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Dual-fuel Cycles to Increase the Efficiency of WtE Installations

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The overall efficiency of municipal waste incineration plants is significant lower (typically 20-24 %) compared to fossil fuel power plants (typically 40-60 %). It is however possible to increase the efficiency of the MSW incinerator by integration with other power plants. Typical power plants considered for such integration are gas turbines and gas engines. There are many possible integration schemes leading to designs with varying levels of complexity. This paper, a short literature overview, will discuss the efficiency improvement aspects of dual-fuel combined cycles involving MSW.

1. Introduction

There are 20 waste incinerators in Norway burning about 1.2 Mt of waste and delivering more than 2 TWh of energy (about 1 % of the Norwegian domestic use) according to Statistics Norway. The incinerators generate about 50 % of the total district heat production. Norwegian incinerators also deliver steam to the industry and for electricity generation. Electricity is produced by only 4 incinerators, but the majority of the planned facilities (new or retrofitted/upgraded) installations are expected to produce electricity in addition to heat. The driving forces for increased energy efficiency can be classified into

- **Legislative forces:** The directive 2008/98/EC on waste classifies WtE as a recovery operation rather than a disposal operation depending on the plant's energy efficiency (defined in the directive in the so-called R1 formula). Furthermore, the Norwegian authorities require an energy utilization level (different from the EC directive R1 formula) of at least 50 % in waste incinerators. However, as indicated earlier, in order to classify as recovery operations in the EU system, it is important that Norwegian plants optimize both heat and electricity production.
- **Economic forces:** Favourable economic conditions, i.e. high energy prices and stable customers, can be considered the main driving force for increased energy efficiency. Evidently, the economic framework may be affected by public policy as mentioned above.

MSW incinerators have a central role in meeting base load district heat demand. There are many methods to improve efficiency (and decrease energy losses) in incinerators involving all the main sections of the plant, such as:

- Feedstock, MSW, especially pre-treatment
- Combustion chamber/process (thermal treatment)
- Heat-exchange section, i.e. boiler and steam/CHP cycle
- Flue gas treatment
- Internal use of energy

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This paper will present and discuss retrofit options to increase the energy efficiency of waste to energy (WtE) with a focus on different configurations of the heat recovery and conversion cycle.

2. Dual-fuel hybrid cycles and integration options

The combustion gases from MSW incinerator contain halogenic acidic compounds and alkali salts. The aggressive nature of the flue gases sets a constraint on the maximum superheat temperature possible to avoid severe corrosion. Thus conventional MSW-fired WtE units have low steam parameters (typically 40 bar and 400 °C) leading to poor efficiency. Further the flue gases from the incinerator can be cooled down only to 200 °C to prevent condensation in the heat exchangers. The electric efficiency of municipal waste incineration plants is significant lower (typically 20-24 %) compared to fossil fuel power plants (typically 40-60 %). Such conventional WtE units recover less than 30 % of the available energy in the waste.

Pavlas et al (2011) show that to achieve the efficiencies to be classified as a recovery operation as defined by the formula R1 (briefly touched upon earlier), it is important to have a product mix of both heat and electricity (with more heat than electricity or pure heat) and high steam parameters. It is however possible to increase the efficiency of the MSW incinerator by increasing the steam parameters externally. This can be done by integration with other power cycles such as gas turbines and gas engines. The hybrid gas-MSW cycle will involve two fuels and two thermodynamic cycles.

There are many possible integration schemes leading to designs with varying levels of complexity. The integration schemes can be broadly classified into: fired or fully-fired (referred to as “completely integrated” here) & parallel powered (referred to as “parallel” here) dual-fuel cycles. A schematic representation of the two categories is shown in Figure 1. Their main characteristics may be described as such:

- “parallel” systems where only heat flows are integrated, i.e. only heat-exchange is combined between the two cycles. No connection (direct contact) is occurring between the MSW combustion products and the exhaust gases from the other process
- “completely integrated” systems where the gas streams are combined, i.e. the exhaust air from the topping cycle is used as combustion air for the bottoming cycle (MSW incineration here). Chemical integration is therefore occurring (in addition to heat integration)

