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# REPOWERING EXISTING UNDER-UTILIZED WTE POWER PLANT WITH GAS TURBINES

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## ABSTRACT

Several Northern European countries are facing an incineration plant capacity larger than national generation of waste, mainly caused by a reduced availability of waste, economic crisis and over-investments. This is causing several WTE power plants to operate at reduced or under-utilized waste input capacity. In the aforementioned context, this paper focuses on two repowering options to improve waste conversion efficiency of an existing under-utilized Waste-To-Energy (WTE) power plant with a Gas Turbine (GT). In particular, this study investigates the feasibility of middle pressure repowering strategies: additional steam is produced in a simplified Heat Recovery Steam Generator (HRSG) fed by the GT exhaust gas. The proposed repowering options are quite simple and easy to adapt to mid-size under-utilized types of WTE power plant. A thermodynamic evaluation of the system feasibility is presented for a typical WTE. For each investigated repowering option, minimum GT size is identified along with optimum plant match condition in terms of plants capacity. A complete thermodynamic simulation of the steam cycle is performed and different plant configurations are examined under different GT commercial units. Detailed modifications to the WTE cycle and the resulting performance improvements are presented for both analyzed repowering options. Furthermore, different key performance indicators have been taken into account to evaluate, for each investigated configuration, the integrated dual-fuel system performance enhancement in comparison with the under-utilized and the original WTE plant. Both power output and efficiency of the repowered WTE plant compare favorably with those of the original stand-alone system: repowered system power output rise up to three times the original one and first law efficiency can reach up to 36%. Furthermore, the integration with GT can enhance the waste utilization, achieving positive synergy effects, as quantified in this study.

**Keywords:** Waste-To-Energy (WTE), Waste, Gas Turbine (GT), Repowering, Middle pressure.

## NOMENCLATURE

Abbreviation	
BC	Bottomer Cycle
C	Compressor
CC	Combined Cycle
CHP	Combined Heat and Power
DEA	DEAerator
ECO	ECONomizer
EVA	EVAPorator
EP	Extraction Pump
FW	Feed Water
GT	Gas Turbine
HCC	Hybrid Combined Cycle
HRSG	Heat Recovery Steam Generator
P	Pump
SI	Synergy Index
SH	SuperHeater
ST	Steam Turbine
T	Turbine
TC	Topper Cycle

52	WFD	Waste Framework Directive
53	WTE	Waste-To-Energy
54		
55	<i>Symbols</i>	
56	E	energy [MWh]
57	F	power input with reference to LHV[MW]
58	m	mass flow rate [kg/s]
59	p	pressure [bar]
60	P	Power [MW]
61	R1	EU regulation energy efficiency criteria [-]
62	Q	thermal power [MW]
63	T	temperature [°C]
64	$\eta$	efficiency [-]

66	<i>Subscripts and Superscripts</i>	
67	e	electric
68	EXH	exhausted
69	NG	Natural Gas
70	O	Outlet
71	s	steam
72	t	thermal
73	W	Waste

75     **1. INTRODUCTION**

76

77       Differently from the past, when incineration plants had only the function of reducing waste volume and remove hygienic

78 issues, nowadays, generation of useful energy from waste conversion has become a required outcome that is gaining the

79 same importance as waste treatment. According to the IEA-International Energy Association-, 0.4% of electricity on a global

80 scale is obtained from waste [1]. This share is more than three times higher (1.3%) in Europe. According to CEWEP-

81 Confederation of European Waste-to-Energy Plants association- estimations [2], the potential production of energy from

82 waste by 2020 amounts to 196 TW (76 for electricity and 120 from heat), and thence nearly double of actual production.

83 Considering that energy from waste is 50 % renewable due to organic materials contained in the waste flow (biomass, etc.),

84 this also means that Waste-To-Energy (WTE) power plants offer a substantial contribution to the exploitation of renewable

85 energy and to the reduction of fossil fuel based CO<sub>2</sub> emission [3].

