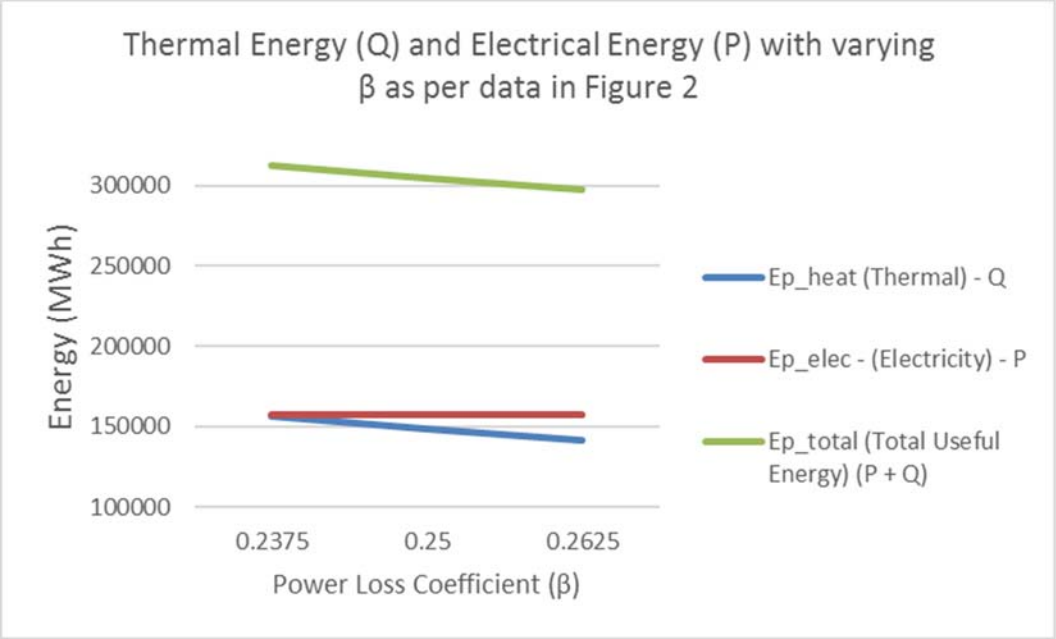


Figure 11 - Total Useful Energy with varying β conditions applied to data in Figure 7

5.3.2 San Zeno EfW – CHP Analysis

The second incineration plant analysed herein is the San Zero EfW facility in central Italy, which is designed to process 42,000 tpa of residual waste [33]. It is a smaller CHP facility, given its capacity and has been in operation since 2000. It is equipped with an adiabatic combustion chamber where temperatures maintained at above 1,100 °C to avoid the risk of corrosion. This is possible by introducing a large excess of combustion air, after the combustion chamber, the hot gases enter the heat recovery steam generator. Herein the first component is the evaporator (EV) that generates steam at about 250 °C and 40 bar. After the EV the gases enter the super heater (SH) increasing the saturated steam temperature to about 380 °C and eventually exchanges the residual heat in the economizer. The SH steam is expanded in a condensing turbine of 3000 kW electric capacity [33]. Condenser temperatures maintained at 50 °C by dry cooling towers, after which water is pumped to the degasser feed by a steam bleed from the turbine at 5 bar. In standard operating conditions, the amount of steam generated is 14,000 kg/h and the turbine net electrical output of about 2,400kW. As discussed, in Chapter 4, this plant is non-R1 compliant due to the economies of scale involved and primarily for its location in an area of insufficient heat demand.

It must be acknowledged the facility was designed for electrical power extraction only from waste combustion via a steam turbine. The author Di Maria et al. [33] in the investigative study presents an operational proposal that improves the EfW efficiency outcome, in an attempt to bring the R1 thermal efficiency figure closer to the set threshold. The team recommends, CHP can be realized through exploiting a given fraction of the saturated steam generated by the EV. The plant is designed to measure the energy content in waste through an online system that operates on the basis of mass and energetic balances concerning the amount of waste incinerated, the steam rate and its hentalpy (i.e. temperature and pressure) [33]. As per the thermodynamic principle any possible use of a fraction of the whole steam rate for the purposes of co-generation reduces the net electrical power generated by the turbine. The analysis assumed a linear relation between steam rate and power, similar to the analysis performed for the Beddington EfW in Section 5.3.1. Di Maria et al. [33] study assumes that steam rate and power is within 50% of the maximum turbine power reduction (i.e. 1,500 kW). The CHP aspect can be implemented through the introduction of an Organic Rankine Cycle (ORC). Essentially this suggests constant use of the co-generated heat at the steam turbine by diverting a fraction of steam to an external unit based on an ORC power unit. ORC systems, like in Figure 12, basically convert thermal energy to electrical energy and is based on the principle whereby a liquid is heated, causing it to evaporate, and the resulting gas is used to turn an engine, which is then connected to a generator, and thus creates power [76]. In this experimental analysis of San Zeno, the heat source is waste heat i.e., rejected heat from CHP system fueled by diesel and landfill gas. In a traditional ORC power unit, the working fluid is water, the evaporated gas steam, and the engine is a steam turbine. ORC technologies use working fluids which boil at much lower temperatures than water, allowing ‘power’ generation from 'low grade' heat sources.

