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Editorial

Energy and Waste Management

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Abstract: Waste management and energy systems are often interlinked, either directly by waste-to-energy technologies, or indirectly as processes for recovery of resources—such as materials, oils, manure, or sludge—use energy in their processes or substitute conventional production of the commodities for which the recycling processes provide raw materials. A special issue in *Energies* on the topic of "Energy and Waste Management" attained a lot of attention from the scientific community. In particular, papers contributing to improved understanding of the combined management of waste and energy were invited. In all, 9 papers were published out of 24 unique submissions. The papers cover technical topics such as leaching of heavy metals, pyrolysis, and production of synthetic natural gas in addition to different systems assessments of horse manure, incineration, and complex future scenarios at a national level. All papers except one focused on energy recovery from waste. That particular paper focused on waste management of infrastructure in an energy system (wind turbines). Published papers illustrate research in the field of energy and waste management on both a current detailed process level as well as on a future system level. Knowledge gained on both types is necessary to be able to make progress towards a circular economy.

Keywords: energy; waste; incineration; pyrolysis; gasification; anaerobic digestion; district heating; LCA; manure; ash; oil; scenarios; wind power; SNG

1. Introduction

In a time with increasing population [1] and wealth [2], energy supply and waste management is under great pressure [3,4]. We are still on a path to go beyond even more safe limits, i.e., the system boundaries set by planet Earth and not by ourselves [5].

Today, globally, energy is mostly supplied by fossil fuels [6], which is a dead end in light of global warming. However, investments in renewable energy supply—such as solar, wind, and hydro power—are constantly increasing while the investment costs, in particular for solar PV, are decreasing [6]. In fact, capital is moving by divestments in "stranded assets" such as coal and oil [6]. Also nuclear power is expanding due to its limited impact on global warming, but it should be emphasized that there is significant environmental impact and risk of health damage associated with nuclear power [7]. In addition, nuclear power suffers from poor resource efficiency [8].

At the same time, waste generation rates are high and increasing [9]. According to the World Bank [4], global waste amounts in 2002 of 0.68 billion tons of municipal solid waste per year and is projected to increase by 2025 to 2.2 billion tons of per year. This is partly due to population growth and urbanization (raising from 2.9 to 4.3 billion urban residents) but increasing wealth also means adopting more intensive consumption patterns (from 0.64 to 1.42 kg/capita day) [4]. Even if re-use and recycling are making progress, most waste is still subject to landfill disposal with poor resource recovery, causing emissions of climate gases and hazardous substances [4].

Often waste management and energy supply (generation and distribution) are treated separately in political discussions, in research, and in practice e.g., in environmental management. However, waste management systems and energy supply systems are increasingly becoming more inter-linked as waste treatment is developed from open dumps and landfill disposal to energy recovery by incineration and anaerobic digestion. Energy recovery from waste by WtE-plants (Waste-to-Energy) is an example of direct connections between energy and waste management. Also waste generated from energy supply such as slag and ash from combustion of solid fuels, nuclear waste, and waste from construction and demolition of energy generation devices are direct connections. The indirect connections are found when climbing higher in the waste hierarchy, entering levels of recycling, re-use, and reduction. In such cases, energy is not recovered from waste treatment but use of energy is avoided as recycled material replaces virgin material and as products are being re-used or waste generation is prevented, energy is saved by avoiding production of such products. To fully address these issues, methods for evaluation and planning must be equally good in taking into account the dynamics of the waste management system and the energy system [10,11].

Papers within the whole field of waste management that focused on energy recovery were welcome submissions to the special issue. Of special interest were papers on the combined assessment of energy systems and waste management systems, investigating how waste could be turned from a problem to a renewable resource by applying waste-to-energy technologies, thereby offsetting the environmental impact from heating, electricity, fuels for transportation, etc., based on fossil fuels. Topics of interest for publication included, but were not limited to: circular economy, life cycle assessment, scenario- and future studies, technology development, feasibility studies, cost benefit analysis, policy analysis, planning and implementation, and education and training.

2. Review of Published Papers

There were, in total, 27 manuscript submissions, with 24 unique contributions. Half of these (n = 12) were rejected by the managing editor before being subject to peer review. The other half was sent for peer review where three papers were eventually rejected, comprising 12.5% of unique submissions and 25% of peer reviewed. Some nine papers have been published (37.5% of unique submissions, 75% of peer reviewed).