86       On a global scale, the incineration market exhibits significant growth trends [4]. This is particularly the case in some EU

87 countries that are experiencing a transition dominated by the aim of phasing out landfills as much as possible (e.g. Italy and

88 the UK); moreover, emerging economies show increasing demand of plant capacity (for example China, where 7 billion tons

89 of waste are still untreated, 35% of which will be provided by incineration facilities) [5].

90       On the contrary, in some countries (Germany and the Netherlands among others) the waste trade has been mostly

91 motivated by an excess available capacity. Figure 1 shows actual and excess capacity for Northern European countries

92 recorded in 2010 [6]. Total actual capacity for Northern EU countries is equal to 45 Mton with 6.9 Mton of excess capacity

93 (corresponding to 15%).

94       Maximum excess capacity is recorded in Germany and Norway, where around 17% of waste treated in WTE plants

95 originates from other countries. Even the United Kingdom, which is currently exporting half of its solid recovered fuels

96 produced in the country to other EU member states, is foreseen to have an overcapacity of 6.9 million tons of waste

97 treatment capacity in the near future and most of this overcapacity is addressed to incineration facilities [7]. Despite the

98 existing overcapacity, the WTE power plants in Europe are expected to further grow through the construction of 48 new

99 facilities (according to [2]) and the increase of already existing facilities in terms of waste treatment capacity. Thus, several

100 Northern European countries are facing an incineration plant capacity larger than national generation of waste, mainly

101 caused by a reduced availability of waste, economic crisis and over-investments. This will cause several WTE power plants to

102 operate at reduced or under-utilized waste input capacity. Plants overcapacity has very high potential impacts on waste

103 treatment prices and WTE proces plants under-utilization and related conversion efficiency performance. Indeed, WTE power

104 plants, mostly based on steam turbine, have very rigid design condition on fuel charactristics and on process parameters [8],

105 in order to achieve best performance. The lack of waste due to non technical factors could lead not to use local waste in

106 order to get the maximum load and the design operation conditions. As a result, waste shipping across national borders

107 could increase unnecessary CO<sub>2</sub> emissions [9]. Moreover this could lead to incinerate potentially recycling and compostable

matter. Germany has already experienced this situation: recycled matter percentage has decreased from 65% to 60% in the period 2009-2014, to face the WTE over-capacity, supporting energy recovery because of WTE strict operation conditions [9].

In the aforementioned context, this paper focuses on an innovative and promising strategy to recover and improve the lost performance in waste conversion, through repowering of an existing under-utilized WTE power plant. A representative mid-size WTE power plant is taken into account. The low-performing WTE, operated in off-design conditions, is here integrated with a Gas Turbine (GT), with the aim to bring back design condition of the existing under-utilized WTE. The choice of a GT rather than a waste combustor is intended to face over-capacity, to avoid waste shipping and in a scenario of increasing waste re-use and recycling options.

Repowering options available according to existing literature and/or actually implemented, especially in the past to repower old-fashioned steam cycle power plants, are briefly reviewed in this introduction in order to illustrate pros and cons of each potential solution. A simulation model was set up to conduct the overall steam cycle performance analysis and the model details are illustrated in Section 2, describing the design and off-design performance of the WTE in study, before the repowering implementation. The repowering modifications investigated for the WTE in study are illustrated in Section 3, according to the selected repowering option. The numerical effects of the introduced modifications on the plant performance, evaluated with the developed numerical model, are provided in Section 4.

### **Repowering options**

A repowered steam plant involves two integrated energy systems: the Topper Cycle (TC) and the Bottomer Cycle (BC). This study focuses in particular on the use of GT units as TC, while BC should be intended as the WTE steam cycle.

Four different repowering arrangements can be identified; schematic layouts are presented in Figure 2 a)-d) [10-12]:

- Feedwater heater repowering (see Fig. 2 a), where heat discharged from TC is recovered to preheat feedwater replacing part of the steam turbine bleeds.
- Middle pressure repowering (also known as parallel repowering or supplemental boiler repowering, see Fig. 2 b), where heat discharged from TC is used to generate additional saturated or superheated steam feeding the original steam turbine.
- Hot Windbox repowering (see Fig. 2 c), where the TC exhaust is supplied to the BC boiler and used as pre-heated combustion air.
- Combined cycle repowering (or Boiler Replacement, see Fig. 2 d) this approach uses a new heat recovery steam generator (fed by TC exhaust) as for a new combined cycle thus, the original boiler is taken out of service, while the existing steam turbine and condenser are reused.