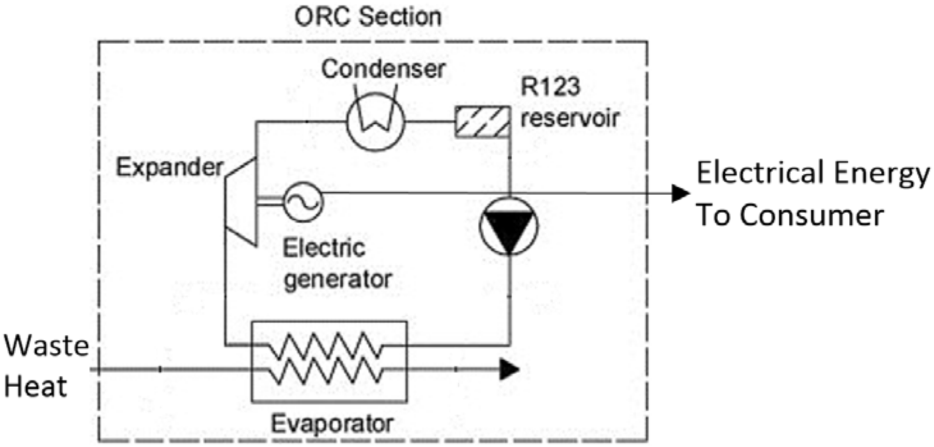
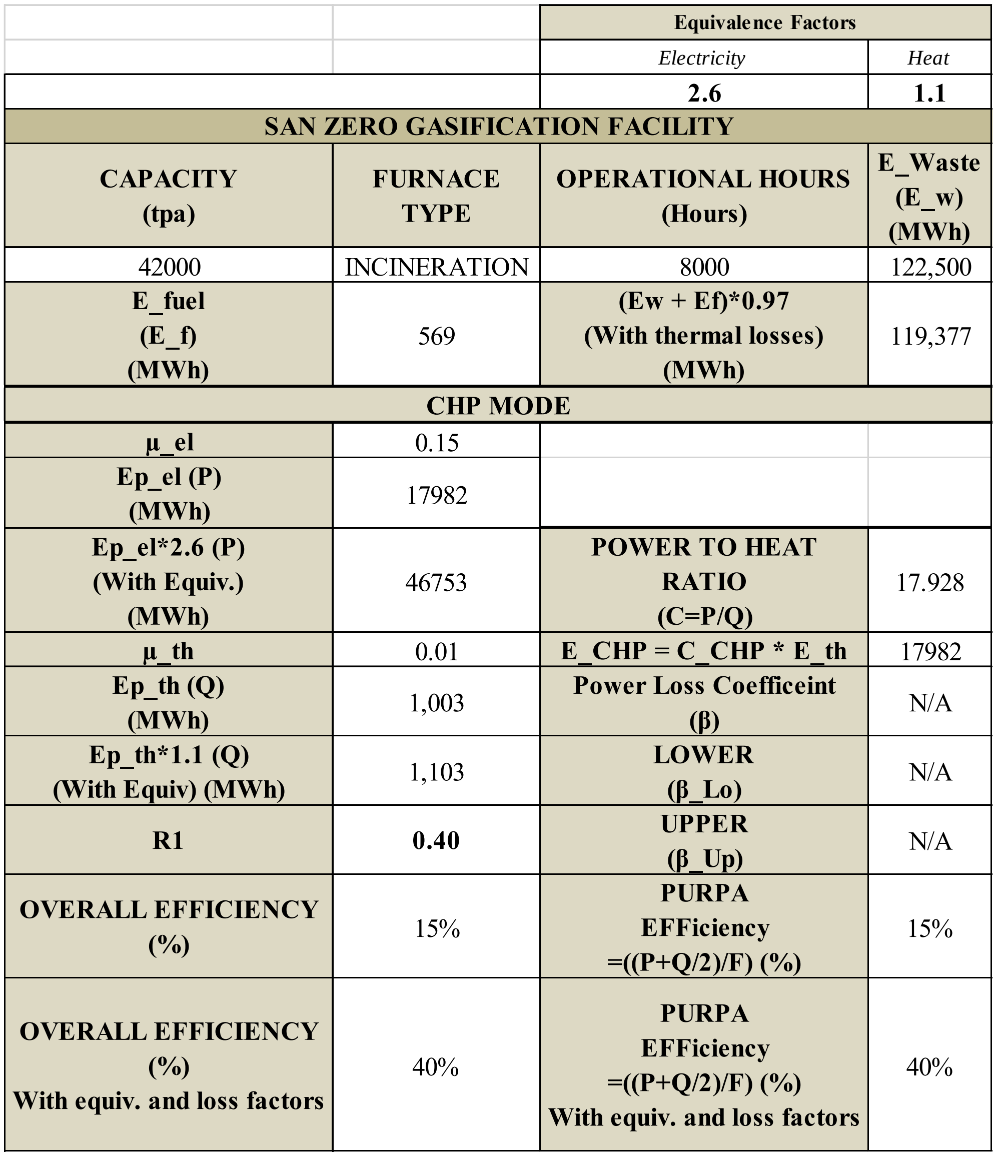


Figure 12 - ORC Model proposed for San Zeno EfW in the study by Di Maria et al. [31]

As explained by The New Energy Company (NewEnCo) [76] the working fluid in an ORC system is contained in a closed loop, such that the working fluid is condensed after it has been through the engine, and then recirculated. The engines used in ORC packages vary in type, including small turbines and purpose designed 'expander' units. Di Maria et al. [33] evaluated ORC performances based on energetic and mass balances. Utilizing ORC-models proposed in previous studies as mentioned by Di Maria et al. [33] and in compliance of the working fluid used, i.e. R123, the experiment gave positive results. It concluded under average operating conditions of the EfW about 2,900 kg/h of steam used for CHP can lead to energetic efficiencies closer to the R1 threshold.



