‘Patented Blunderings’, Efficiency Awareness, and Self-Sustainability Claims in the Pyrolysis Energy from Waste Sector

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Historically, pyrolysis technologies occupied a niche, producing materials with useful chemical functionality from wood, by the continuous *application* of heat. In the 21st century pyrolysis is promoted as an "advanced" technology for the *extraction* of heat from municipal refuse, at the same time as claiming "sustainable" and "efficient" credentials. This paper examines the concept of pyrolysis, and the potential for a phenomenon which demands energy to be considered as something which can be engineered to provide energy. Using literature review and case study methods, along with civil permit applications and experimental results, it shows that a pyrolysis plant for self-sustaining Energy from Waste is thermodynamically unproven, practically implausible, and environmentally unsound. A linkage between widespread commercial failures and a lack of focus on thermodynamic fundamentals is also identified, along with an environment of indifference or ignorance towards energy balances and sustainability when these technologies are presented, assessed and financed. Though proposals to build machines which violate physical laws is not new, in a modern context this phenomenon is found to be stimulated by competitive financial rewards. The situation presents a high risk to investors and has the potential to adversely impact on societal transitions to a more sustainable future.

Keywords: Pyrolysis, Energy, Waste, Thermodynamics, Efficiency, Sustainability

1. Introduction

Below is an extract from the second series of Henry Dircks' book *Perpetuum Mobile* (Dircks, 1870). In it the author is describing a futile and ignoble search for self motive power during a period of six hundred years, with emphasis on a further eighty patents filed in the nine years since his initial Series One publication:

> *"The present century is rife in the reproduction of patented blundering, serving only to prove the ignorance and mental imbecility of a certain class of infatuated, would-be inventors, whom no history can teach, no instruction reform, nor any amount of mechanical mishaps persuade to abandon their folly"*.

Written with a style likely considered impolitic by today's conventions, Dircks' words properly describe the consensus of feeling towards contemporary engineers who propose (and patent) mechanical designs which violate the laws of thermodynamics - laws which unperpin engineering and indeed all universal interactions[1] (Eddington, 1928). It is used

[1] The first law of thermodynamics states that energy must be conserved, thus providing a useful tool for quantifying system energy and mass balances. The second law states that whenever there is energy transfer

here to illustrate and preview new accusations of the phenomenon one hundred and fifty years later in the "novel" Energy from Waste (EfW) sector, a recurrence which incidentally shows that Henry Dircks was overtly optimistic when he predicted in 1870 that these incidents would "*..shortly be a thing of the past, to be remembered only as an amazing piece of folly"*.

The subject of these accusations, and this article, is pyrolysis as an option for converting municipal refuse into energy; specifically modern concept systems which claim to be self-sustaining, and which exhibit on behalf of those involved a seemingly collective amnesia to an extensive library of research that describe the technology's thermodynamic limitations. Pyrolysis occurs when solid organic matter is heated, resulting in the evolution of gas and oils (also known as "tars") and leaving residual charcoal, hence the word's etymological root of 'loosening or change by fire' (Antal Jr and Grønli, 2003).

Although there have been a couple of bulletin-style publications which have raised awareness of the situation by evidencing commercial failures and alleging some unscrupulous practices, they were perhaps limited in what they could achieve because they did not explain in sufficient detail the technical reasons for failures, nor give sufficient weight of evidence from peer reviewed literature (Dowen, 2016; Tangi and Wilson, 2017). The academic community has however so far remained largely aloof to the current situation.

About a decade ago Germany was an early trialist of the pyrolysis EfW concept. After widespread failures its engineering professionals raised concerns about the lack of "*plausible"* (Quicker et al., 2015), or the provision of "*insufficient*" (Gleis, 2012) mass and energy balances in system design proposals. When, rather than receiving censure, the technology providers sought and found international translocation, one author was prompted to comment with a sarcasm not usually associated with this type of reporting (Gleis, 2012):

> *"It would be sensible to slowly accept the fact that thermodynamics and entropy are not bound by national borders".*

Henry Dircks' objective was to save the foolish from wasted labours. But, in the 21st Century the pursuit of machines which violate thermodynamic principles has additional significance because of how they impact on energy and resource use, therefore adversely affecting society's transition to a sustainable future (Gleis, 2012):

> "*Belief may indeed move mountains, but modern society cannot afford to ignore the physical laws of thermodynamics and entropy. A full recovery of raw materials may be a highly anticipated wish; nevertheless it will not come true if we ignore the first or the second law of thermodynamics. This can only lead to failure and ultimately to unecessary costs*".

To this end, the present article explores the status of energy and efficiency awareness in the pyrolysis EfW sector, drawing on peer reviewed literature, environmental planning permit documents and experimental data, alongside both historic and recent antecedents. It assumes the research question to be one of testing the following hypothesis, which restates an assertion made by Williams (2012):

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some quantity must always be lost to a system's surroundings (measured as "entropy"), thus making *perpetuum mobile* impossible.

Pyrolysis of municipal refuse is thermodynamically self-sustaining, in that it produces gases with sufficient chemical energy to supply the plant's own energy needs.

Its broader scope is to provide greater transparency on the capabilities and limitations of pyrolysis technology. The work is considered to be of interest to decision makers, civil servants, funding providers, and investors, along with the would-be patented blunderers themselves.

2. Definitions and Scope

The concept of large-scale thermochemical EfW is near the bottom of the waste hierarchy (European Commission, 2008). It is also considered as extraneous to the model of a Circular Economy (Ellen MacArthur Foundation, 2013). Reasons for this status are multiple: the stoichiometric release of greenhouse gases, the annihilation of chemical functionality, toxic air pollution, entropic implications of turning matter into energy, and claims that it encourages the manufacturing of products with built-in obscolescence, or "feeding the beast in a throwaway society" (Clark, 2007; Gouleke, 1975). Its environmental merit rests upon the premise that liberating useful energy from waste could offset the burning of fossil fuels (Mutz et al., 2017). But, if system efficiency is low (*e.g.* where much of the waste's energy density is lost in order to stabilise the process) such benefits are undermined; and where the system is so ill that more fossil fuel-derived energy is input than can practically be extracted from the feedstock as waste-derived energy (negative efficiency), the notion of EfW is completely refuted.

Incineration combusts the waste directly, literally "burning it to cinders". Before combustion can occur, waste has to pass through both drying and pyrolysis stages, both of which require a continuous supply of energy (European Commission, 2017). Advanced Thermal Treatment (ATT) technologies, namely pyrolysis and gasification, both utilise thermal decomposition, but avoid oxidation. They are designed to inhibit the combustion process by limiting oxygen ingress while still providing high temperatures, thus stopping thermal decomposition prematurely to produce a complex mixture of unburned hydrocarbons (Kiel et al., 2004). Their aim is to convert the waste into a different form (solid, liquid, or gas) which is then useable as a commodity, invariably a "fuel", in its own right (Bridgwater, 2006). Ultimately however, all EfW processes must combust these products to liberate energy, thus releasing the same quantity of carbon dioxide than if the waste had been incinerated directly. For plastics and other petrochemical-derived materials, their existence in product form has merely been an intermediary stage in the combustion of fossil fuels.

"Feedstock" represents the fuel input to EfW machines, in the form of matter, and this paper is concerned with Municipal Solid Waste (MSW). The definition also extends to derivatives of mixed refuse which have been reconstituted from MSW after it has been subjected to varying levels of pre-sorting and/or pre-treatment, the energy requirements for the production of which are almost never taken into account in energy or cost audits (Vehlow, 2016). These derivatives are called: “refuse derived fuels” (RDF) and “solid recovered fuels” (SRF), but any differences between them can be merely titular; the latter is a designation applied by the European Union (EU) for purposes of creating a variety of standardisation categories (British Standards Institution, 2011). Consideration will also be given to sewage sludge, by definition a municipal waste, although invariably collected and managed separately. EfW technologies which use MSW and its derivatives are also currently (and euphemistically) described as "multi-fuel" plants (National Infrastructure Planning, 2018).

The EfW sector conventionally defines process efficiency based on the conversion of feedstock energy density (termed "calorific" or "heating" value), *e.g*. how much energy has been made available and how much has been lost (TwE, 2014). These are unsuitable metrics with which to appraise process energy and resource use, for they exclude other necessary material and energy flows that derive from multi-stage and energy intensive feedstock sorting, conditioning, drying, and shredding, often the input of fossil fuels, the use of lime, and auxiliary energy inputs to improve the fuel conversion efficiency, particularly with the ATT concepts (Quicker et al., 2015; Suzuki and Nagayama, 2011; Vehlow, 2015; Vehlow, 2016; Rollinson, 2018). For satisfactory process appraisal, energy balances should be on net system energy efficiency basis (where all energy inputs and outputs are included) - the approach taken in this study. Such 'net energy analyses' are akin to Energy Return on Investment (Murphy and Hall, 2010). Economic efficiency (aka profitability) does not form part of this article, although it is referred to incidentally.