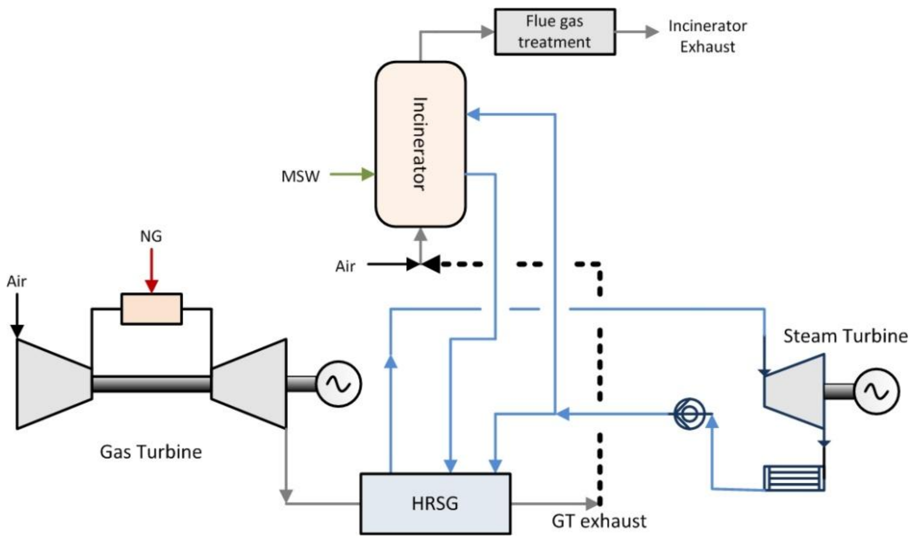

Figure 1: Generic process flow diagram of parallel scheme and completely integrated schemes for efficiency improvement. The completely integrated case incorporates the GT exhaust to the incinerator (represented by thick dashed line).

These arrangements may be seen as co-combustion of two fuels taking place not in the same furnace but in two separate processes. Such combinations/integrations are expected to lead to higher efficiency for the two-fuel system as a whole compared to the plants taken separately because of thermodynamic and technical synergies between the two sub-cycles. The primary integration of such a hybrid cycle is on the water/steam side. The generation of saturated steam in the MSW incinerator boiler reduces the mean temperature difference in the HRSG reducing irreversibilities and thereby increases efficiency.

The steam path in the hybrid cycle can be coupled in many different configurations. Table 1 lists the possible options for a single pressure steam cycle. The option WtE/HRSG for the superheater implies that the WtE unit partially superheats the steam prior to it being fed to the HRSG. The simplest and most commonly studied steam path in literature is Option 1 where all steam is generated in the WtE unit. Options 5 and 6 are also studied extensively in the literature. The complex steam path Option 8 has not been studied in literature. The steam path will of course depend on the number of pressure levels in the steam cycle. For gas turbine in the range 50-200 MW a single pressure steam cycle is normally used in a hybrid cycle while for larger capacity gas turbines (200-400 MW) a triple pressure steam cycle is used in the HRSG while the WtE contributes to one of the pressure levels.

Table 1: Possible steam path configurations for a single pressure level steam cycle

	Economizer	Boiler	Superheater
1	HRSG	WtE	HRSG
2	HRSG	WtE/HRSG	HRSG
3	HRSG/WtE	WtE	HRSG
4	HRSG/WtE	WtE/HRSG	HRSG
5	HRSG	WtE	WtE/HRSG
6	HRSG	WtE/HRSG	WtE/HRSG
7	HRSG/WtE	WtE	WtE/HRSG
8	HRSG/WtE	WtE/HRSG	WtE/HRSG

Other integration options for the hybrid cycles are the different options for air preheat to the WtE unit, steam bypass options and relative size of the WtE unit in the hybrid cycle.