		Equivalence Factors	
		Electricity	*Heat*
		2.6	**1.1**
SAN ZERO GASIFICATION FACILITY			
CAPACITY (tpa)	**FURNACE TYPE**	**OPERATIONAL HOURS (Hours)**	**E_Waste (E_w) (MWh)**
42000	INCINERATION	8000	122,500
E_fuel (E_f) (MWh)	569	**(Ew + Ef)*0.97 (With thermal losses) (MWh)**	119,377
CHP MODE			
μ_el	0.15		
Ep_el (P) (MWh)	17982		
Ep_el*2.6 (P) (With Equiv.) (MWh)	46753	**POWER TO HEAT RATIO (C=P/Q)**	17.928
μ_th	0.01	**E_CHP = C_CHP * E_th**	17982
Ep_th (Q) (MWh)	1,003	**Power Loss Coefficeint (β)**	N/A
Ep_th*1.1 (Q) (With Equiv) (MWh)	1,103	**LOWER (β_Lo)**	N/A
R1	**0.40**	**UPPER (β_Up)**	N/A
OVERALL EFFICIENCY (%)	15%	**PURPA EFFiciency =((P+Q/2)/F) (%)**	15%
OVERALL EFFICIENCY (%) With equiv. and loss factors	40%	**PURPA EFFiciency =((P+Q/2)/F) (%) With equiv. and loss factors**	40%

Figure 13 - San Zeno EfW - Calculated Parameters in Power and CHP mode and Application of Formulas for Comparison

This heat was used for feed and ORC able to produce up to 250 kW with an average electrical efficiency of about 13%, comparable to the one of the EfW in power only mode. ORC technology improves the overall efficiency of a system via waste heat recovery and produces no emissions.

When we compare the figures presented using the annual values of energy consumption and production presented in Figure 6 to the analysis figures presented from the study by Di Maria et al. [33], it can be seen they are similar. The calculations take in consideration the thermal efficiency and electrical efficiency to present the overall efficiency as a CHP system. The efficiency formulas presented in Section 5.2 are applied to the plant data of San Zeno EfW. The San Zeno facility in power only mode has a very low electrical efficiency of 14%. However, if operated in the CHP mode there is significant improvement in the overall plant efficiency considering the equivalency factors for heat and power.

5.4 PROCESS EFFICIENCY

The solution proposed to improve the performance of EfW plant, explained through example of the San Zeno EfW facility is one amongst several other process efficiency solutions that can be implemented for optimum plant performance. Process efficiency solutions, when implemented can realize economic and operational benefits for an EfW facility. The overall aim is to bring better efficiency performance as an overall system. There are some general principles that can be followed to improve energy efficiency of EfW processes (as listed below):

- By using energy-efficient equipment, operators can minimize the energy consumption of the plant.
- High quality insulation can be applied to limit thermal radiation, hence minimize heat losses.
- Improving the burnout of residues can minimize the amount of feedstock that is not properly converted.

- Boiler performance can be improved by minimizing its fouling effects.

The European Commission [77] document on Best Available Techniques on Waste Incineration lists out some specific methods that can be adopted, in order to improve the overall EfW efficiency:

- Waste feed pre-treatment (homogenization and separation)
- Improved boiler design (surface allowed for heat transfers and protection system against corrosion)
- Preheating of the combustion air to dry the feedstock
- Means of cooling grated
- Heat pumps design (compressor driven heat pumps, absorption heat pumps...)
- Flue-gas circulation (recirculation, reheating)
- Steam-water cycle improvements (increase steam pressure, heating secondary air...)

Herein a hypothetical study has been presented in improving the process efficiency through the use of an efficient steam turbine. It generally depends on the make and the technical specification that dictates its designed heat to power ratio. There is enough evidence available on steam turbine efficiency performance, this analysis introduces a turbine with a varying heat to power ratio to the Beddington EfW. Figure 14 demonstrates a drop in electrical energy from a steam turbine, due to extraction of ‘useful’ heat. Firstly, it can be seen the overall CHP efficiency improves with the application of useful heat from the turbine. Secondly, Steam turbine configurations are explored, essentially referring to the [53] report where in it states a drop in electrical export by up to 20% when switching to CHP mode. As per the report, the maximum heat that can be extracted from the turbine is 20MW for the Beddington facility. Heat to power ratio has been reported as 4:1, i.e. for each 1000 kW of heat generated there is a decrease of 250 kW of electricity production. This can notably be improved through turbine selection and is not necessarily a constant. The impact on R1 compared to the overall operational efficiency is presented by Figure 7 for turbines which have a higher and lower heat to power ratio that one selected for the facility.