3. Thermodynamic Fundamentals of MSW Pyrolysis

Pyrolysis is an initial stage in all thermal decomposition processes, with standard methods specifying a temperature of 550°C (Ripley, 2014). However, the process is reportedly not complete up to 800°C (Okumura et al., 2009). Variations in the fraction of tars, oils, and chars produced are a complex function of pyrolysis conditions and feedstock properties due to secondary and tertiary synthesis (Vreugdenhil and Zwart, 2009; Garcia-Nunez et al., 2017). Extensive research undertaken over the last thirty years has shown that without catalyst, tar still remains as a process-line contaminant even at reactor temperatures above 1200°C (Vreugdenhil and Zwart, 2009):

“*The rate of thermal cracking is such that high temperatures are required – in the order of 1200°C or higher (also depending on the residence time at high temperature) – in order to break down enough tars so that the remaining fuel gas can be used problem-free in a downstream device such as a gas engine, gas turbine or catalytic synthesis processes.*”.

To attain this temperature requires large amounts of energy and makes engineering more costly. Where pyrolysis is proposed as an EfW option, the additional gas cleaning steps are more numerous and energy intensive which further reduces efficiency and invariably leads to abandonment (Seltenrich, 2016).

In a singular pyrolysis reactor, oxygen must be excluded otherwise more of the gas, oils, and char will burn, thereby losing products and reducing efficiency. But it still needs energy to drive the process so this is provided allothermally from electricity or by burning additional fuels. Because of its need for an extraneous energy supply, rather than being an EfW technology, pyrolysis has historically been implemented to produce useful substances such as methanol, acetone, acetic acid, and creosote from wood in predominantly batch process retorts prior to petrochemical production routes (Garcia-Nunez et al., 2017).

Figure 1 illustrates how pyrolysis is also the core stage of gasification, and is used here to show the thermodynamic inter-dependencies. An exothermic zone is created by allowing a small amount of air to enter, thus burning some portion of the feedstock and sacrificing fuel conversion efficiency for process stability. This provides the energy for pyrolysis, and for other endothermic reaction zones (drying and reduction). These energy and chemical fields easily become destabilised and impossible to control with heterogeneous feedstocks unless external heating is applied and even then the process is highly challenging (Consonni and Viganò, 2012):

"*… even for a much better defined feedstock like coal the variation of feedstock properties produces a major impact on the design, performance, maintenance and cost of gasification – ultimately on its feasibility. And even if technical challenges could be overcome, at the small scale typical of waste treatment plants net energy conversion efficiencies are likely to be lower than those of combustion plants, while investment and operating costs tend to be higher.*"

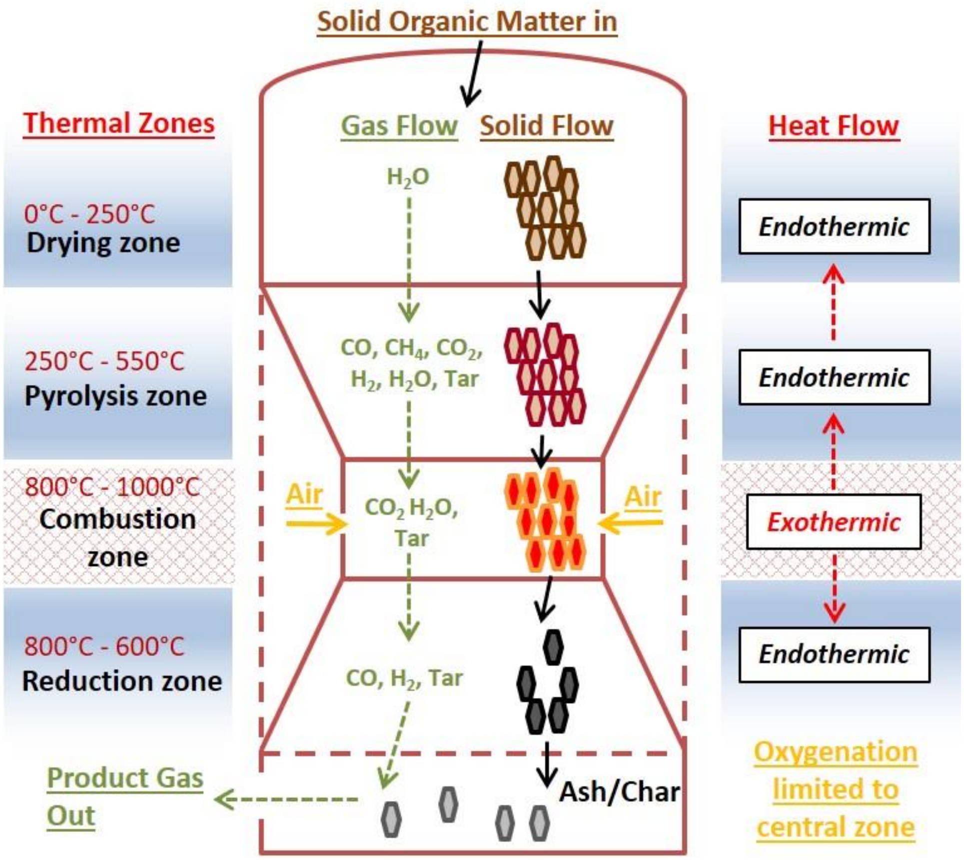

Figure 1. Schematic of a gasifier showing pyrolysis zone enabled by heat from combustion zone, along with thermochemical interdependencies and material flows.

When ATT systems go wrong, the symptoms are soot and tar in the product gas. But the cause is a chemical reactor labouring at the task of trying to maintain internal temperatures in order to produce a clean and useful gas from an unsuitable feedstock, in reactors which are not fit for purpose unless bolstered by external heating. Historically, the technology has been proven to function in small reactors only (due to physical thermodynamic limitations), and fed with strictly controlled homogeneous solids (Kaupp, 1984; Reed and Das, 1988, Consonni, S., Viganò, 2012; Rollinson, 2018). This is succinctly described by a former President of the International Waste Association (Mavropoulos, 2012):

"*Waste is not a homogenous fuel. It has so far turned out to be too heterogenous to be able to treat in a gasification or pyrolysis process, irrespective of how you pre-treat the waste. It is absolutely not applicable for mixed MSW with today's technology. Another very negative factor is that the energy balance very often has turned out to be negative*".

No standard exists for assessing ATT feedstock. Reed and Das (1988) determined that one must include a measurement of all the following: particle size and shape, particle size distribution, char durability, fixed-carbon content, and ash. Therefore, though proposed fuels such as SRF and RDF may have a greater calorific value this does not necessarily make them better feedstocks for pyrolysis or gasification.

A pyrolysis and gasification EfW system in theory offers some potential efficiency benefits over combustion, namely the ability to combust the gas directly at higher temperature (by Carnot's theorem), and in internal combustion engines where the absence of a working fluid means that heat losses could theoretically be minimised via the second law of thermodynamics. But, auxiliary energy demands and gas cleaning requirements impose additional problems and lower net efficiencies (Woolcock and Brown, 2013; Rabou et al., 2009; Zwart et al., 2009). To overcome this, many "ATT" systems operate as "close-coupled" or “two-step oxidation” schemes, or as others have called it, they can only maintain stability while operating as “incinerators in disguise” (GAIA, 2006).

4. Case Studies on the Possibility of a Self-sustaining MSW Pyrolysis Plant

In modern academic literature, though there are many reviews and appraisals of the technologies proposed for pyrolysis EfW, a perusal of these documents reveals that they lack satisfactory information on energy balances and net operational efficiency (Chen, et al., 2014; Bosmans and Helsen, 2010; Ateş et al., 2013, Knapp, 2002; Dong et al., 2016; Czajczyńska et al., 2017; Garcia-Nunez et al., 2017). One of the first to present the technology, and currently the most cited, is by Malkow (2004), actually titled "*… technologies for energy efficient and environmentally sound MSW disposal*". Some energy efficiency values are stated, albeit infrequently, but these are only "aimed” at or "quoted" design specification values. Interestingly, fourteen years after this publication, the enterprises promoting the technologies described no longer exist or have focussed attention on other equipment such as grate incinerators (Leckner, 2015). Despite this, academic literature reviews continue to be published in which these plants are listed as being extant (Garcia-Nunez et al., 2017).

There is currently a notable absence of information in peer reviewed scientific literature on the operational performance of pyrolysis EfW plants in sufficient detail for the reports to be deemed rigorous. Industry has been taciturn about failures, though there are a few case studies on the subject by reputable sources (Williams and Barton, 2011; Vehlow, 2016; Quicker at al., 2015; and Gleis, 2012).

From 1983 to 2015 a MSW pyrolysis plant operated at Burgau, Germany, despite continuous technology related weaknesses; and no other plant of its type has been built since (Vehlow, 2016). The feedstock was pre-treated and residual char had to be disposed of as hazardous waste (Quicker et al., 2015). With specific relevance to this study, the pyrolysis gases were reported to provide only 20% of the power requirements of the pyrolysis reactor (Lombardi et al., 2015).