More in detail, the feedwater heater repowering option is accomplished by installing a gas turbine to produce additional power. Its exhaust energy is used to heat a portion of the feedwater in the original plant, which bypasses the existing feedwater heaters [10, 12]. Thus, an increase in steam mass flow rate has to be managed by the low pressure section of the original steam turbine and by the condenser section, requiring either extensive modification of the steam turbine or limiting the repowered plant performance. Operational flexibility is provided by being able to run the GT alone when the steam plant is shutdown and the original steam plant can run utilizing existing feedwater heating when the GT is unavailable. The capital cost for feedwater heater option, based on the total net capacity of the repowered unit, ranges from \$90-110/kW for smaller fossil steam units to \$75-80/kW for larger units [10].

In the middle pressure repowering GT exhaust are fed into a HRSG unit which provides saturated or superheated steam to the existing steam turbine. Even in this case, an increase in the steam mass flow rate that both ST (both HP and LP sections) and condenser must manage is expected. Thus, performance improvement for this repowering option are strictly related to ST existing capacity and its ability to accommodate additional steam [10, 12]. This repowering options requires very few modification in the pre-existing components of the bottomer cycle (i.e. WTE boiler) and a very simple layout of the Heat Recovery Steam Generator (HRSG). Particular attention must be paid in selection of topper cycle: GT size must be carefully selected according to existing ST and condenser maximum capacity.

The hot windbox repowering consists of installing one or more GTs exhausting into the windbox of an existing boiler; this option entails major steam generator redesign thus, it has the highest degree of technical complexity of all the combustion-turbine-based repowering options. As gas turbine exhaust is used as oxidant for combustion, the combustion air preheater is no longer required. The turbine bleed steam is reduced (or neglected) due to lower water flow through the original

feedwater heaters. Thus, steam flow through the low pressure section of the turbine increases and more power is generated. Due to the high degree of complexity required by this repowering option, it appears to be competitive for larger, newer oil/gas-fired units [10, 11]. Modifications in the existing boiler involves: the air heaters, the ductwork, furnace burners and the convective parts of the furnace. Other necessary modifications can include bypass ducts for admitting variable amounts of combustion turbine exhaust directly to the back end economizer section, a steam air heater to allow independent operation of the existing boiler when the combustion turbine is not available, an induced draft fan to reduce the back pressure on the combustion turbine, and a combustion turbine bypass stack for unit startup. Hot windbox repowering can add from 0-25% additional capacity to the unit, improve the efficiency by 10-20%, improve part load efficiency and cycling capability, and reduce NO<sub>x</sub> emissions [10].

The most diffused repowering option is the Combined Cycle (CC) repowering [10- 14], where the existing boiler is replaced by a combustion turbine and a heat recovery steam generator. This approach increases the unit's net generating capacity by about 150-200%, it reduces the heat rate by up to 30-40% and reduces NO<sub>x</sub> emissions. Due to the relatively large capacity increase, this approach is normally considered for older units less than 250 MW with steam pressures up to 120 bar. The issues, which must be addressed in CC repowering, include optimizing the existing steam turbine performance with the new combined-cycle components or installing a new steam turbine. New steam turbines, main transformers and other equipment add to the capital cost, but may be justified by gains in output, efficiency or to provide reliable operation. The capital cost usually ranges between \$450/kW to \$750/kW [10].

A well-integrated repowering configuration is proposed in this study focusing on middle pressure repowering option: two variants in terms of HRSG assembly are considered. For each analyzed configuration the selection of GT used as topper, strictly connected to bottomer cycle existing capacity, is discussed in details.

The viability and performance results of a representative mid-size WTE power plant repowered with different GT commercial units are shown and discussed.