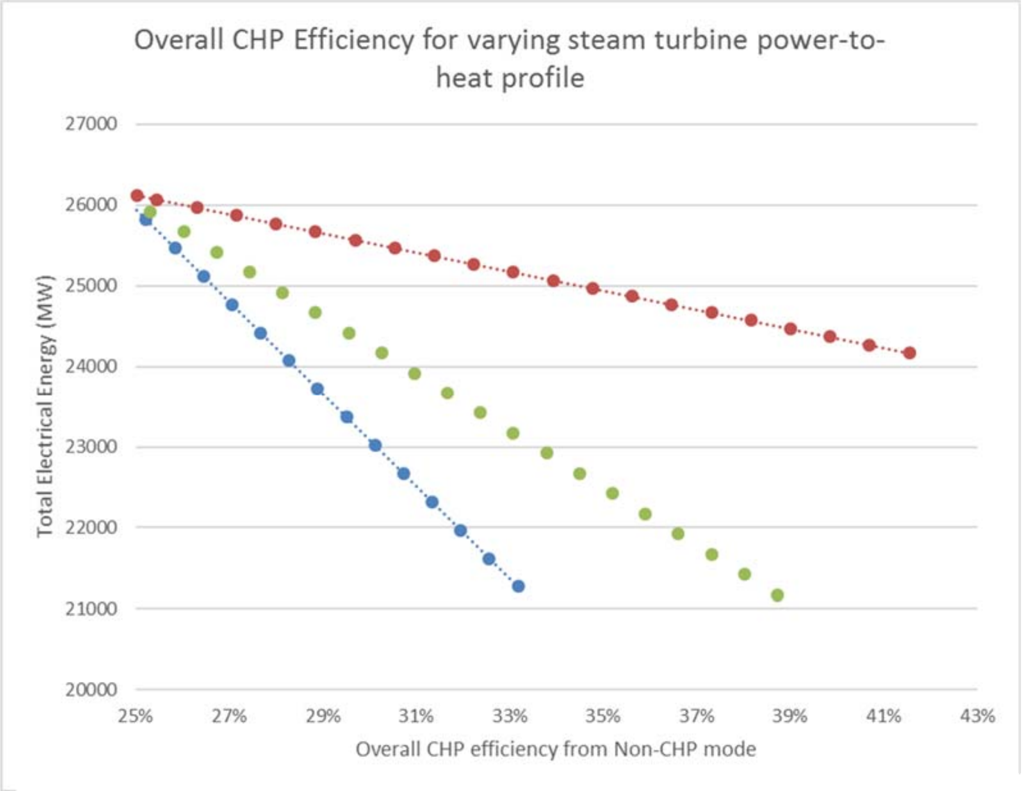


Figure 14 - Overall CHP Efficiency Profile for Steam Turbines of different heat to power profile

Essentially, Figure 14 leads us onto Figure 15, to visualize for the same thermal output of 1000kW increments, the electricity that can be generated at those specific stages varies and hence the R1 outcome will vary. In The ‘power’ only mode for the Beddington EfW, the R1 outcome was 0.6505 (Ref: Figure 7). Upon switching to CHP mode with the turbine as per design this would become 0.74 (Ref: Figure 7). However, when other turbine heat-to-power profiles are considered, a further improvement can be observed in the R1 outcome and overall CHP efficiency. This effectively is a non-conventional method to explore the process efficiency that can be achieved in an EfW facility. It would ideally come under the strategy of selection of energy-efficient equipment to optimize the energy consumption of the process.

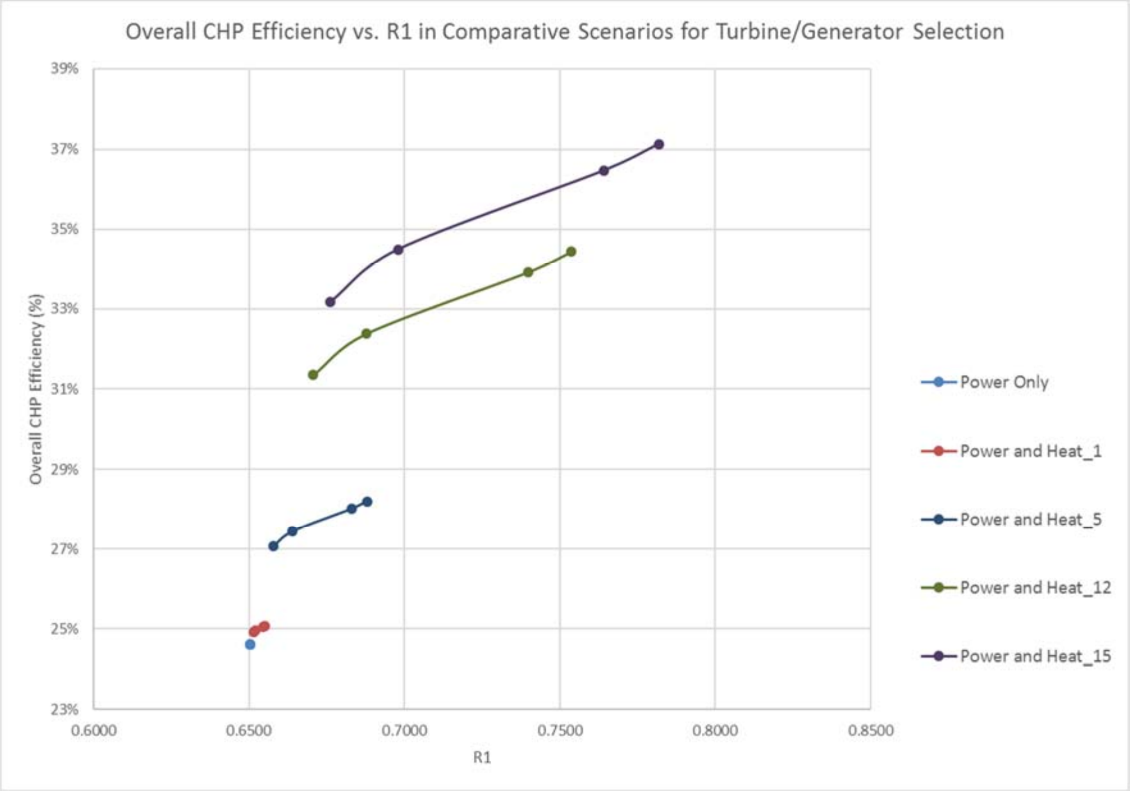


Figure 15 - Overall CHP Efficiency and R1 when considering different turbine heat to power profile for the same thermal

5.5 CONCLUSION

This chapter explored application of CHP principles to R1 energy-efficiency formula, in keeping with the guidelines as per the WFD of two EfW facilities. It follows on from the work presented in Chapter 4 and presents an elaborate analysis of EfW operations from a CHP perspective. The initial part of the chapter looked at representation of CHP formula based on the R1 efficiency formula parameters. This resulted in a list of formulas relevant to CHP calculation, which can be applied to the case study data from Chapter 3.