Of the other failures, and notwithstanding a lack of information on energy balances, the impracticalities of feeding and products removal are cited as the main challenge of MSW pyrolysis. Batch processing accentuates the problems as loading immediately cools the reactor thus disturbing the thermodynamic equilibrium within (De Filippis, et al., 2015):

"*Due to the intrinsic nature of the batch technology, it is impossible to maintain a constant gas quality that will follow periodic variation during the process*"

For MSW pyrolysis gas to engine systems, the gas is too dirty for supply to an internal combustion engine, and where it has been attempted it has been a failure (Williams and Barton, 2011; Vehlow, 2016). Despite this, some commercial ventures have no qualms about proposing the concept as a "*Proven process that is operationally efficient and reliable with low parasitic load*" (Brown, 2018).

It is however superficial to assume that the paucity of reliable information on energy and mass balances in permit applications may be attributable to the complexities and lack of resolution concerning pyrolytic thermal decomposition in academic literature. Energy and mass balances are elementary engineering design principles, taught in all credible undergraduate courses; the calorific value of the waste feedstock, though variable, can be easily calculated using standard bomb calorimetry methods or by formulae based on proximate analyses; the energy needed to raise steam is also well understood and easily calculated; and with these, a basic appraisal can easily be made using generic values for heat losses which can be assigned to components and process line using standard factors. Furthermore, another elementary and fundamental design method for chemical engineering is to size reactors based on feedstock reaction kinetics, a relatively simple method based on results of proximate analysis. These elementary features, in these authors' experience, have been totally absent throughout all British ATT permit proposals (see for example: Iceni Projects Limited, 2012; Rollinson, 2015; Enzygo, 2016; Derby City Council, 2017).

Pyrolysis as a pre-treatment method prior to secondary incineration and/or when operating as EfW through the Rankine cycle is in theory more feasible, though not obviating energy requirements, as long as there is close-coupling, because the pyrolysis gas can be burnt immediately thus mitigating tar issues. This still however leaves problems caused by a heterogeneous feedstock with a high inorganic composition, corrosion, feeding, and char removal issues, factors which caused the failure of the Andco-Torax concept and limited the Thermoselect system to efficiencies of less than 8.5%, though on what basis the parameter is measured is not disclosed (Gleis, 2012). The same problems are also cited as causing the failure of the RWE-ConTherm plant at Hamm, Germany (Chen et al., 2014).

It is important to make a distinction between the gasification/pre-incineration-stage pyrolysis concepts which have reportedly operated in Japan with some apparent success, and the self-sustaining pyrolysis concepts described by this article. The former are "melting systems", derivatives of blast furnace designs and operating in close-coupled mode, descriptions of which can be found in the following references (Tanigaki at al., 2012; Quicker et al., 2015; Suzuki and Nagayama, 2011). They necessitate high temperatures (ca. 1400°C), and as previously mentioned, have required an input of fossil fuels (natural gas and coke), lime, oxygen-enriched air to support and stabilise the reactor (Rollinson, 2018). Leckner (2015) proposes that there were legal/economic factors which led to their prolonged use in Japan before recently moving back to a preference for grate incineration combined with greater focus on 'reduce, re-use, and recycle' strategies. Other reasons are cited as being due to how the technology was managed: for waste reduction rather than profit and limited to a maximum of nine months' operation per year (Suzuki and Nagayama, 2011).

5. Can a Pyrolysis Plant be Self-sustaining?

Type into an internet search engine "pyrolysis" along with the acronym "MSW" and the result will be a list of websites belonging to private sector corporations offering concept systems. The companies describe themselves as experts in their field, their patented systems being able to convert any waste into renewable energy, and their technologies offering an opportunity for a 'high return on investment'. The systems propose to use the pyrolysis reactor's own gas, oil or char to self-sustain the plant, and claim that the system is "*proven, tried, and tested*"; supporting evidence on this will not however be accessible. The premise is hereby put up for scientific scrutiny.

5.1. A Pyrolysis Waste Disposal Plant using Pyrolysis Gas and Oil

Figure 2 is a schematic of a theoretical pyrolysis system. It is not an EfW design, since it provides no useful energy, and as such its utility would be waste destruction. In this case it represents the minimum of components necessary for assessing the plausibility of a self-sustaining pyrolysis plant. The theory is that component A - the Pyrolysis Reactor is supplied with heat from component B - the Combustion Chamber. The Combustion Chamber (B) is in turn fed with gases liberated by pyrolysis from A, whereupon B combusts those gases and returns the heat back to A to thereby liberate more gases, *in perpetuum*.

The theoretical system is of course supplied with waste feedstock, so is not *perpetuum mobile*. Of note also is that a prior batch of waste must initially be externally heated to evolve pyrolysis products which could then be burned to generate heat to pyrolyse the next batch; and in this regard, the external energy input to the base of the reactor provides that cold start-up energy. The Gas Storage Tank (C) would in theory allow repeated cold-starts following shut-down. Although by the second law of thermodynamics there must be heat losses from each component, these, along with the start-up energy, gas cleaning and other practical aspects of the 'plant' - which would be essential lest tars are released directly to sewer or air - are at present arbitrarily excluded for purposes of simplicity and to assess the concept in its most generous and permissive terms. The question then becomes one of answering the introductory hypothesis:

"*Do the gases contain sufficient energy to supply the requirements of the pyrolysis plant*?"

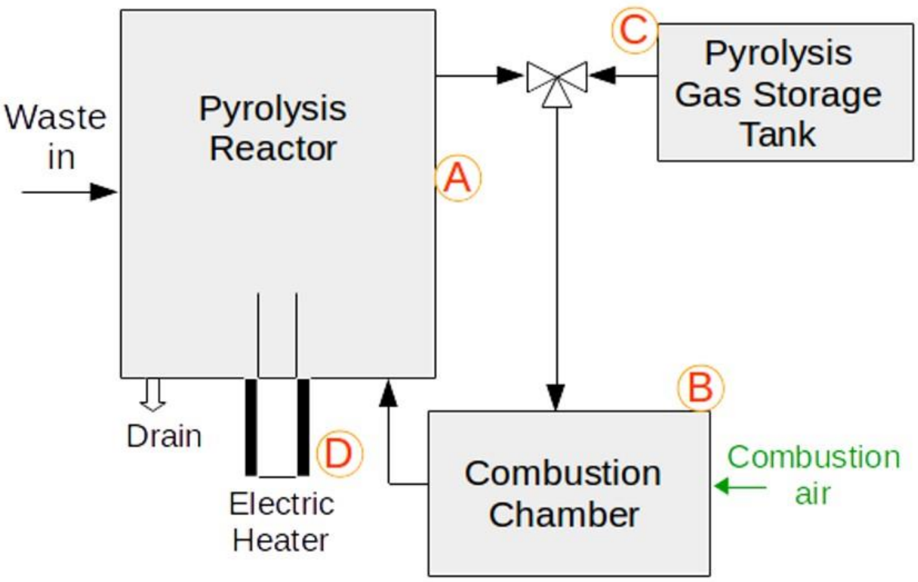

Figure 2. Theoretical Refuse Pyrolysis system

5.1.1. Literature Review

It is important to note that the energy needed for pyrolysis must include both sensible and reaction enthalpy, *i.e.* the energy needed (at constant pressure) to both raise the temperature of the feedstock *and* the additional energy needed for the reaction to proceed. Together this is defined by Reed and Gaur (1997) as enthalpy ***for*** pyrolysis, and differentiated from simply the reaction heat ***of*** pyrolysis. It is only the former which is relevant for pyrolysis engineers. As stated by Reed and Gaur (1997):

*"There is a great deal of confusion about the value of the heat required **for** the pyrolysis of biomass under various conditions of heating. We have been surprised that workers in the field typically have no idea of even the magnitude of heat required for the pyrolysis step in pyrolysis, combustion and gasification."*

In laboratory experiments, Daugaard and Brown (2003) calculated the energy input requirements (enthalpy) ***for*** pyrolysis as between 0.8 (±0.2) ≤ $MJ.kg^{-1}$ ≤1.6 (±0.3) for oak, pine, oat hulls, and corn stover (all on a dry basis) at temperatures of 500°C. Yang et al. (2013) found relatively similar values for pyrolysis enthalpy, again on a dry basis, for five different samples as between 1.1 (±0.2) ≤ $MJ.kg^{-1}$ ≤1.6 (±0.2) for temperatures of 460 ≤ °C ≤ 550. Reed and Gaur (1997) reported higher enthalpy values of 2.9 ≤ MJ/kg ≤3.5 on a dry basis (birch dowels), and when the same material had 55% moisture content the enthalpy for pyrolysis increased to 8.1 ≤ MJ/kg ≤ 8.6.

A crude comparison with these enthalpy values quoted for pyrolysis and the energy density of MSW shows that a self-sustaining system may perhaps be feasible. Lower Heating Values (LHV) of MSW are generally in the region of 6 ≤ $MJ.kg^{-1}$ ≤ 10, though these can vary due to composition, and whether they have been subjected to pre-treatment (European Commission, 2017; Lin et al., 2015). The SRF categories for example range between 3 ≤ $MJ.kg^{-1}$ ≤ 25 (British Standards Institution, 2011). But there are additional factors, one of which is how the pyrolysis process distributes energy between the different product fractions, with others being related to engineering practicalities and of course inherent second law of thermodynamic inefficiencies.