## 2. EXISTING LOW-PERFORMING WTE STEAM CYCLE

The existing low-performing power plant, considered as reference in this study, is a conventional WTE. A schematic layout of the WTE power plant is shown in Fig. 3. It was originally projected to work with two steam lines, namely L1 and L2 fed with two separated WTE boilers. The WTE plant can ensure the disposal of  $240 \cdot 10^3$  tons/year of waste, of which a maximum of  $30 \cdot 10^3$  tons can be special waste (max. of  $5 \cdot 10^3$  tons of hospital and medical waste) while the remaining fraction is composed by municipal waste with typical composition. The average value of waste Lower Heating Value fed into the boiler is equal to about 12.6 MJ/kg.

The steam conditions in each line were supposed to be the following: L1 (high pressure line) with an input waste capacity equal to 78.5 MW<sub>t</sub>, generating superheated steam at 50 bar and 380°C; L2 (middle pressure line) with an input waste capacity equal to about 27.5 MW<sub>t</sub>, generating superheated steam at 20 bar, 360°C.

Both projected lines were supposed to have a natural-circulation type steam generator, integrated with the combustion chamber. The energy recovery section comprises several radiation channels with vertical flue gas flow and a convection section containing superheaters, evaporators and economizers.

Both high pressure and middle pressure superheated steam mass flows, produced by the steam generators, were supposed to feed a condensation type Steam Turbine (ST).

A controlled low pressure ST extraction is used to feed the Deaerator (DEA). Despite the original WTE project, L2 middle pressure line (dotted line in Fig. 3) has not been put in operation resulting in a ST, condenser and DEA components overcapacity. Thus, the investigated case can be generalized to WTE facilities currently working with a current trend of reduced waste input and thus, system components over-capacity. As most of the plant components has been installed as expected in the original project, the power plant works in off-design conditions with reduced electric power output.

### System modelling

The scheme outlined in Fig. 3 has been numerically simulated using Thermoflex™[15], a modular thermodynamic simulation code. This numerical tool allows to simulate energy systems performance based on a lumped parameter modeling approach including real gas behavior and pressure losses. The software, used in power plant industry for complex energy system characterization and performance prediction, basically solves mass and energy balance equations in steady state conditions for each component (heat exchangers, expanders, compressors, pumps, etc.), providing flows, thermodynamic states, exchanged heat and power between the system components.

To simulate system design and off-design behavior, waste input capacity (mass flow rate and LHV), steam mass flow rate, evaporative pressure and temperature values in each heat exchanger section have been input to the simulation code along with DEA operating pressure and condenser pressure values (only in case of design operation).

According to actual WTE operation, off-design of ST have been obtained considering a throttle pressure controlled method where, as a consequence of steam mass flow variation, valve close as necessary to maintain the desired set point pressure upstream of the valve. As a consequence of selected ST off-design, ST bleed pressure, condenser operating pressure, steam outlet quality and ST isentropic efficiency in off-design condition changes. The waste boiler feeding high pressure steam line (L1 in Fig. 3) is not affected by off-design operation since off-design operation involves only the shutdown of L2 waste boiler.

Main thermodynamic results, reproducing design and off-design operation of WTE are listed in Table 1.

WTE design performance results, according to project data, show a power plant power output equal to about 25 MW with an overall plant efficiency equal to 23.5%. High pressure and middle pressure superheated steam mass flow rate equal to about 24 kg/s and 9 kg/s, respectively. The steam expanded up to 0.12 bar and exits the ST with an outlet quality equal to 0.88.

Exhaust gas outlet temperature, equal to about 174 °C, is in line with typical mid-size WTE values [8, 16].

Off-design performance results, according to actual WTE operations, show a decrease in power plant power output equal to more than 5 MW due to the absence of middle pressure steam mass flow. On the contrary, WTE overall plant efficiency shows an increase of about 1.6 percentage points compared to design value. The efficiency gain can be explained considering that the power output decrease due to off-design operation is lower than the decrease in waste input capacity due to L2 line shortage.

It must be outlined that ST off-design operation, due to reduced steam mass flow rate, also causes a decrease in ST isentropic efficiency. The h-s diagrams for both design and off-design ST operation are reported in Fig. 4 and 5.