Incorporating some essential assumptions related to CHP operations, the next part of the chapter reported on findings of the CHP formula applied to case study data. Beddingtion ERF and San Zeno EfW has been presented with CHP analysis. It is essential to note in terms of CHP analysis the following assumptions were applicable to the case study, for an accurate understanding of the energy balance and overall improvement in system efficiency. The electric efficiency of the turbine from the ‘power’ only mode to the ‘CHP’ mode remains unchanged. The decrease in heat utilized for power generation, when switching to ‘CHP’ mode from Power-only mode, is due to ‘steam bleed’ at the turbine and is directed to the boiler contributing to the overall ‘useful-heat’ production. When in CHP mode, the maximum electricity that can be extracted from the turbine is not equal to the electricity produced when in Power-only mode. In optimum CHP mode, the turbine and other equipments related to power generation is not loaded 100%. This was also necessary in order to work through detailed calculations without the need to have temperature and pressure values. From the analysis presented on Beddington ERF, two scenarios were drawn in which Scenario 1 is most applicable to the CHP operation.

The energy balance is proven through the sum of ‘useful-heat’ in CHP mode compared that with the Power mode. In the power mode the total useful heat was 503,933 MWh which contributed to the total power generation of 26.17 MW. In the CHP mode, based on Scenario 1, total useful heat is 505,417 MWh which translates to electric power of 21.17 MW and thermal power of 20 MW. The balance heat from the total input of 765,394 MWh, is rejected by the system. The power to heat ratio as per equation 5.9 gave a result of 0.3, which is closer to the reported power loss coefficient of the system 0.25. The FERC efficiency value as per Equation 5.3 is 27% and overall efficiency as per equation 5.8, Overall Efficiency which represents the ratio (μ_{CHP}) stands at 43%. R1 when calculated in this scenario is 0.65, which is favourable.

San Zeno facility has also been analysed for CHP mode and therein a elaborate look at the ORC was taken. This was proposed to improve the existing system, as it is not a well performing facility in the area. Given the scale of operations, it is challenging for the facility to meet the R1 threshold and continues to be a disposal operation. The chapter then presents a discussion on process efficiencies that can be implemented by EfW facilities. These steps when implemented can result in economic and operational benefits. A hypothetical study was presented on one aspect of process efficiency that can be achieved through the use of an efficient steam turbine. The data from the Beddingtion ERF was utilized to demonstrate the impact on efficiency in a varying heat-to-power profile of the steam turbine. Discussions in this chapter are substantial and further emphasizes the need for EfW as CHP operation for its relevance in the long term. It is essential to have heat consumers and only through operation in CHP can lead to overcoming obstacles related to plant size or location. The R1 scores of plants in CHP mode mostly keeps with the EU WFD guidelines.

CONCLUSIONS AND FUTURE WORK

6.1 INTRODUCTION

This research addressed some key issues in EfW industry, related to operational efficiency. The need for an assessment criteria was introduced by the European Commission to standardize its waste treatment practices. In doing so, a clear strategy was put forth to differentiate between facilities practicing energy recovery and those solely as disposal operations. The R1 criterion, which is used to assess and classify EfW facilities was updated by the European Commission in 2015. The revised guidelines and proposed formulas for correction by Ozansoy [8] of R1 was implemented in this research. The key achievements of this investigative study has been captured in this chapter. Primarily the long term implications of results achieved when comparing the outcome of the EU WFD formula, that corrects for climate with the results of applying correction factors proposed in Ozansoy [8]. It provides an insight, in the development of the EU policy.

The R1 criterion; 0.65 established through the European WFD is applicable to EfW plants in any given climate condition, type and size. Essentially the correction factors for climate and size have been developed to assist those EfW facilities that find it a challenge to meet the threshold. The challenge is justified for the EfW facility due to its geographical location and/or the designed waste throughput capacity and hence a lack of sufficient energy demand. The developed correction factors make an impact on such facilities and assists in achieving that R1 criterion.

Section 6.2, summarizes the key achievements. It is established through various literary works, EfW is growing in importance and will play a part in Australia's future strategy to manage waste as done in Europe. Section 6.3 briefly discusses Australian EfW infrastructure and challenges. The need for such analytical research on EfW operations across the globe will grow in order to develop an environment that is cleaner, safer and sustainable while at the same time bring economic benefits. Finally, taking into consideration the vast prospective of EfW and relevance to this research, potential future work has been discussed in Section 6.4.

6.2 SUMMARY OF ACHIEVEMENTS

The prime focus of this research has been application of the R1 policy. It has evolved given the range of case studies considered and correction factors applied. Hence, key achievements have been itemized below given the diversity of milestones.

- **Analysed operational data from 'live' EfW facilities**

Chapter 3 included a table of operational data, in Section 3.4. The data was compiled from various contractor and public review documents for the plants. San Zeno data was compiled from the study presented by Di Maria et al. [33]. While collecting the data was an accomplishment, mapping this onto Figure 2 and Figure 3, while at the same time utilizing the R1 Efficiency Calculator tool is a key success. Also the case studies data is from plants located in the three different geographies and varying capacities.

- **Implemented R1 computations of 'live' EfW facilities**

Following on from the analytical step, the operational data has been explicitly utilized in the R1 Efficiency Calculator tool. The tool also incorporated the current R1 formula by EU and was able to compare both the results. The R1 computations were also compared to the independent R1 assessment at source. A clear reference stands between the mapped process flow for incineration and gasification in Chapter 3 with the calculation tool applied in Chapter 4.