Bridgwater (2012) provides a comprehensive review of pyrolysis, describing the consensus that its endothermicity requires a substantial heat input to get the feedstock to reaction temperature. In the context of this current hypothesis he states that for fast pyrolysis:

"*The char typically contains about 25% of the energy of the feedstock, and about 75% of this energy is typically required to drive the process. The by-product gas only contains about 5% of the energy in the feed and <u>this is not sufficient for pyrolysis</u>*".

Three recent studies have however claimed that self-sustaining pyrolysis could be theoretically attainable. The first, by Crombie and Mašek (2014) measured how literature values for pyrolysis enthalpy compared with the calorific value of the gas from their own allothermal reactor operating at a range of temperatures. Dry samples only were used, and gas LHV was estimated by off-line analysis. Results were variable, with some gas samples having less and some slightly more energy than the literature predicted values for pyrolysis.

The second by Mcnamara et al. (2016) considered all the products (gas, oil, and char) obtained from the pyrolysis of pre-dried sewage sludge biosolids. The method again involved using literature values for pyrolysis enthalpy and an energy balance based on literature values for product heat capacities. With wide variability in their results, the authors concluded that theoretically the process could be either energy positive or negative, depending on input parameters and uncertainties. By "process", drying energy was again excluded from consideration.

Finally, Hossain, et al. (2009) also determined the enthalpy for pyrolysis of three sewage sludge samples ($0.8 \le MJ.kg^{-1} \le 1.1$, no error analysis) and compared this with theoretical values for pyrolysis gas energy density. Only one of the three samples was found to theoretically yield a combined product with sufficient cumulative heating value to match the demands of the comparator pyrolysis process. Reasons for this solitary positive result can be explained by the sample in question using dry sludge solids (moisture content of 5.7%), rather than sewage sludge which is *ca*. 95% water.

Moisture is present in all solid organic waste (even visibly dry material), existing at both surface and cellular level, therefore unless drying is set outside the system boundary it must be included in energy balances. Removing this water is highly energy intensive due to the high latent and sensible enthalpy demands in both liquid and steam phases, and high enthalpy of vaporisation (Twigg, 1996). These endothermic phenomenae are known as parasitic enthalpy demand, and are well understood from extensive work with steam cycles. The energy requirements to raise the temperature of water from 25°C to 550°C are 3.4 $MJ.kg^{-1}$.

Of note is that the three studies quoted above involved complex extrapolation methodologies, often with multiple assumptions. More telling however is that no study could be found which reported on an actual self-sustaining pyrolysis system.

5.2. A Pyrolysis EfW Plant using all Products

If the pyrolysis plant proposal in § 5.1 could not be self-sustaining on its own gas, then an EfW concept sustained only on pyrolysis gas is absurd. But, though not part of the introductory hypothesis, it is pertinent for completeness to consider whether self-sustaining EfW by pyrolysis is feasible using product char in addition to pyrolysis oil and gas. Figure 3 refers. Here the same key components from Figure 2 are present, with the pyrolysis reactor (A) supplied with waste, and electricity from component D. The cycle is once again completed because component A both supplies energy vectors (in the form of gas, char, or oil) *to* the Combustion Chamber (B) and is in turn is supplied with energy (in the form of heat) *from* the same source.

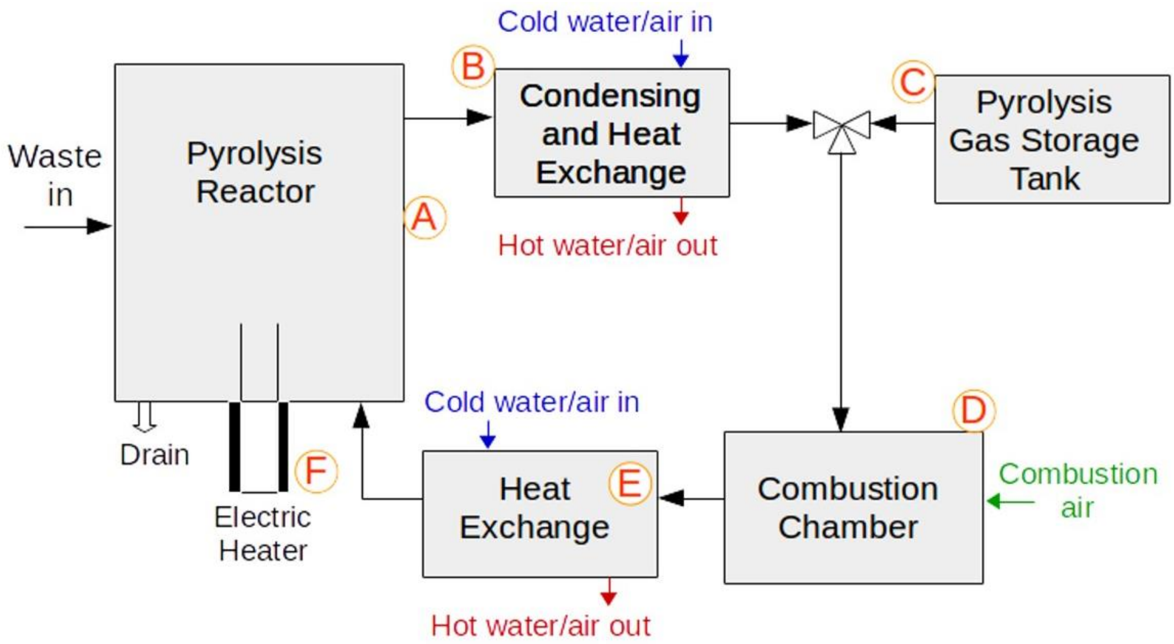

Figure 3. Schematic of a theoretical pyrolysis energy from waste plant

But, as the Figure 3 pyrolysis plant is EfW, to achieve its purpose it must liberate sufficient *surplus* energy to either raise steam and/or provide space heating via the two Heat Exchange units (E) and (F). The source of heat to these exchangers comes from tapping the loop of the Pyrolysis Reactor/Combustion Chamber cycle. Although in practice different reactor outlets, and likely additional combustion chambers, would be necessary to cater for the different pyrolysis products, thus incurring additional challenges and efficiency losses, these complexities are excluded in order to again present the concept in its most generous terms. Similarly, no gas cleaning systems are appended to this theoretical system which would be essential, and which would incur additional energy and resource inputs lest the tars are emitted directly to sewer or air, nor are any second law thermodynamic efficiency losses applied for these same reasons, and as with Figure 2.

Char is the structural solid (conventionally known as "fixed") carbon framework of lignocellulosic organic matter, with a higher energy density than the gas or oils. Assuming that its energy density can be sufficient, the thermodynamic feasibilty of such a system then depends on the quantity of char, the purity of char, along with practical aspects concerning char management.

5.2.1. Quantity of Char Available from Pyrolysis of MSW

Many pyrolysis reactor variables can affect how products split into different chemical phases and compositions, but this mainly affects oil and gas production (Garcia-Nunez et al., 2017). Beyond 500°C char yields vary only mildly with, or are independent of, furnace temperature, and for wood this usually results in a char fraction of between 10 and 20% by dry weight (Garcia-Nunez et al., 2017; Cozzani et al., 1995). Prior to this reaction temperature pyrolysis will remain incomplete and therefore stopping the process below this temperature will not discount the remaining energy requirements but merely shift them to being a parasitic load on the subsequent combustion chamber. The system operator is therefore no better off in energy terms.

The limiting factor in char formation is the feedstock lignocellulosic properties. In municipal refuse the fixed carbon content can be very low, often zero for plastics (Sørum et al., 2001; Reed and Das, 1988; Zhou et al., 2015; Chen et al., 2014). This is illustrated in Figure 4 which shows identical thermogravimetric pyrolysis experiments on a Corsican pine (A) and mixed textile fibre (B) sample. Standard proximate analysis methods were used as reported in Rollinson and Karmakar, (2015). Details on the Corsican pine sample are also contained in the same reference source, while information on the textile is contained in Rollinson (2014). Figure 4 shows how the textile yielded only 4.7% of its mass as char under relatively slow (therefore favourable) char production conditions. When sewage sludge biosolids are considered as pyrolysis feedstocks, char production is so low that its energy content can be ignored (Ma et al., 2018).