2.1 Advantages and synergies

In addition to potential efficiency gains, other advantages (especially compared to two separate power cycles) can be foreseen when building new or retrofitting waste incinerators to dual-fuel combined cycles:

- Bigger steam turbine means higher attainable efficiencies “One final advantage of integration is the higher steam turbine efficiency ensuing by its larger size.” (Consonni and Silva, 2007; Poma et al, 2010). It is especially true for new plants rather than retrofits.
- The integration of two power plants reduces the number of components compared to two separate units (Wiekmeijer, 1990; Stenhede, 2001; Consonni and Silva, 2007; Poma et al, 2010).
- All proposed combined cycles "are using either standard, readily available items or conventional engineered and fabricated equipment. The use of these proven components contributes to operability, reliability, maintainability and low capital investment” (Lowry and Martin, 1990)
- Eliminating the superheater (some systems) from the WTE boiler reduces corrosion problems and therewith expensive materials in heat exchangers, forced outages and costly maintenance (Consonni and Silva, 2007; Poma et al, 2010).

3. Calculated/expected electrical efficiencies of dual-fuel combined cycles

3.1 Efficiency considerations

Many terms and definitions are used in literature when reporting the efficiencies in a dual-fuel combined cycle. Efficiency may refer to the overall Combined Cycle (CC), i.e. based on total energy input, or the sub-cycles separately. Even though determining the “updated” efficiencies of each sub-cycle in new arrangements may appear as an appealing idea, such “separated” efficiencies calculations are not straightforward, but arbitrary and conditional to the definition of the various systems’ boundaries as discussed by Petrov and Hunyadi (2002). There are three main approaches:

(1) MSW-based efficiency where efficiency of electricity generation from MSW in the cycle is expressed by the ratio {total power output of the system minus the maximum (or average) power output achievable by natural gas (NG) alone (a stand-alone GT)} / MSW energy input.
(2) NG-based (same principle as (1) but for NG)
(3) CC global efficiency.

In approach (1) and (2), the “incremental”, “additional” or “added” capacity is respectively attributed solely to the MSW sub-cycle or to the NG sub-cycle while the other sub-cycle is considered to operate at average or optimal efficiency.

The reference line used for evaluating efficiency gains is also important and should be stated clearly. To sum up, efficiency may be reported overall/global, MSW- or NG-based, gross or net, thermal or electric (power generation). For more details see Petrov (2003) and Petrov and Hunyadi (2002).

After reviewing many articles, we believe that the most straightforward and explicit way of approaching the efficiency benefits of a dual-fuel combined cycle appear to be by comparing the CC overall efficiency to the sum of the (average) efficiencies of two independent cycles taking into account size/scale effects.

3.2 Calculated/expected efficiency gains from literature

17 publications from the literature reviewed to establish the expected gains from dual-fired combined cycles are listed in Table 2. The hybrid cycles deliver higher efficiencies compared to two stand-alone sub-cycles; typically 1-5 percentage points higher than two stand-alone sub-cycles Due to space limitations results from each publication is not presented but a generic overview of the expected efficiency gains is discussed here.

Apart from the problems posed by different efficiency notions (see previous section), it appears almost impossible to compare different articles as the turbine/engine (type, size, and manufacturer) and the WtE plant (size, technology, MSW composition) and layout chosen are almost always different. However, all the publications agree on two points: (1) Dual-fuel combined cycles give an increase of the efficiency of energy recovery compared to the averaged performance of two separate single-fuel units and (2) the energy gains attainable vary by unit.

As a general rule, it can be expected that a higher degree of integration and/or complexity is accompanied by higher efficiency gains but it is not automatic and will also frequently imply technical issues. This is seen in most results in literature in that the "completely integrated" configurations do not outperform the "parallel" configurations over all ranges of natural gas firing percentages.

Almost all studies evaluate the performance of the different configurations by varying the percentage of natural gas fired. The relative efficiency gain of the steam path configurations vary subject to the heat flow balances over the range. For instance, Option 1 (in Table 1) will perform poorly compared to Option 2. In Option 1, as the natural gas firing percentage is increased, the heat available for the economizer and superheater in HRSG will increase while the steam generated in the WtE unit will be constant leading to an imbalance in the HRSG which can be utilized by generating some steam as in Option 2.

The integrated configuration should be designed in light of not only efficiency (and efficiency gains) but also cost, and simplicity in construction, operation and maintenance. A generic conclusion that can be gleaned from the different studies in the literature is that, the dual-fuel combined cycles give an efficiency gain over a stand-alone WtE unit and the simplest configuration – "parallel" external partial superheating (Option 1 or 2) – provides the best balance and efficiency gain, simple design and economic incentive.