- **Application of proposed climate and size correction to the R1 outcome and comparison to the current EU R1 formula**

Further analysis, considered the impact of external variants, like prevailing climate and size to the performance of an EfW plant. The set of proposed size and climate correction formulas from Ozansoy [8] was built into the R1 Efficiency Calculator tool. Such an approach enables engineers to compute a quick overall thermal efficiency assessment without the need to carry out complex and time consuming computational processes or modelling of equipment based energy utilization systems. The holistic view of the energy at the energy system boundaries enables such a calculation with ease. This research directly addresses issues concerned with the bias in the existing R1 formula. It validates the use of the proposed formulas in Ozansoy [8] and proves that it is conservative compared to the current formula as per European Commission [18] in 2015. The detailed investigation, utilizing real life case studies, provided a complete view about the impact of external variants on the R1 formula. It emphasizes on the importance of the correction factors and its criticality to either make or break EfW plants 'energy-recovery' status. The tool has been applied to three plants at different geographies, and applying the climate and size CFs to the datasets demonstrated how the overall R1 value can be scaled minimizing the handicap on facilities with smaller modular sizes and those located in warmer regions of the world.

- **Application and illustration of mathematical equations in terms of R1 parameters as CHP metrics and applied to EfW plants, FUE, FERC analysis**

The detailed development of the mathematical equations for EfW plant as CHP operation is an important contribution for achieving an analytical model that is comparable to the R1 formula parameters. This enables an assessment of the EfW plant in terms of CHP efficiency and compares this to the R1 outcome. While the parameters do not consider the impact of correction factors, it however draws out ratios that is comparable to assess the overall performance of the plant. This would assist to better understand the importance of CHP operation and hence proves significance in identifying suitable 'heat' consumers in early development stages of an EfW project. CHP operation is further validated when comparing the hypothetical Figure 6 to the analytical study results in Figure 8 and 9. Overall CHP achieves better operational efficiency scores than SHP.

- **Explored the impact of power loss coefficient for a steam turbine in an 'EfW'**

The hypothetical analysis conducted in Chapter 5, is a key milestone. While the chapter assist to visualize the impact of CHP on the overall operational efficiency, it also presents an analytical element wherein better thermal efficiency figures can be achieved. The chapter proposes opportunities that may exist in optimizing the performance of an EfW facility and brings into picture the power loss coefficient of the steam turbine. The variance that is practically possible in the operational parameter given the set of assumptions has been highlighted and this is a key criterion for the evaluation of the complete system for FUE and FERC analysis. The comparisons to the R1 score is also an added value as one can visualize the impact this (however much it may be) can have.

6.3 EFW IN AUSTRALIA AND OBSERVING THE ROLE OF THERMAL EFFICIENCY R1

Recent literary works, discussion papers and policies [9, 11, 25, 49] drafted in Australian states of NSW, VIC, WA and SA evidence to the viability of implementing an EfW model that supports the growth of the industry. State of VIC aims to operate EfW plants by 2025 starting with a group of local councils in the western suburbs which combine their waste management contracts to feed a 300,000 tonne per annum incinerator near existing landfill sites. The proposed Kwinana EfW facility by Phoenix Energy [49], in Western Australia aims to utilize the Martin Grate incinerator-based technology and the plant will process MSW from the city of Kwinana designed to a capacity of 80

MW. Once completed, the facility will have a significant 300,000 tonnes per annum capacity, making it able to supply 15% of the city's electricity needs. The NSW EPA has stipulated thermal efficiency criteria where it must be demonstrated that 25% of the energy generated by thermally treating a waste will be captured as electricity. While SA has begun work drafting its policy on EfW, and implementation of increased landfill levies across Australia, the path towards EfW implementation is clear. It is established that Australia intends to implement a strategy to encourage the growth of EfW. R1 has been adopted in the EPA policies of WA, VIC and NSW. However, with the diversity of energy demand and significantly warmer weather pattern of Australia compared to Europe, the long term application of R1 (without correction factors) as a differentiator could potentially be open to debate.

The range of climate experienced in Australia and availability of adequate waste feedstock and energy demand is to be considered. Another reason is the stand on EfW technology, with a bias towards direct incineration over technologies such as gasification, pyrolysis, plasma gasification and thermal depolymerisation. In order to strike the balance, of significant heat demand and generated electrical energy, it would be safer to adopt larger EfW facilities with thermal waste treatment capacities in excess of 250,000 tonnes per annum. In doing so, Australian EfW plants would satisfy the R1 criteria. However, as proven by the case study of San Zeno, improvements to efficiency can be realized in smaller EfW facilities in CHP operation. With current advances in technologies and utilizing equipment with superior efficiency performance with emphasis on methods highlighted in Section 5.4, smaller modular EfW facilities could be economically feasible when constructed closer to significant energy consumers in the cooler regions like VIC and Tasmania. This could translate to higher capital expenditure for the initial construction which can be offset by tie-in contracts with the industrial consumers of heat and electricity, energy subsidies and suppliers of high calorific value waste.

Legacy barriers exist such as noise, odors, air emissions and pollution, water supply and waste water discharge, occupational health and safety, land reclamation, community acceptance and involvement in the project. Along with Greenhouse gas emissions listed in World Bank report [48] are also relevant barriers to deployment of EfW in Australia. However, in Australia the major challenge will be overcoming the limits set to air emissions and pollution. Airborne pollutants from the combustion process are emitted through the stack. Assuming an optimal combustion process for complete destruction of particles and gases, the applied flue gas cleaning and the height of the stack are decisive for the resulting contribution to the air quality. The anticipated emissions, as a function of cleaning technology, is always meticulously scrutinized in order to maintain the GHG emissions. The facility must comply with air emissions regulations. This is not negotiable and can represent a significant portion of the overall facility cost. It also means that a degree of quality control must be applied to the "fuel" in order to keep contaminants within acceptable limits.

Australia practices some of the highest safe working standards in the world and trade unions are aligned to this goal. Occupational health and safety standards are amongst the most stringent. In an EfW facility, workers in the waste reception hall are always exposed to exhaust fumes from the trucks delivering the waste. The air quality in the reception hall is further negatively influenced by odor, dust, and micro-organisms released during unloading. Decomposition of waste in the pit/hopper further degrades the air quality. Prolonged storage of large volumes of waste may result in anaerobic conditions followed by depletion of oxygen and formation of methane.