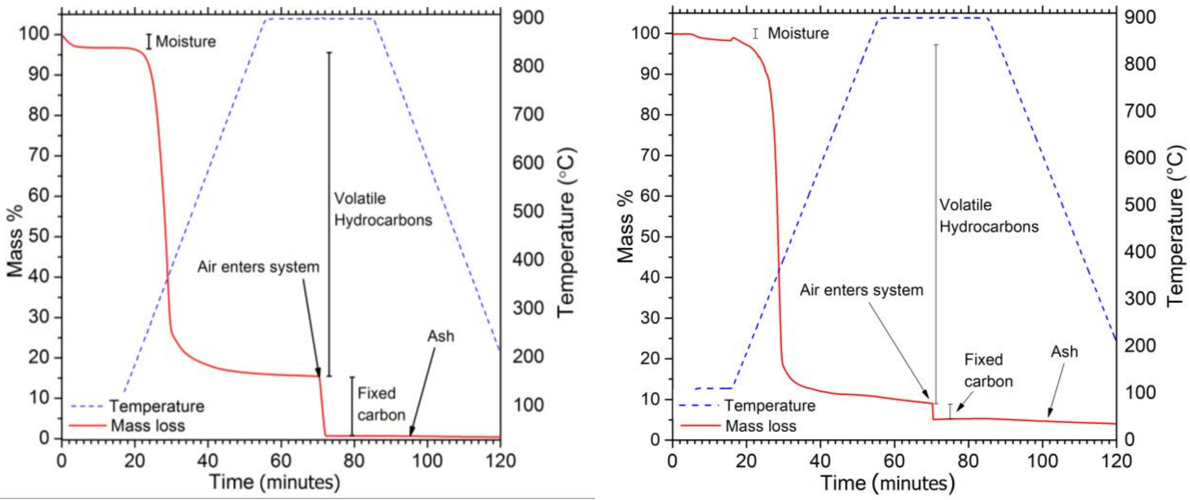

Figure 4. Standard pyrolysis test results for determining volatile, fixed carbon, and inorganic content of fuels.

It is therefore of paramount importance that any pyrolysis system which proposes to accept mixed waste and claim to generate energy for the process by burning char must be aware of feedstock quality, specifically its likelihood of low fixed carbon (char availability), and high compositional variability. Another interesting factor is that when char yield is low, the greater is the endothermicity of the pyrolysis reaction, thus imposing more energy demands on the system. This phenomenon has been reported in a number of research works though the effects are sometimes transient (Hosokai, et al., 2016; Milosavljevic et al., 1996;. Reed and Gaur, 1997).

5.2.2. Purity of Char Available from Pyrolysis of MSW

There are numerous practical aspects of burning MSW char which are challenging and environmentally unsound, hence why the material was disposed of as a hazardous waste at the Burgau plant (see § 4). Similar aspects apply to sewage sludge with its high concentration of heavy metals (Hossain et al., 2009). A review on the subject is contained in a paper by Chen et al. (2014). Here the researchers found that the toxicity rating of PCDD/F products from pyrolysis was three times the input at full operational performance and eleven times the input at pilot scale, and that these toxins were also present in both gas and oil. The researchers also noted the propensity for heavy metals to accumulate in the char, and after appraising this alongside other current evidence they felt it appropriate to state:

"Pyrolysis cannot be safely believed to be a PCDD/F-inhibiting process. However, oil products should be used with care because they can be contaminated with PCDD/F, and the

output of oil from MSW pyrolysis should either be avoided or its destination stipulated beforehand…Therefore industrial waste streams are not suggested to mix with MSW in pyrolysis facilities where char is the output".

Despite the above, and the case study experiences, it is still suggested by modern pyrolysis EfW designs that they burn the residual char to provide energy for all aspects of the process including the raising of steam. This was the case with proposals recently submitted for building thirteen commercial char-combusting pyrolysis EfW systems in the UK. These suggested that the left-over char could not only self-sustain the pyrolysis reactor but also generate copious volumes of steam, and after it had done this dry the feedstock from 40% to 0%, then also heat the gas clean-up systems (Rollinson, 2015).

5.3. Additional Engineering Practicalities of MSW Pyrolysis

Whether self-sustaining pyrolysis is theoretically achieveable is fundamental to reactor designs, but satisfactory engineering of the concept is paramount. There are multiple practical engineering fundamentals unaddressed by either Figure 2 or Figure 3, namely: the intrinsic engineering challenges associated with cleaning tar from the internal surfaces of the reactor and other process piping (otherwise system heat transfer impairment and a total system clean out after one operational batch), how metals within the char are to be captured, how other pollutant emissions will be controlled, the difficulty of stabilising temperature fluctuations when loading the reactor up with waste, and the removal of char. These tacit operational aspects are outside the scope of this work but described by the references contained in § 3 and § 4. On top of these are inherent second law of thermodynamics heat losses.

With regard to Figure 3, such a system must use more energy, and therefore be more expensive for the system owner to operate, than by heating the water directly using, say, electricity. This is because the second law of thermodynamics dictates that the extra process stages increase inefficiencies due to heat losses, meaning that the system is, in effect, an energy intensive water heater with numerous additional process challenges and pathways to environmental pollution. Moreover, to keep tar above its dew point, the process lines prior to the combustion chamber must be heated too thus incurring additional energy demands and additional (second law of thermodynamics) heat losses. The only way to overcome this is to have the Combustion Chamber "close-coupled" to the Pyrolysis Reactor, which would then mean that the system was in effect an incinerator, with best practice determining that it should be grate fired for complete mixing, and then the whole design concept becomes redundant.

The caveat to both Figure 2 and Figure 3 is the heating element at the base of the Pyrolysis Reactor (A). Though shown as electricity, this could be Natural Gas, diesel oil, or coal. As mentioned, it is essential for start-up, but also at any other time when the system is labouring and producing a dirty gas. (Rollinson, 2016). It is common for permit applications to state that this is only used when necessary, albeit with duration not quantified this leaves the possibility open for extended usage (Enzygo, 2016; Icena Projects Limited, 2014).

6. Non-conventional Pyrolysis (Plasma and Microwave)

The thermodynamic principles and practical aspects described above are generic. However, for completeness, two 'non-conventional' pyrolysis methods are worthy of mention – plasma and microwave – though both are not currently deemed as practicable for EfW when using municipal refuse (Chen et al., 2014; Garcia-Nunez et al., 2017). The consideration of these concepts is increasing with companies pitching their feasibility at both large and pilot scale plants, although research information remains restricted to laboratory-scale testing, where weak evaluation of energy balances and net efficiencies are coincident with a tone of general optimism.

Plasma is a highly energetic ionised gas. It has been proposed as a method of thermally decomposing MSW, and there have been some attempts at commercial testing. In this process, the MSW is exposed to extremely high temperatures (ca. 1500 ≤ °C ≤ 7,000) which has advantages because tar is eliminated. But, this comes at an energetic cost with values of energy input from plasma arc gasification between 400 and 1000 kWh per tonne of MSW compared with the potential electricity production of ca. 830 kWh per tonne, and as such these systems are not considered as compatible with the idea of EfW by many authors (Leckner, 2015; Chen et al., 2014).

Microwave pyrolysis is more novel. It offers rapid and selective in-core heating, but it has numerous disadvantages which mean that it is limited to waste destruction (not EfW) and is practicable only with homogeneous feedstocks such as dried sewage sludge, shredded plastics and tyres (Chen et al., 2014; Ma et al., 2018). The feedstock must be finely shredded and mixed with heterogeneous metal catalyst or other wave absorbing materials (e.g. char); and the process requires high input energy, is prone to uneven internal heating, has scale limitations, and has associated electrical fire and system damage hazards particularly where metals are present in the feed (Chen et al., 2014; Garcia-Nunez et al., 2017; Ma et al., 2018). Research authors have a tendency to present results with positive connotations in terms of “Energy Recovery” or “Conversion” efficiencies, despite huge overall energy demands. In studies by one research group, the concept was described as “high efficiency”, but their experimental results showed that the system operated with gross negative efficiencies, using between 5 and 87 times (mean average = 34) more energy than could be obtainable from the pyrolysis products (Gao et al., 2017; Zhang et al., 2017). In an alternative study, Ma et al. (2018) presented results which showed similar negative efficiencies; in this case the system demanded between 18 to 21 times more energy than was contained in the pyrolysis products.

7. Discussion

Governments throughout the world are under great pressure to support MSW-fed pyrolysis concepts, currently advertised as a silver bullet for solving waste disposal problems in addition to offering lucrative business/investment opportunities and contributing positively to energy supply (Mutz et al., 2017). In the last five years the United Kingdom has succumbed and encouraged technology providers through varying avenues of financial subsidy (House of Parliament, 2014; House of Parliament, 2015; Green Investment Bank, 2016; UK Government, 2016). This has in turn led to an unprecedented number of applications seeking permission to build and operate concept MSW pyrolysis plants (Dowen, 2017). Though until now not widely reported, it is common for the information on these system designs to be devoid of satisfactory energy balances and to promise capabilities which appear to ignore thermodynamic laws at the same time as purporting to create "sustainable" (Brown, 2018), "renewable" (REA, 2011), or even in one case "reuseable" energy (Derby City Council, 2017). This seeming indifference or ignorance to both antecedents and thermodynamic principles has been the rationale for this study.

If society is to make a transition to a more sustainable future it is imperative that there is clarity on how these newly proposed EfW technologies manage energy and resource consumption. Equally, if the engineering profession is to maintain credibility it is fundamental that the laws of thermodynamics are obeyed in designs which are put forward for investment. Furthermore, it is also an ethical and professional duty of science to challenge misdirected or spurious claims.