Comparing ST expansion lines it is evident that, despite the decrease in ST outlet pressure, the lack of middle pressure superheated steam entails also a decrease in specific enthalpy value at ST middle pressure inlet stage, negatively affecting the ST specific work.

### 3. REPOWERING EVALUATION METHODOLOGY

#### Middle Pressure Repowering Options: Case A and Case B

Repowering solutions with gas turbine (GT) have been sought in order to bring back the WTE design conditions and improve its performance. In this paper we focus in particular on two different middle pressure repowering options. Determine how to technically integrate GT exhaust heat into the existed WTE power plant is the first step in the design process [16, 17]. Two different HRSG arrangements are proposed, shown in Figure 6, namely Case A and Case B. In Case A repowering option, Fig. 6 a), superheated steam at medium pressure is produced in a proper recovery boiler fed by the GT exhaust and it expands into the ST of the pre-existing plant in addition to the main steam flow. This solution involves a simple layout (i.e. simple HRSG arrangement) and few modifications to the existing components. In Case B, Fig. 6 b), in addition to middle pressure superheated steam generation, the HRSG would generate also low pressure saturated steam necessary to feed DEA, thus excluding the original ST bleed.

Case A option does not involve variations in the ST performance compared to design operation, since the original condition of middle pressure steam mass flow are maintained. Vice versa, Case B involves a slight change in the ST performance and efficiency: the elimination of ST bleed causes an increase in low pressure ST steam mass flow rate however compatible with ST normal operation. Both solutions do not involve any modification to the WTE boiler or to the energy recovery section.

#### Topper GT selection

It is necessary to underline that, to repower an existing WTE plant, the GT optimal size is not random but strictly connected to the bottomer cycle size. One major design challenge, when repowering an existing plant, is to match the steam production capability of the topper cycle and HRSG with the steam needs of the existing steam turbine. Figure 7 and 8 shows GT exhaust outlet temperature ( $T_{O,GT}$ ) and mass flow rate ( $\dot{m}_{exh}$ ) values versus GT electric power output for several market available GT units, respectively. Exhaust temperature values show a slight correlation with power output. Exhaust mass flow rate values are instead strictly correlated to GT power output: bigger GT units exhibit higher exhaust mass flow rate values (see dotted trend in Figure 8).

The two GT parameters,  $\dot{m}_{exh}$  and  $T_{O,GT}$ , affect the exhaust thermal power ( $Q_{exh}$ ) which can be estimated according to the following equation:

$$Q_{exh} = \dot{m}_{exh} \cdot \overline{c_{p,exh}} \cdot (T_{O,GT} - T_{O,HRSG}) \quad (1)$$

where  $\overline{c_{p,exh}}$  is the exhaust gas mean specific heat and  $T_{O,HRSG}$  is the exhaust temperature at HRSG outlet (in Fig. 9 assumed equal to 100°C as minimum value).

Figure 9 shows the  $Q_{exh}$  values versus the GT unit power output. A correlation between GT exhaust heat and power output is evident in Fig. 9: GT size increase causes an increase in the amount of exhaust discharged heat.

In order to define the optimal WTE-GT matching, i.e. the minimum optimal GT size, given the steam cycle parameters (namely, middle pressure steam mass flow rate, superheated steam pressure and temperature) the following relations have been considered:

- In case A, GT exhaust thermal power ( $Q_{exh}$ ) must equalize the thermal power necessary to economize, vaporize and superheat the requested middle pressure mass flow rate. Thus, the following equation must be satisfied:

$$\dot{m}_w \cdot \Delta h = \dot{m}_{exh} \cdot \overline{c_{p,exh}} \cdot (T_{O,GT} - T_{O,HRSG}) \quad (2)$$

where  $\dot{m}_w$  is the steam mass flow rate (equal to 9.04 kg/s),  $\Delta h$  is the enthalpy difference between the superheated steam outlet condition (20 bar and 360°C) and water inlet condition (i.e. DEA outlet condition, 2 bar and 120°C).