A site will be needed for an EfW facility. This site will require development approval and appropriate licensing. Satisfying these requirements can be a lengthy and expensive process in Australia. There must be community acceptance of the facility. Community consultation must be commenced early and be both sustained and transparent. Past experience has taught that if this is not achieved, the difficulties facing the project will escalate dramatically. Ensuring and demonstrating that EfW does not cannibalize resource recovery will be an important consideration. There exists significant scope of further work focused on steps taken to mitigate these barriers with live examples. The deployment of Kwinana EfW facility in WA can be a case-study to review the measures taken to overcome these barriers, as Australia attempts to pave the way forward for EfW.

6.4 FUTURE WORK

The research conducted in essence, covers some diverse aspects of the R1 application. However given the growing importance of EfW, there exists several branches this can be extended onto. With reference to EfW technologies in Chapter 3, the case studies included EfW technology incineration and gasification. Impact of R1 on pyrolysis, ATT technology can be explored. Current studies have considered incineration-based EfW given the wide availability of data and also being commercially mainstream. While gasification technology has been predominant in Japan, it has not been adopted elsewhere as preferred method of thermal treatment of waste. Similarly, pyrolysis of waste and other ATT are not preferred options. Adding such analytical work and system energy boundary map for the relevant technology, to extend this research will add further depth and knowhow for the R1 Efficiency Calculator tool.

From the perspective of pure mechanical engineering, applying the understanding of thermal sciences to perform an exergetic (2^{nd} Law of Thermodynamics) analysis would provide further sophisticated depth of understanding of the energy transfer process. Here the exergy accounts for the quality of energy, and 1 kJ of electricity has more exergy (value) than 1 kJ of heat transfer at 500 ^{o}C which has more exergy than 1 kJ of heat transfer at 50 ^{o}C; i.e. electricity has more value than heat transfer, and a hot heat transfer has more value than a cold heat transfer. This could form the basis of further in-depth work in the future.

Sensitivity analysis, is another aspect that can be considered for future work. Given the wide list of formulas and various sub-dependent parameters, it would be interesting to draw out sensitivity analysis to provide an understanding on the scale of performance. Chapter 4, illustrated the comparison of calculated R1 with proposed correction factors for climate and size only. While the application has been at the system energy boundaries, as part of further work, it can be isolated to major components in the EfW facility, such as boiler and steam turbine generator. In essence, bringing the analytical step to major equipment level to understand energy balance. This too can be developed into the R1 efficiency calculator tool to get an equipment level picture of the energy balance.

Section 2.6, Chapter 2 briefly looks upon the potential of EfW in Australia while there is more discussion here that is prevalent and can be done in future works. R1 formula has been adopted by VIC and WA EPA and with a recent project implemented in WA, the Kwinana EfW, it would be apt to compile operational plant data and apply the R1 Efficiency Calculator tool. Given the different climate patterns WA experiences compared to EU, the results would be an interesting find. In Australia, given its distant location from the rest of the world, developing adequate onshore EfW facilities is the way forward for the industry over the option to landfill. Studies related to the scale, complexity, capital/operational costs, and key differentiator to the European EfW infrastructure model is relevant and are currently being pursued to develop this sector.

Hoque et al. [65] acknowledges all three case studies presented involve the combustion process of waste generating heat and electricity as well as GHG's and mainly CO_2. These are an in-evitable by-products of the basic combustion process. In this era where GHG's and climate change is on top of the environment protection agenda a detailed study would be beneficial that links CO_2 balance with conservative power plant emissions and its relation to maintaining R1 ratio. This research can be branched to link GHG's and R1 criterion.

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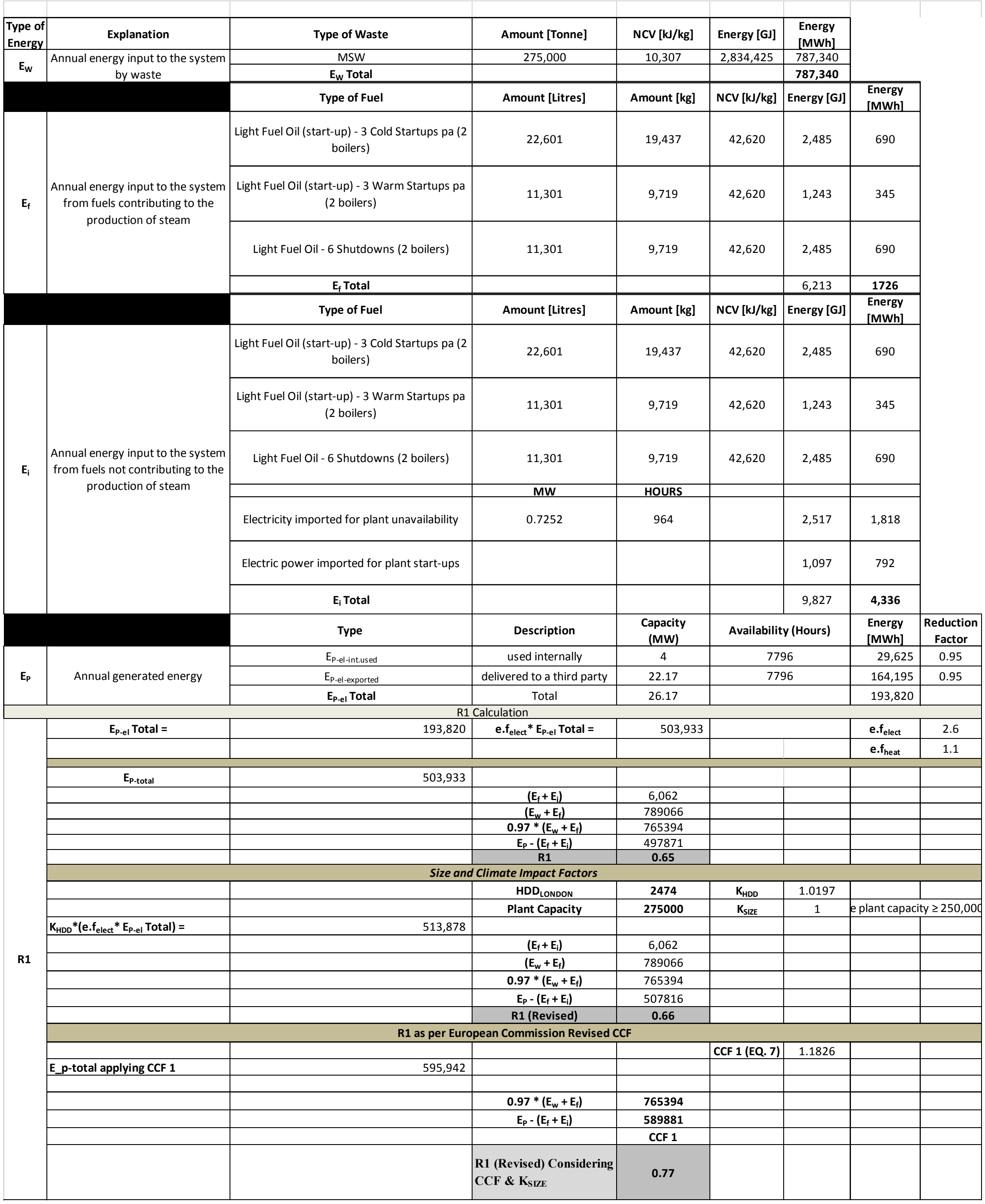
Appendix A – R1 Efficiency Calculator Tool