Assuming that, contrary to the state of knowledge reported in this paper, the modern pyrolysis EfW technology developers have not, independently and in secret, achieved something as yet unreported in scientific literature, the question of why claims of self-sustaining MSW pyrolysis are made is of importance. Proposing to build machines which have previously experienced technical problems is not evidence *per se* of patented blunderings. But, when resultant failures are widespread and seemingly ignored, they do however provide circumstantial evidence that something is amiss in a broader context. The key factor can be attributed to an indifference or ignorance towards the first, and particularly the second, law of thermodynamics. Similar reasons were identified one hundred and fifty years ago by Henry Dircks, who also speculated on what drives such endeavours (Dircks, 1870):

"It being certain that no government reward exists to tempt the unwary into this perplexing pursuit, it must be presumed that some persons follow it for amusement, others for renown, and all from sheer simplicity and ignorance".

This study has found that the status of energy use and efficiency awareness in the pyrolysis of waste sector is at best poor, and that the failures of previous plants are not merely teething troubles of a new industry but due to fundamentals flaws with the concept in general and how it is presented, seemingly based on bias towards the theoretical plausibility of a technological innovation. Such ignorance (whether simply lack of knowledge, blind optimism, or intentionally 'turning a blind eye'), has recently been suggested as an explanation for why those promoting or supporting MSW pyrolysis systems receive subsidy rather than censure (Gleis, 2012):

> *"To understand and explain why highly industrialised member states like Great Britain are keen on making their own negative experiences with the mentioned technologies under the financial support of the state, and considering the fact that Germany suffered significant financial losses following similar steps, one can only assume that when such policy decisions are made, foreign experiences are very likely ignored".*

In Henry Dircks' speculations he indicated that government rewards did not exist in 1870; but this is not the case in the 21st Century. In one of the few academic papers to discuss the subject, financial rewards are acknowledged as being in part responsible for the growth of the concept above and beyond the current state of knowledge (Levidow and Upham, 2017):

"ATT is driven by the UK subsidy regime, which perversely gives more support to unproven technologies in the UK residual waste treatment market"

Like many countries, the UK has obligations to legislate for climate change mitigation and waste reduction, but it does not widely implement the 'reduce and re-use' tiers of the waste hierarchy (European Commission, 2008). This approach is considered as representative of a current (and therefore unprogressive) mode of consumption which aims to perpetuate a "throwaway society" and represents an antithesis to the Circular Economy (Gregson et al., 2013). It may explain why EfW is preferred as part of a waste management strategy over options higher up the hierarchy while somewhat paradoxically new retail product efficiency is encouraged by legislation (European Commission, 2010). The environment is also typical of an "economy as usual" model (Cottey, 2018) with weak regulation and where speculation exists based on zeal for the ultimate technological solution and probable technical ignorance of investors (Tangri and Wilson, 2017).

An important factor is that the search for alternative EfW technologies has been driven, not for pure technological reasons, but in the main by the negative publicity associated with incineration, the economic ramifications of which impact on political and private sector proposals to build a waste incineration plant (Seltenrich, 2016; Vehlow, 2015). Consequently, during the last decade, professional representatives of the EfW sector have published guides to "assist" decision makers on the merits of waste pyrolysis and gasification (REA, 2011). While other highly respected organisations have literally blundered in the attempt to separate the term 'EfW' from incineration despite it being the most widely applied plant design (ImechE, 2008):

"It is important to note that an EfW plant is not the same as an 'incinerator' and it is highly misleading to describe it as such".

The academic community has also had the attraction of government rewards provided through the inducement of competitive research funding. Such rewards are known to create ethical hazards which can lead to undermining the academic (Mertonian) norms of communalism, universalism, disinteredness, and organised scepticism (Cottey, 2016). Specifically, these hazards concern the temptation to focus only on the positive "selling points" in grant applications and research outputs (the latter of which are then used in the pursuit of further funding) and to simultaneously not disclose technical concept limitations. Compounding this, recent years have seen a preference in Anglo-America and Australasia for research funding which links academia with private sector innovators (see for example UK Government, 2016; Australian Government 2018), thus creating additional ethical hazards based on possible dilemmas: firstly, where reporting or presenting full transparency might have a detrimental impact on the interests of the commercial partners, and secondly because these partnerships must be fostered for grant eligibility. The above could explain the lack or reporting on fundamental energy balances, why there has been insufficient research devoted to properly elucidating this most fundamental of concepts, and perhaps also why "patented blunderings" have not so far been openly challenged by academics.

In summary, in the search for alternative energy sources and solutions to the societal problem of municipal waste, it seems that many in the EfW sector have drifted away from the tenets of engineering design efficiency and the need for sustainability. With this, and without a complete information base, the scaling up of pyrolysis EfW systems to industrial implementation is easily identified as an improperly assessed technology, and one which can only result in a huge drain on future financial and material resources when put into practice. To counter this, proper assessments and evaluations must be enforced by civil assessors and academic peer reviewers, with candour required across all areas of the sector. As with this study, such reporting is not based on a desire for overt criticism, but to seek out universal truths and through these to assist in the development of robust engineering science, aims which are appropriate for any new technology but equally, as in this case, the revisiting of an old concept. Such transparency underpins knowledge development and is beneficial for all, even where technical limitations are found to be insurmountable, for then it permits the identification of a technology's most appropriate societal niche. This indeed may be the case with pyrolysis when oil reserves are expended, whence it may return as the only method of producing certain useful chemicals. However, as an alternative energy source, and in answer to the immediate and escalating problems of global municipal refuse, it is recommended that the solution does not lie with pyrolysis systems at all; rather in the widespread implementation of strategies for "reduction" and "re-use", along with a preference for creating products with in-built recyclability and/or which are built to last.

8. Conclusions

This review has shown that when appropriate system boundaries are applied, a pyrolysis plant for self-sustaining EfW is thermodynamically unproven, practically implausible, and environmentally unsound. Modest positive energy balances have been reported but only under the impractical and unsustainable conditions of:

1. When the drying energy has been set outside the system boundary.
2. Without considering fundamental (second law of thermodynamic) heat losses.
3. Discounting essential auxiliary energy to manage the plant such as, but not exclusively, gas cleaning, pre-processing, and supplementary fuels to the reactor.

Three claims of self-sustaining pyrolysis feasibility have been reported in literature on the basis of these restrictive conditions, using methodologies based on assumptions and extrapolation. No practical examples of a self-sustaining MSW pyrolysis plant, using either gas, oil, or char were found. With this, combined with case study information and other academic literature which refutes the conjecture, it is concluded that the hypothesis tested by this research is found to be disproven.

If it is not possible for a pyrolysis waste destruction concept to operate with positive net efficiency in these circumstances, then it is impossible for it to provide *surplus* energy, and hence to be considered as EfW without the input of extraneous resources. As such, the hypothesis of an EfW pyrolysis plant being self-sustaining using its own gas and oil products must also be null.

The utilisation of the high energy density char fraction, possibly in combination with associated gas and oil products, could in theory provide sufficient energy to self-sustain a pyrolysis plant. This however remains unvalidated when considering waste as a feedstock. Numerous practical aspects of the concept also appear to refute its feasibility, namely the low char generation potential of municipal refuse, its toxicity when derived from waste, the thermodynamic and practical challenges associated with feeding and emptying the reactor, entropic heat losses, and mitigating tar production. In addition, antecedents prove that, though the concept has been "tried and tested", it still remains at present "*un*-proven".

By using additional energy to heat the pyrolysis reactor, plus by designing for the input of additional energy and resources to scrub and clean the product gases, and/or by pre-treating the feedstock through sorting, segregation, and pre-heating, the system may be made operational to a degree of efficacy. But, it is misrepresentative to describe these pyrolysis systems as being sustainable EfW concepts. Such claims merely set the necessary energy and resource usage outside of the system boundary. MSW pyrolysis cannot yet be considered as something which can sustainably provide energy for society, and it is advised that before embarking on future attempts at designing, assessing, or investing in, such a concept, a full appraisal of antecedents is made. Moreover, it is essential that proper energy balances are determined and in place at the outset, made possible by the first law of thermodynamics, and with a consideration of total plant energy and resource use. Furthermore, and in keeping with the historic pursuit of perpetual motion, it is imperative that the second law of thermodynamics is not simply ignored (Dircks, 1870):

A man presents a complicated machine, combining various wheels, bands, levers, pipes, cisterns, pumps, and water, demanding that it shall be proved to be impossible that such a machine will work of itself. A wise man will reply - Try, and it will certainly fail.

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10.References

Antal Jr, M.J., Grønli, M. 2003. The art, science, and technology of charcoal production, *Ind. Eng. Chem. Res.*, **42**, pp.1619-1640.

Ateş, F., Miskolczi, N., Borsodi, N. 2013. Comparison of real waste (MSW and MPW) pyrolysis in batch reactor over different catalysts. Part 1: Product yields, gas, and pyrolysis oil. Bioresource Technol., **133**, pp.443-454.

Australian Government, 2018. Global Innovation Linkages (online). Accessed 23rd October 2018. Available from: https://www.business.gov.au/assistance/global-innovation-linkages-programme

Bosmans, A., Helsen, L. 2010. Energy from waste: review of thermochemical technologies for refuse derived fuel (RDF) treatment. In: International symposium on energy from biomass and waste edition 3, Venice, Italy, 8th to 11th November 2010.