The first study published looks into the issue of heavy metals leaching from incineration fly ash [12]. By treating fly ash in a planetary ball mill, heavy metals will be less soluble in landfill leachate. The efficiency of such treatment was analyzed using various methods such as laser particle diameter analysis, electron microscopy, and X-ray diffraction and florescence analysis. Fly ash from a circulating fluidized bed (CFB) incinerator located in Hangzhou, Zhejiang Province, China was used where some ash was washed and some not. Ball milling was performed and pH in combination with methods mentioned above was used for different observations. The study concludes that mechanochemical treatment "reduces the leaching concentration of Cu, Cr, and Pb, and a preliminary water washing pretreatment effectively promotes the efficiency of stabilization by removing the soluble salts". Using high-energy ball milling drastically reduces particle size in fly ash. In addition, different conclusions for Cu, Cr, and Pb were made.

In another paper, almost the same research team investigates the leaching behavior of CFB air pollution control (APC) residue in a washing process [13]. The washing of fly ash is a method to reduce the content of chlorides which in turn affects the speciation of Cd. Chloride concentration can be determined using an electrical conductivity method which is proposed in the paper. The method was used to evaluate the efficiency of different designs of the washing process. The study concludes that "water washing pretreatment is essential for cement solidification of APC residue or co-combustion of APC residue in a cement-producing kiln, and EC measurement is a practical method in the water washing pretreatment".

Besides solid waste, liquid waste such as used oil also needs to find a proper treatment. In a study made by Mahari et al. [14] microwave pyrolysis was used to recover energy from waste shipping oil (lubricating oil used in operation of the engine). Experiments were conducted, using filtered oil from fishing boats operating outside East Coast of Malaysia, where the yield and composition of byproducts were investigated under different process temperatures. In the rapid heating process, the oil is heated to 600 °C where pyrolysis oil (66%), gases (24%), and char residues (10%) are formed. Results on chemical composition as well as elemental analysis were obtained. The results also showed higher calorific value, mass yield, and thus energy recovery with increasing process temperature. The pyrolysis oil can be used for energy purposes with a heating value of 47–48 MJ/kg which actually is in the higher range of traditional liquid fuels from fossil fuel at 36–48 MJ/kg.

The next paper changes focus completely from energy recovery from waste management to waste recovery from energy supply [15]. The study does not focus on present systems, but rather a future perspective, and asks a question about how to quantify and characterize waste materials from wind turbines. Wind power plants are complicated structures, comprising huge amounts of different metals and plastic. The paper suggests a method to make forecasts on awaiting waste amounts and illuminates this proposal with a Swedish case study. Such quantifications are important to be able to perform accurate LCAs, to retrieve information on what recycling capacity has to be in place, and to determine when (i.e., scrap market research) and which components and material types are in focus. Estimations on annual growth of waste from decommissioned wind power plants are 12% until 2026 and a stunning 41% until 2034. The paper reports on what waste amounts in terms of steel and iron, aluminum, copper, electronics, and blade materials will be in absolute numbers in relation to current recycling capacities. In addition, three different end-of-life scenarios are investigated which suggest that building up the capacity of re-use markets can extend expected material lifespans until improved recycling systems are in place.

From wind power to horse power; horse manure is often seen as a problematic waste due to impurities, high solids content, and heterogeneity with respect to amount and type of bedding material, leaving it with no other treatment options than managed or unmanaged composting [16]. Another possible option would be to treat the manure by anaerobic digestion, thereby recovering both nutrients and energy which imply a higher resource recovery. Another option is incineration with energy recovery in large or small scale plants. A life cycle assessment of different treatment options would reveal the environmental performance of each type of treatment. As such, treatment of horse manure is rare; process data is poor, making it hard to draw clear conclusions except for anaerobic digestion with thermal pretreatment where the climate benefit compared to the other examined methods (unmanaged and managed composting, large (CHP), and small scale incineration) is significant due to avoided use of fossil vehicle fuels. The results are based on horse manure using wood chips as bedding material and a mesophilic anaerobic digestion in a CSTR (continuous stirred tank reactor) including thermal hydrolysis with steam explosion as pretreatment. The produced biogas is used in biogas vehicles, replacing diesel oil with 5% FAME (fatty acid methyl esters) and digestate is spread on arable land, replacing chemical fertilizer. Various factors affecting the result are listed with a recommendation to pursue further research as to come to more clear conclusions.