Type of Energy	Explanation	Type of Waste	Amount [Tonne]	NCV [kJ/kg]	Energy [GJ]	Energy [MWh]		
E_W	Annual energy input to the system by waste	MSW	275,000	10,307	2,834,425	787,340		
		E_W Total				787,340		
		Type of Fuel	Amount [Litres]	Amount [kg]	NCV [kJ/kg]	Energy [GJ]	Energy [MWh]	
E_f	Annual energy input to the system from fuels contributing to the production of steam	Light Fuel Oil (start-up) - 3 Cold Startups pa (2 boilers)	22,601	19,437	42,620	2,485	690	
		Light Fuel Oil (start-up) - 3 Warm Startups pa (2 boilers)	11,301	9,719	42,620	1,243	345	
		Light Fuel Oil - 6 Shutdowns (2 boilers)	11,301	9,719	42,620	2,485	690	
		E_f Total				6,213	1726	
		Type of Fuel	Amount [Litres]	Amount [kg]	NCV [kJ/kg]	Energy [GJ]	Energy [MWh]	
E_i	Annual energy input to the system from fuels not contributing to the production of steam	Light Fuel Oil (start-up) - 3 Cold Startups pa (2 boilers)	22,601	19,437	42,620	2,485	690	
		Light Fuel Oil (start-up) - 3 Warm Startups pa (2 boilers)	11,301	9,719	42,620	1,243	345	
		Light Fuel Oil - 6 Shutdowns (2 boilers)	11,301	9,719	42,620	2,485	690	
			MW	HOURS				
		Electricity imported for plant unavailability	0.7252	964		2,517	1,818	
		Electric power imported for plant start-ups				1,097	792	
		E_i Total				9,827	4,336	
		Type	Description	Capacity (MW)	Availability (Hours)		Energy [MWh]	Reduction Factor
E_P	Annual generated energy	$E_{P\text{-el-int.used}}$	used internally	4	7796		29,625	0.95
		$E_{P\text{-el-exported}}$	delivered to a third party	22.17	7796		164,195	0.95
		$E_{P\text{-el}}$ Total	Total	26.17			193,820	
R1 Calculation								
R1	$E_{P\text{-el}}$ Total =	193,820	$e.f_{elect}$ * $E_{P\text{-el}}$ Total =	503,933			$e.f_{elect}$	2.6
							$e.f_{heat}$	1.1
	$E_{P\text{-total}}$	503,933						
			$(E_f + E_i)$	6,062				
			$(E_w + E_f)$	789066				
			0.97 * $(E_w + E_f)$	765394				
			$E_P - (E_f + E_i)$	497871				
			R1	0.65				
	Size and Climate Impact Factors							
			HDD_{LONDON}	2474	K_{HDD}	1.0197		
			Plant Capacity	275000	K_{SIZE}	1	e plant capacity ≥ 250,000	
	K_{HDD}*($e.f_{elect}$* $E_{P\text{-el}}$ Total) =	513,878						
			$(E_f + E_i)$	6,062				
			$(E_w + E_f)$	789066				
			0.97 * $(E_w + E_f)$	765394				
			$E_P - (E_f + E_i)$	507816				
			R1 (Revised)	0.66				
	R1 as per European Commission Revised CCF							
					CCF 1 (EQ. 7)	1.1826		
	E_p-total applying CCF 1	595,942						
			0.97 * $(E_w + E_f)$	765394				
			$E_P - (E_f + E_i)$	589881				
				CCF 1				
			R1 (Revised) Considering CCF & K_{SIZE}	0.77				

The **R1 Efficiency Calculator Tool**, developed first in [8] in MS Excel has been adopted for this research. This carries out computations as per the formulas presented in Chapter 2. The table (above) shows the R1 score of Beddington ERF in CHP mode. The calculations and work through is demonstrated in Figure 4, Table 3 and Table 4, in Chapter 4.