Bridgwater, T. 2006. Biomass for Energy. *J. Sci. Food and Agriculture*, 86, pp.1755-1768.

Bridgwater, A.V. 2012. Review of fast pyrolysis of biomass and product upgrading. *Biomass Bioenerg*., **38**, pp.68-94.

British Standards Institution. 2011. Solid recovered fuels - Specifications and classes. BS EN 15359:2011.

Brown, G.R. 2018. Converting Waste into Electricity as a Sustainable Source of Energy. Water and Energy Sustainable Innovation and Industry (WESII) Conference and Exhibition, University of Bahrain, 23rd April 2018 (online). Available from: http://wesii.uob.edu.bh/presentations

Chen, D., Yin, L., Wang, H., He, P., 2014. Pyrolysis technologies for municipal solid waste: A review, *Waste Manag.*, **34**, 2466-2486.

Clark, J.F.M., 2007. 'The incineration of refuse is beautiful': Torquay and the introduction of municipal waste destructors, *Urban Hist.*, **34** (2), 255-277.

Consonni, S, Viganò, F., 2012. Waste gasification vs. conventional Waste-To-Energy: A comparative evaluation of two commercial technologies, *Waste Manag.*, **32**, 653-666.

Cottey, A. 2016. Reducing ethical hazards in knowledge Production. *Sci. Eng. Ethics*, **22** (2), pp. 367-389.

Cottey, A. 2018. Environment change, economy change and reducing conflict at source. AI Soc., **33** (2), pp.215-228.

Cozzani, V., Nicolella, C., Petarca, L., Rovatti, M., Tognotti, L. 2006. A fundamental study on conventional pyrolysis of a refuse-derived fuel. *Ind. Eng. Chem. Res.*, **34**, pp.2006-2020.

Crombie, K., Mašek, O. 2014. Investigating the potential for a self-sustaining slow pyrolysis system under varying operating conditions. *Bioresource Technol.*, 162, pp.148-156.

Czajczyńska, D., Anguilano, L., Ghazal, H., Krzyżyńska, R., Reynolds, A.J., Spencer, N., Jouhara, H. 2017. Potential of pyrolysis processes in the waste management sector. *Thermal Sci. Eng. Prog.*, **3**, pp. 171-197.

De Filippis, P.D., Scarsella, M., Verdone, N., Carnevale, G.B. 2015. Batch waste gasification technology: characteristics and perspectives. In: Syngellakis, S. (ed), Waste to Energy, WIT Press: Southampton, pp. 125-132.

Derby City Council. 2017. Permit reference PPC/SWIP1/2017 Schedule 13A Installation permit, p.5. Not available online but held in public registry and accessible to view by appointment or on request from environmental.services@derby.gov.uk

Dircks, H. 1870. Perpetuum Mobile: or a history of the search for self-motive power from the 13th century to the 19th century (Second Series). E. & F. N. Spon: London.

Dong, J., Chi, Y., Tang, Y., Ni, M., Nzihou, A., Weiss-Hortala, E., Huang, Q. 2016. Effect of operating parameters and moisture content on municipal solid waste pyrolysis and gasification, *Energ. Fuel.*, 30, pp. 3994-4001.

Dowen, S. 2016. UKWIN Briefing. Gasification failures in the UK: Bankruptcies and abandonment (online). Accessed 20th June 2018. Available from:. http://www.ukwin.org.uk/files/pdf/UKWIN_Gasification_Failures_Briefing.pdf

Eddington, A.S. 1928. The Nature of the Physical World. Cambridge University Press: London. pp.68-71.

Ellen MacArthur Foundation. 2014. Towards the Circular Economy, Accelerating the scale-up across global supply chains, pp. 14-15 (online). Accessed 12th June 2018. Available from: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Towards-the-circular-economy-volume-3.pdf

Enzygo, 2016. Operational Techniques and Monitoring Plan, Derby Plant for Envirofusion Limited CRM.092.001. Environmental Permit. Available from: https://www.derby.gov.uk/council-and-democracy/consultations/ycys-closed/envirofusion-environmental-permit/

European Commission. 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives L312/3. pp.1-28 (online). Accessed 2nd August 2018. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098

European Commission, 2017. JRC Science for Policy Report. Best Available techniques (BAT) reference Document on Waste Incineration. Industrial Emissions Directive 2010/75/EU.

pp.382-401 (online). Accessed 31st July 2018. Available from: http://eippcb.jrc.ec.europa.eu/reference/BREF/WI/WI_5_24-05-2017_web.pdf

European Commission. 2010. Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products (online). Accessed 7th June 2018. Available from: https://eur-lex.europa.eu/eli/dir/2010/30/oj

GAIA. 2006. Incinerators in Disguise (online). Accessed 20th July 2018). Available from:. http://www.no-burn.org/wp-content/uploads/Incinerators-in-Disguise-Case-Studies-of-Gasification-Pyrolysis-and-Plasma-in-Europe-Asia-and-the-United-States-.pdf

Gao, Z., Zhang, H., Ao, W., Li, J., Liu, G., Chen, X., Fu, J., Ran, C., Liu, Y., Kang, Q., Mao, X., Dai, J. 2017. Microwave pyrolysis of textile dyeing sludge in a continuously operated auger reactor: Condensates and non-condensable gases, *Environ. Pollut.*, **228**, pp. 331-343.

Garcia-Nunez, J.A., Palaez-Samaniego, M.R., Garcia-Perez, M.E., Fonts, I., Abrego, J., Westerhof, R.J.M., Garcia-Perez, M. 2017. Historical developments of pyrolysis reactors: a review. *Energ. Fuel.,* 31, pp. 5751-5775.

Gleis, M. 2012. Gasification and Pyrolysis - reliable options for waste treatment? In: Thomé-Kozmiensky and Thiel, S. (eds), *Waste Management* **3**, Vivis, TK Verlag. pp. 403-410.

Gouleke, C.G. 1975. Effect on lifestyle from governmental and free enterprise cooperation. *Water Air Soil Pollut.*, **4** (2), pp.303-309.

Green Investment Bank. 2016. Summary of transactions. http://greeninvestmentgroup.com/media/44912/gib_transaction-table_101215.pdf (accessed 12th February 2018).

Gregson, N., Crang, M., Laws, J., Fleetwood, T., Holmes, H. 2013. Moving up the waste hierarchy: car boot sales, reuse exchange and challenges of consumer culture to waste prevention. Resour. Conserv. Recy., **77**, pp. 97-107.

Hossain, M.K., Strezov, V., Nelson, P.F. 2009. Thermal characterisation of the products of wastewater sludge pyrolysis. *J. Anal. Appl. Pyrol.*, **85**, pp.442-446.

House of Parliament, 2014. The Contracts for Difference (Definition of Eligible Generator) Regulations 2014. No. 2010.

House of Parliament, 2015. The Renewables Obligation Order 2015. No 0000.

Hosokai, S., Matsuoka, K., Kuramoto, K., Suzuki, Y. 2016. Practical estimation of reaction heat during the pyrolysis of cedar wood. *Fuel Process. Technol.*, **154**, pp.156-162.

Iceni Projects Limited, 2012. Planning Statement prepared for Clean Power Properties Ltd and Network Rail Infrastructure Ltd. Available from: http://eplanning.idox.birmingham.gov.uk/publisher/docs/D1BEBA978DE61053EDEC486C93A1965C/Document-D1BEBA978DE61053EDEC486C93A1965C.pdfp

IMechE. 2008. Energy from Waste - a wasted opportunity (online). Accessed 6th August 2018. Available from: http://www.imeche.org/policy-and-press/reports/detail/energy-from-waste-a-wasted-opportunity

Kaupp, A. 1984a. Gasification of Rice Hulls theory and praxis. Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH: Eschborn.

Kaupp, A., 1984b. State of the art for small-scale gas producer-engine systems, First published by the German Appropriate Technology Exchange (GATE), Reissued by the Biomass Energy Foundation Press: Golden.

Kiel, J.H.A., van Paasen, S.V.B., Neeft, J.P.A., Devi, L., Ptasinski, K.J., Janssen, F.J.J.G, Meijer, R., Berends, R.H., Temmink, H.M.G., Brem, G., Padban, N., Bramer, E.A., 2004. Primary measures to reduce tar formation in fluidised-bed biomass gasifiers. Final report SDE project P1999-012, ECN-C—04-014. Energy Research Centre of the Netherlands.

Knapp, S. 2002. The market for small-scale waste gasification/pyrolysis projects - preliminary scoping study. In: Recovering Energy from Waste: various aspects. Eds: Grover, V.I., Grover, V.K., Hogland, W. Science Publishers Inc: Enfield, pp. 317-330.

Leckner, B., 2015. Process aspects in combustion and gasification Waste-to-Energy (WtE). *Waste Manag.*, **37**, 13-25.

Levidow, L., Upham, P. 2017. Socio-technical change linking expectations and representations: Innovating thermal treatment of municipal solid waste. *Sci. Publ. Policy*, **44** (2), pp.211-224.