- In case B, the balance equation results:

$$\dot{m}_w \cdot \Delta h + \dot{m}_{DEA} \cdot \Delta h_{DEA} = \dot{m}_{exh} \cdot \overline{c_{p,exh}} \cdot (T_{O,GT} - T_{O,HRSG}) \quad (3)$$

where the additional term  $\dot{m}_{DEA} \cdot \Delta h_{DEA}$  represents the thermal power requested to vaporize the steam mass flow necessary to feed the deareator. Thermal power necessary in case A and B are equal to 24.1 MW<sub>t</sub> and 32.5 MW<sub>t</sub> respectively, corresponding to the minimum thermal power that must be provided by the GT exhaust.

Based on calculated minimum GT discharged thermal power, the corresponding GT size ranges suitable for both, Case A and Case B, are identified in Figure 9 among market available units.

Suitable GT size ranges between 16 to 19 MW and between 21 to 28 MW, for Case A and Case B, respectively. For each repowering configuration, two different machines have been selected as topper cycle, for a total of four considered GTs (see Table 2): GT1 (Kawasaki GPB180D) and GT2 (General Electric LM2500PH) for case A; GT3 (Siemens SGT-600) and GT4 (General Electric LM2500+PK) for case B. Power output of the selected GT units match respectively with lower and upper bound of the size range identified.

Selected GTs differ also in terms of efficiency and, as a consequence, of exhaust outlet temperature: as obvious, GTs with higher efficiencies have lower temperature values.

Middle pressure repowering options have been simulated for the selected GT machines. Additional pressure drops at GT outlet have been included due to HRSG. Heat exchangers have been simulated taking into account the following design parameter: subcooling temperature difference for the economizer section, saturated steam mass flow rate for evaporator and superheated steam outlet temperature for the superheater section.

#### 4. WTE-GT REPOWERING RESULTS

The performance results of the repowering options with commercial GT units are shown in Table 3. All the investigated configurations provide a gain in power output in comparison with the stand-alone WTE off-design operation. The repowered system total power output can vary from 42 MW up to 54 MW depending on the selected GT unit and layout case, with a significant increase compared to the original off-design WTE operation. The highest ST power increase, equal to 6.5 MW, can be achieved with Case B repowering solution.

Due to the bi-fuel configuration of the investigated repowered plant options, the conversion efficiency quantification is not a simple task. For this reason, different key performance indicators have been taken into account as illustrated in Table 3. A detailed description of performance indexes and output allocation approaches applicable in case of multi-fuel power plants, such as the repowering solutions proposed in this study, can be found in [8, 18]. Few important aspects are recalled here.

The First Law Efficiency (named here  $\eta_l$ ) is a basic well known index, which considers both fuels, i.e. natural gas (NG) and waste (W), with equal importance. For the plants in study,  $\eta_l$  is defined as the ratio between total power output ( $P_{WTE+GT}$ ) and thermal input with fuels ( $F_{NG}+F_W$ ):

$$\eta_l = \frac{P_{WTE+GT}}{F_{NG} + F_W} \quad (4)$$



The  $\eta_i$  value can be compared to a reference scenario efficiency ( $\eta_0$ ) with two separate plants (GT and WTE stand-alone) respectively producing  $P_{WTE}$  and  $P_{GT}$  and fed by the same two input fuels:

$$\eta_0 = \frac{P_{WTE} + P_{GT}}{F_{NG} + F_W} \quad (5)$$

The repowering options is convenient in terms of first law conversion, i.e. a gain in power output occurs, if the following condition is true:  $\eta_i > \eta_0$ . Results in Table 3 show that First Law Efficiency is in the range 32-36% and maximum occurs for GT4 and Case B. Moreover, the considered repowering options, for each analyzed case, allows to achieve significant efficiency increase, compared to the separate systems scenario: 4 and 5 percentage points of efficiency increase are achieved in Case A and Case B, respectively.