Anaerobic digestion is sometimes referred to as bio-gasification, apart from thermal gasification which can be used to produce SNG (synthetic natural gas). Kabalina et al. [17] evaluated such technology using RDF (refuse derived fuel) applied to a polygeneration district heating and cooling system. The paper is based on a systems perspective, as with the previous study, but instead of calculating environmental impact, the focus is on energy figures and cost estimations based on the use of thermodynamic and economic models in a parametric analysis of key parameters. The key issue is upgrading traditional district heating and cooling (DHC) systems to polygeneration systems where low value resources are transformed into a mix of outputs such as ethanol, chemicals, fertilizers, biogas, SNG, heat, and electricity. Interestingly, using RDF in such polygeneration systems is not well documented in literature. The case study is an existing natural gas-fired DHC system in Lisboa, Portugal which is described in a computer model. A polygeneration system is proposed built on a gasifier where RDF is converted to syngas, char, and ash. Surplus heat is recovered in the DHC system. Syngas is partly used in a gas turbine with heat recovery and partly in a SNG production unit. Steam is reused internally between different components of the system. Thermodynamic results show that low temperature heat is in excess and cannot be absorbed by the DHC system and the SNG production has a high demand for electricity affecting the system output of electricity significantly. The economic results show a payback period of three years. Also, the economic results are highly sensitive to the production rate of the SNG but profitability is good due to high revenues from the value-added product sales.

The most comprehensive system study in the special issue is the environmental assessment of possible future waste management scenarios [18]. In the paper, one comprehensive LCA model, five different future (2030) scenarios, and four waste management policy instruments are combined in a Swedish context. The LCA model (called SWEA) works together with two other models to interact over economic development and treatment costs. Process/performance data in the LCA model comes from various sources, among these are ORWARE which was also was used in [16]. Waste from two sectors (industry and public sector; households) distributed in 49 waste categories are treated resulting in 5 types of recovered resources (materials, fertilizer, electricity, heat, and biogas) and the associated environmental impact from waste treatment and avoided processes is presented in 18 impact categories, even if any arbitrary chosen impact assessment can be applied. In Sweden, with a high degree of material recycling and efficient energy recovery both with CHP and anaerobic digestion, waste management contributes with environmental benefits. This is also expected to be the case in the future, but the benefit will be less as energy and transport systems will be less polluting and less waste will be generated. A key issue is whether fossil plastic will be phased out as the model results indicate a substantial contribution to GWP (Global Warming Potential) by emissions of CO_2 from waste incineration. Several policy instruments have been tested using the model but the effect is, in most cases, limited. This indicates that such instruments have to be stronger and possibly also combined to be effective in developing a circular economy. The assessment is complex and relies on a number of assumptions, prognoses, and simplifications. However, the model is in many ways unique with its national focus, the feature of evaluating waste prevention measures, and a hard-linked relation to economic optimizing models.

Combining the experimental approach used in [12,13] with anaerobic digestion and manure [16] set the scene for the study performed by Müller et al. [19], where the effect on methane yield and efficiency from substrate recirculation is investigated. Recirculation of substrate between fermenters or from raw digestate to fresh material is a recommended practice to support and secure the biogas process, but to what extent parameters—such as recirculation amount (RA) and recirculation rate (RR)—affect the methane yield is not known. The case study uses a small thermophilic biogas system (120 m^3 plug-flow digester) located at a dairy farm. Digestate from the reactor is placed in a second fermenter with 2000 m^3 capacity. Feedstock consists of 93% manure slurry and 7% energy crops, such as corn silage and grain debris, while the biogas is used in a CHP. Tests were performed where RA of 10 m^3/day (RR 40%) (referred to as "best practice") was decreased stepwise down to 5.5 m^3/day (RR 27%). Results clearly show that the lowest RR value stabilized the fermentation process, thus resulting in significantly higher methane yield in combination with an optimal acid concentration in the substrate.

The last paper ends where we started—in the incineration plant. Using a systems approach, the combined assessment of different parameters crucial for the outcome of environmental assessment of waste management, including incineration, is made using mathematical calculations [20]. The key parameters included are design of the incineration plant (heat only boiler (HOB), condensing plant (CP), or combined heat and power plants (CHP)), avoided energy generation (HOB, CP, CHP), degree of efficiency, electricity efficiency in CHP, avoided fuel (waste, biomass, oil, coal, wind power, natural gas), CO_2 emission level of the avoided electricity generation, and avoided waste management (material recycling, landfill disposal). A complete LCA would be too complex in this case, which is why a simplified approach just looking at CO_2 emissions from incineration of 1 kWh mixed combustible waste is applied. Three factors are more important than others; the power-to-fuel ratio in waste CHP plants, the emission factor for avoided electricity generation, and finally the type of avoided waste management. Designing incinerators as CHP is strongly advised based on the findings. Worth notice is that the emission factor for landfill disposal of 1 kWh waste is of the same magnitude as emission factors for high polluting electricity. The study uses a plant-to-plant comparison approach which is very useful in understanding the consequences when, for example, old incinerators are replaced with new ones or when incineration replaces landfill disposal. The issue of waste export from countries with landfill disposal to countries with efficient waste CHP is discussed for different time perspectives where the short-time recommendation (yes to export) and long term recommendation (improved source separation facilitating recycling and building domestic incineration capacity off-setting use of natural gas) are not the same.