Lin, X., Wang, F., Chi, Y., Huang, Q., Yan, J. 2015. A simple method for predicting the lower heating value of municipal waste in China based on wet physical composition, *Waste Manag.*, **36**, pp.24-32.

Lombardi, L., Carnevale, E., Corti, A. 2015. A review of technologies and performances of thermal treatment for energy recover from waste. *Waste Manag.*, **37**, pp. 26-44.

Ma, R., Sun, S., Geng, H., Fang, L., Zhang, P., Zhang, X. 2018. Study on the characteristics of microwave pyrolysis of high ash sludge, including the products, yields, and energy recovery efficiencies, *Energ.*, **144**, pp.515-525.

Malkow, T. 2004. Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal. *Waste Manag.*, **24**, 53-79.

Mavropoulos, A. 2012. History of Gasification of Municipal Solid Waste through the eyes of Mr Hakan Rylander (online), 19th April 2012 (Accessed 13th July 2018). Available from: https://wastelessfuture.com/lets-speak-about-waste-to-energy/

McNamara, P.J., Koch, J.D., Liu, Z., Zitomer, D.H. 2016. Pyrolysis of dried wastewater biosolids can be energy positive, *Water Environ. Res.*, **88** (9), pp. 804-808.

Milosavljevic, I., Oja, V., Suuberg, E.M. 1996. Thermal effects in cellulose pyrolysis: relationship to char formation processes. *Ind. Eng. Chem. Res.*, **35**, pp. 653-662.

Mutz, D., Hengevoss, D., Hugi, C., Gross, T. 2017. Waste-to-Energy options in municipal solid waste management. A guide for decision makers in developing and emerging countries. Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH. pp. 1-57.

Murphy, D.J., Hall, C.A.S. 2010. Year in review - EROI or energy return on (energy) invested. Annals of the New York Academy of Sciences: *Ecol. Econ. Rev*., 1185, pp. 102-118.

National Infrastructure Planning. 2018. Ferrybridge Multifuel 2 (FM2) Power Station (online). Accessed 1st August 2018. Available from: https://infrastructure.planninginspectorate.gov.uk/projects/yorkshire-and-the-humber/ferrybridge-multifuel-2-fm2-power-station/?ipcsection=docs

Okumura, Y., Hanaoka, T., Sakanishi, K. Effect of pyrolysis conditions on gasification reactivity of woody biomass-derived char, (2009), *P. Combust. Inst.,* **32**, pp. 2013-2020.

Quicker, P., Neuerburg, F., Noēl, Y., Huras, A., 2015. Status of alternative techniques for thermal waste treatment - expert report for the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Project No. Z6-30345/18, Report No. 29217, English translation: Bār, H. Rheinisch-Westfälische Technische Hochschule Aachen Unit of Technology of Fuels (TEER) Wüllnerstraße 2 52062 Aachen.

Rabou, L.P.L.M., Zwart, R.W.R., Vreugdenhil, B.J., Bos, L. 2009. Tar in Biomass Producer Gas, the Energy Research Centre of the Netherlands (ECN) Experience: An Enduring Challenge, *Energ. Fuel.*, **23**, pp. 6189-6198.

REA, 2011. Energy from Waste. A guide for decision-makers. Renewable Energy Association. Available from: https://www.r-e-a.net/pdf/energy-from-waste-guide-for-decision-makers.pdf

Reed, T., Das, A. 1988. Handbook of Biomass Downdraft Gasifier Engine Systems, Solar Energy Research Institute: Colorado.

Reed, T.B., Gaur, S. 1997. The high heat of fast pyrolysis for large particles. In: Developments in Thermochemical Biomass Conversion Volume 1. Edited by A.V. Bridgwater and JD.G.B. Boocock, Blackie Academic and Professional: London, pp. 97-103.

Ripley, J.T. 2014. Routine caol and coke analysis: collection, interpretation, and use of analytical data MNL57-2ND (2nd Edn), Chapter 5: Proximate Analysis. ASTM International: West Conshohocken, pp. 29 - 48.

Rollinson, A.N. 2015. Scientific and engineering appraisal of the Washwood Health Environment Agency permit application EPR/RP3132ND (online). Available from: http://ukwin.org.uk/files/pdf/Rollinson_March_2015_Washwood_Heath_Assessment_EPR_RP3132ND_A001.pdf

Rollinson, A.N. 2018. Fire, explosion and chemical toxicity hazards of gasification energy from waste. *J. Loss Prevent. Proc.,* **54**, pp.273-280.

Rollinson, A.N., Karmakar, M.K. 2015. On the reactivity of various biomass species with CO_2 using a standardised methodology for fixed-bed gasification. *Chem. Eng. Sci.*, **128**, pp. 82-91.

Rollinson, A.N. 2014. Downdraft gasification trials of recycled textile. University of Nottingham, pp.1-8. Available from: http://blushfulearth.co.uk/wp-content/uploads/2018/08/BWF-Recycling-Gasification-Report.pdf

Sørum, L., Grønli, M.G., Hustad, J.E. 2001. Pyrolysis characteristics and kinetics of municipal solid wastes. *Fuel*, **80**, pp.1217-1227.

Seltenrich, N., 2016. Emerging waste-to Energy technologies: Solid waste solution of dead end? *Environ. Health Persp.*, **124**, DOI:10.1289/ehp.124-A106

Suzuki, A., Nagayama, S., 2011. High efficiency WtE power plant using high-temperature gasifying and direct melting furnace. Proceedings Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium, Cagliari, Italy, 3-7 October 2011. CISA Publisher: Italy.

Tanigaki, N., Manako, K., Osada, M., 2012. Co-gasification of municipal solid waste and material recovery in a large-scale gasification and melting system. *Waste Manag.*, **32**, 667-675.

Tangri, N., Wilson, M. 2017. Waste gasification and pyrolysis: high risk, low yield processes for waste management. A technology risk analysis (online). Accessed 7th August 2018. Available from: http://www.no-burn.org/gasification-pyrolysis-risk-analysis/

Twigg, M.V. 1996. Catalyst handbook (2nd Ed.) London: Manson, pp. 17-282.

TwE. 2014. Gasification Technologies Review - Technology, Resources and Implementation Scenarios. Final revised Report. Talent with Energy for the City of Sydney's Advanced Waste Treatment Master Plan (online). Accessed 20th June 2018. Available from: http://www.cityofsydney.nsw.gov.au/__data/assets/pdf_file/0012/215211/2014-370487-06-Appendix-Gasification-Technologies-Review-FINAL-edit.pdf

UK Government, 2016. Innovate UK (online). Accessed 10th August 2018. Available from: https://innovateuk.blog.gov.uk/2016/05/02/innovate-uk-funding-competitions-for-april-2016/

Vehlow, J. 2015. Air pollution control systems in WtE units: an overview. *Waste manag.*, **37**, pp.58-74.

Vehlow, J. 2016. Overview of the Pyrolysis and Gasification Processes for Thermal Disposal of Waste In: Löschau, M. (ed), *Air Pollutant Emissions from Combustion Processes and their Control*, Vivis, TK Verlag. pp. 431-444.

Vreugdenhil, B.J., Zwart, R.W.R., 2009. Tar formation in pyrolysis and gasification, ECN-E—08-087. Energy Research Centre of the Netherlands.

Williams, P.T. 2012. Fuels, chemicals and materials from waste (online). Royal Society of Chemistry ECG Bulletin July 2012. Available from: https://www.envchemgroup.com/paul-williams.html

Williams, P.T., Barton, J.R. 2010. Research, monitoring and evaluation of the Scarborough Power/GEM pyrolysis facility in Seamer Carr, Scarborough, Yorkshire, 5th March 2010.

Woolcock, P.J., Brown, R.C. 2013. A review of cleaning technologies for biomass-derived syngas, *Biomass Bioenerg.*, **52**, pp.54-84.

Yang, H., Kudo, S., Kuo, H-P., Norinaga, K., Mori, A., Mašek., Hayashi, J. 2013. Estimation of enthalpy of Bio-oil vapor and heat required for pyrolysis of biomass. *Energy Fuel.*, 27, pp.2675-2686.

Zhang, H., Gao, Z., Ao, W., Li, J., Liu, G., Fu, J., Ran, C., Liu, Y., Kang, Q., Mao, X., Dai, J. 2017. Microwave pyrolysis of textile dyeing sludge in a continuously operated auger reactor. *Fuel Process Technol.*, **166**, pp. 174-185.

Zhou, H., Wu, C., Onwudili, J.A., Meng, A., Zhang, Y., Williams, P.T. 2015. Polycyclic aromatic hydrocarbons (PAH) formation from the pyrolysis of different municipal solid waste fractions, *Waste Manag.*, **36**, pp.136-146.

Zwart, R.W.R., Van der Drift, A., Bos, A., Visser, H.J.M., Cieplik, M.K., Könemann, H.W.J. 2009. Oil-based gas washing – the flexible tar removal for high efficient production of clean heat and power as well as sustainable fuels and chemicals, *Environ. Prog. Sustain.*, 28, pp324-334.