The integration must be considered on an individual basis to assess the most viable and economic solution according to local conditions, existing waste incineration plant and operating requirements.

Table 2: Literature references for efficiency gain discussion

Wiekmeijer (1990), Haneda (1995), Otoma et al. (1997), Holmgren (1998), Håkansson (1998), Korobitsyn et al. (1999), Egard et al. (2000), Stenhede (2001), Petrov and Hunyadi (2002), Petrov (2003), Consonni and Silva (2007), Qui and Hayden (2009), Pavlas et al. (2010), Poma et al. (2010), Udomsiri et al. (2010), Pavlas et al. (2011), Udomsiri et al. (2011)

4. Technical and non-technical issues at stake

4.1 Part-load performance

One of the most central issues to deal with when it comes to dual-fuel hybrid combined cycles is their part-load/off-design operation in terms of efficiency, safety and reliability. A foreseeable (and severe/critical) off-design mode is the operation of only one of the sub-cycle while the other one is under maintenance (or forced outage) as different power cycles will have different shut down routines (Consonni and Silva, 2007). The results presented in Consonni and Silva (2007) show that this hybrid combined cycle configuration is best suited for cases where priority is given to waste incineration with the GT being used as a supplementary energy output device when required/necessary (peak demand for example). It is important to keep in mind that the off-design performance is greatly influenced by the specific parameters of the topping engine and the bottoming steam cycle (Petrov, 2007).

4.2 Availability

Availability (as well as safety and overall performance) may also be improved by the implementation of back-up operating modes (during major equipment maintenance), stand-by or bypass equipment as well as the duplication of crucial devices (heat exchangers) (Lowry and Martin, 1990 and Petrov, 2003). However, this implies the purchase and maintenance of underutilised components (Petrov, 2003).
Wiekmeijer (1990) proposes a global-risk analysis looking at the impacts of the unexpected failures of one main component on the availability of the whole plant. The failures considered are (a) failure of the incinerator (considered as the most probable), (b) failure of the steam turbine, (c) failure of the gas turbine, (d) failure of the waste heat boiler. The overall conclusion of this risk analysis is that the disastrous consequences of these different failures scenarios (especially the complete shutdown of the hybrid combined cycle) can be avoided or mitigated by simple and cheap means.

4.3 Industrial attitude

Hybrid combined cycles involving MSW are still a rarity and many designers and plant operators share the view that MSW and gas turbines “simply don’t mix” and are therefore reluctant to combine cycles. This can be attributed both to the negative image of waste in the power industry in terms of operational problems as well as the assumed complexity of such integration and the little known advantages.
Another industrial (power) argument against hybrid combined cycles presented by Schu and Leithner (2008) is that there is no sense in using precious fossil fuels like oil or natural gas for superheating steam from WtE plants. These fuels can be burned much more efficiently in separate power plants. However, this argument can be, at least partly, refuted: firstly, calculations clearly show that a higher efficiency can be obtained by combining combined cycles; secondly, integration should be envisioned with MSW as the central fuel and the power plant as the provider of additional heat.

5. Conclusions

The increasing focus on sustainability and renewability (MSW is about 50 % biogenic on an energy basis in the EU) as well as the legislative context in the EU, such as the EU 20-20-20 goals, are pushing for higher efficiencies in waste to energy facilities. Combinations of a waste incinerator together with another power cycle in dual-fuel combined cycles appear as a promising alternative to increase efficiency. Calculations have shown that combined systems, without exceptions, will:

- Deliver a larger energy output than to two stand-alone sub-cycles
- Deliver higher efficiencies compared to two stand-alone sub-cycles; typically 1-5 percentage points higher than two stand-alone sub-cycles
- Lead to reduced specific CO_2 emissions (kg/kW)

Many variations exist but the most common one is the “external superheating” where all or part of the superheating for the steam cycle of the waste incinerator is provided by GT exhaust outside of the very corrosive waste environment in order to reach higher steam parameters without worsening corrosion. The complexity probably hinders the widespread use of such configurations and explains that many in the industry are sceptical to these configurations. A more favourable context (economical, political, legislative, and societal) might improve the situation.

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