3. Discussion and Conclusions

The published papers show a variety of different research approaches, waste types, energy types, and treatment methods. In Table 1, the papers are compared with respect to different descriptors.

Table 1. Overview of published papers, Y = Yes, N = No.

Descriptor	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]
Energy recovery	Y	Y	Y	N	Y	Y	Y	Y	Y
Energy infrastructure	N	N	N	Y	N	N	N	N	N
Residues from WtE-plants	Y	Y	N	N	N	N	N	N	N
Manure	N	N	N	N	Y	N	N	Y	N
Energy gas	N	N	Y	N	Y	Y	Y	Y	N
District heating (and cooling)	Y	Y	N	N	Y	Y	Y	N	Y
Experimental	Y	Y	Y	N	N	N	N	Y	N
Use of models	N	N	N	N	Y	Y	Y	N	N
Systems perspective	N	N	N	Y	Y	N	Y	N	Y
Future scenarios	N	N	N	Y	Y	Y	Y	N	N

All papers but one cover energy recovery from solid waste. This was more or less expected as it is the most obvious way to combine energy and waste management. The study on wind power plants [15] is the exception to the rule. In the transition from fossil fuels to renewables, more such studies are welcome to illustrate how the decommission of large and old plants using fossil fuels can be conducted, as well as investigating construction, maintenance, and lifetime expectancies for renewable technologies, including not just wind power plants but also solar PV.

Two studies, mainly made by the same research team, are focused on residues from incineration plants. This is increasingly important as many countries likely will incinerate more waste in the future as they finally realize that incineration with energy recovery reduces GHG (greenhouse gases) both by decreased landfill disposal and by replacing fossil fuels in the energy system. More incineration means more ash and slags which in turn calls for improved management of such residues with respect to content of hazardous substances (addressed in the papers [12,13]); which in turn may make it possible to use some residues as construction material.

The waste type in most studies is municipal solid waste (MSW), but two studies [16,19] deal with manure. Wet anaerobic digestion of liquid manure from livestock [19] is a fairly well established technology in contrast to anaerobic (wet or dry) digestion of horse manure. Biogas from manure also presents two environmental benefits: avoiding methane emissions from traditional manure treatment and avoiding emissions from conventional fuels in vehicles or in heat and power supply.

There are four papers working on energy gas (biogas or SNG), even if one study does not have gas in focus [18]. MSW contains plastic which makes it a mix between a biofuel and fossil fuel. Likewise for energy gas from waste management where biogas is the renewable gas and SNG is the fossil gas from used waste shipping oil and a mix from RDF (depending on the properties of the RDF). It may seem contradictory to, on one hand, fight global warming by improved waste management and, on the other hand, produce SNG from mineral oil. However, until renewable alternatives can be used for lubricant in engines or until combustion engines have been switched to hydrogen, LNG, or electrical engines, measures must be taken to minimize the environmental damage from such used oils.

Most studies include district heating (and cooling). Two studies have electricity generation in focus [15,19] while one study recovers oil as fuel which can later be used for different purposes. Depending on local climate conditions, district cooling may be more interesting than district heating in many parts of the world. How to facilitate efficient energy recovery in warm climates is perhaps a challenge where polygeneration may be the key to produce other valuable products such as vehicle fuel.

Around half of the studies are based on experiments on a laboratory scale [12–14] or pilot scale [19]. Some non-experimental studies use models [16–18] while two studies [15,19] are based on calculations which cannot be considered complex mathematical models. Experimental papers are often shorter and focused on a limited set of parameters, while model studies cover large systems with a lot of data, making the papers longer and more comprehensive. Irrespective of if you are an experimentalist or a theorist, uncertainties always have to be addressed. Many times data from experiments or tests are used in calculations or computer models.

Half of the studies apply a systems perspective [15,16,18,20], often in combination with some kind of future studies [15–18]. Research is about obtaining new knowledge and new insights, from a detailed level to a system level, for a current situation or as decision support affecting the future. The included papers illustrate this variety, which demonstrates that all contributions are needed to be able to improve energy and waste management.

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