The extra power generated as a consequence of WTE-GT integration, can be assigned to NG or W input [8, 18]. If the benefit is assigned to NG, the Natural Gas Synergy Index ( $SI_{NG}$ ) can be used to measure the WTE-GT incremental performance (and it can be compared with the GT efficiency) as:

$$SI_{NG} = \frac{P_{WTE+GT} - P_{WTE}}{F_{NG}} \quad (6)$$

The calculated  $SI_{NG}$  results, which depend on the repowering option and on the GT used as topper, show that if the benefit of integration is attributed to NG, efficiency can be comparable with typical values of one-pressure-level combined cycle power plants. Values up to about 47% can be achieved in the best case, using GE LM2500+PK and Case B repowering.

Taking into account a different point of view, the extra power due to integration can be assigned to waste. Thus, the Waste Synergy Index ( $SI_W$ ) can be considered to measure the WTE-GT incremental performance compared to the WTE stand alone; in this case, a reference constant conversion efficiency, equal to 41%, of a reference 1-pressure-level Combined Cycle has been taken into account. The corresponding  $SI_W$  formula is:

$$SI_W = \frac{P_{WTE+GT} - 0.41 \cdot F_{NG}}{F_W} \quad (7)$$

In the considered cases, the  $SI_W$  values are positive and higher compared to original WTE efficiency (i.e., 25%).

Finally, a Multi-Fuel Fuel Synergy Index ( $SI$ ) can be introduced to measure the actual WTE-GT marginal performance in comparison with the separated reference WTE and GT power plants, defined as:

$$SI = \frac{P_{WTE+GT} - (P_{WTE} + P_{GT})}{(P_{WTE} + P_{GT})} \quad (8)$$

The  $SI$  results provided in Table 3 show remarkable increase of performance of the proposed solutions, compared to the reference scenario of separate exploitation of the two fuels, as the calculated  $SI$  values are in the range 13- 16%.

Also the HRSG effectiveness, i.e. the ratio between the heat exploited in HRSG and the maximum amount of heat that could be exploited if temperature of GT exhaust gas would be decreased down to ambient temperature ( $T_{amb}$ ), has been calculated and reported in Table 3. The highest HRSG effectiveness values (corresponding to the lowest HRSG outlet temperature) are achieved with the GT3 machine in Case B.

Beside the issue of conversion efficiency for a bi-fuel energy system, another aspect to be solved with practical implication, in particular dealing with incentivized fuel (such as waste), is: which is the contribution of each input fuel to the total power output? How can it be properly quantified? Two different approaches can be used, as investigated in details in [18], to calculate the contribution of NG and of W. In case of Approach #1, the two output contributions are directly proportional to the two fuel input terms, using  $\eta_i$  as weighting factor (see [18]). In case of output allocation Approach #2, a different weighting factor is used, which is a function of the relative fuel Synergy Index (see [18]). This second approach recognizes a higher contribution in terms of power output to the fuel with higher gain in efficiency in comparison with the reference scenario.

Interesting differences can be observed considering output allocation results: in case of Approach #1, the power associated to NG ( $P'_{NG}$ ) is lower than the actual GT power ( $P_{GT}$ ) in all considered repowering options. On the other side, in case of output allocation with Approach #2, the calculated power associated to NG is higher than the actual GT power. Indeed, the GT exhaust heat is partially recovered in the HRSG and used by the bottoming steam cycle; this means that a fraction of power produced by the ST can be seen as due to the GT contribution, rather than integrally due to the waste contribution. On the other side, with this Approach #2, the power due to waste ( $P'_w$ ) is lower than the actual ST output power in the integrated configurations, but higher than the WTE off-design reference plant power.

374 **5. CONCLUDING REMARKS**

375 A thermodynamic analysis on the achievable performance of a typical, existing and under-utilized WTE plant repowered  
376 with GT, using two different middle pressure layout options (Case A and B) has been presented, taking into account different  
377 GT manufacturers and models. The design matching between GT and the steam cycle has been investigated. Both layout  
378 repowering options with all the investigated GT commercial units guarantee a power output increase, in comparison with  
379 both the design and the actual WTE stand-alone off-design operation. The total power output of the integrated system can  
380 be increased from 42 MW up to 54 MW, with a significant rise compared to the original design WTE operation (24.9 MW).  
381 Instead, a power increase in the ST output, compared to the design WTE stand-alone case, can be achieved only in Case B. In  
382 this case, a maximum ST power increase, equal to 6.5 MW, can be achieved with GT4.

383 The First Law Efficiency increases significantly, ranging between 32-36% (compared to 25% of WTE actual operation and  
384 23% of the original design operation). Benefit of repowering, compared to separated system generation have been  
385 quantified: 4 and 5 percentage points of efficiency increase are achieved in Case A and Case B, respectively.

386 The NG relative Synergy Index is relevant (reaching values up to about 47% in the best case, with GT2 machine and Case B  
387 layout), showing that if the benefit of integration is attributed to NG, the efficiency can be comparable with typical values of  
388 1-pressure-level combined cycle power plants. Also Waste relative Synergy Index values (in the range 26-30%) are positive  
389 and higher compared to both the original and the under-utilized WTE plant efficiency (23.5% and 25%). Overall, the  
390 calculated multi-fuel Synergy Index is largely positive, demonstrating the convenience of the integration in comparison with  
391 the considered separate fuel utilization scenario.

392 Finally, the study shows that the power output of the integrated WTE-GT plant can be attributed to the two fuels with  
393 different approaches. The final and more correct allocation approach considers and amount of power output due to NG  
394 larger than the GT output power. The power output allocated to waste is instead lower than the original WTE plant.  
395 Nevertheless, in case of Layout B and with GT4, the output due to waste of the integrated plant is larger than the power of  
396 the under-utilized WTE plant (21.8 MW vs 19.7 MW), demonstrating also from another point of view the energy viability of  
397 the proposed solution.  
398

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438 **Figure Captions**  
439 Figure 1: WTE Actual capacity and Excess incineration capacity in Northern European countries in 2010.  
440 Figure 2: schematic of repowering options  
441 Figure 3: schematic of WTE power plant.  
442 Figure 4: h-s diagram showing Design steam expansion line  
443 Figure 5: h-s diagram showing Off-design steam expansion line  
444 Figure 6: schematic of WTE middle pressure repowering options: Case A (a) and Case B (b)  
445 Figure 7: GT commercial units exhaust temperature values versus power output.  
446 Figure 8: GT commercial units exhaust mass flow rate values versus power output.  
447 Figure 9: GT commercial units discharged heat values versus power output.

448  
449 **Table Captions**  
450 Table 1: comparison of on-design and off-design WTE operation.  
451 Table 2: Selected Gas Turbines performance data.  
452 Table 3: Case A and Case B WTE middle pressure repowering results.  
453

FIGURES

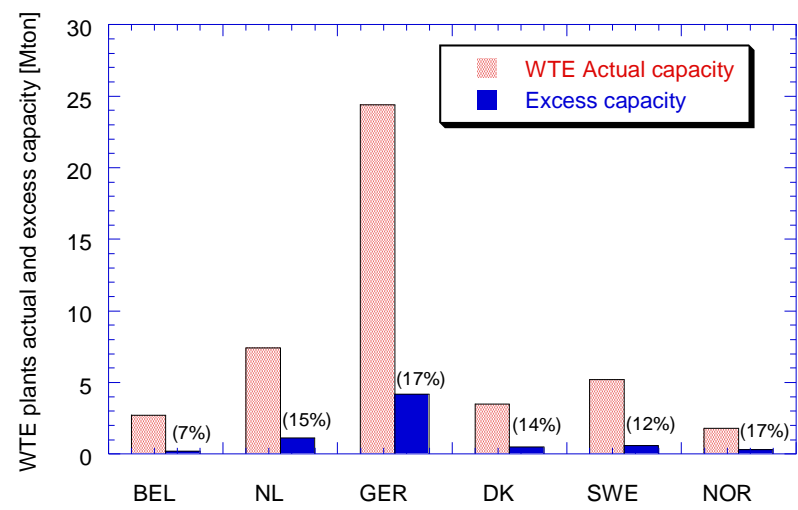


Figure 1: WTE Actual capacity and Excess incineration capacity in Northern European countries in 2010.

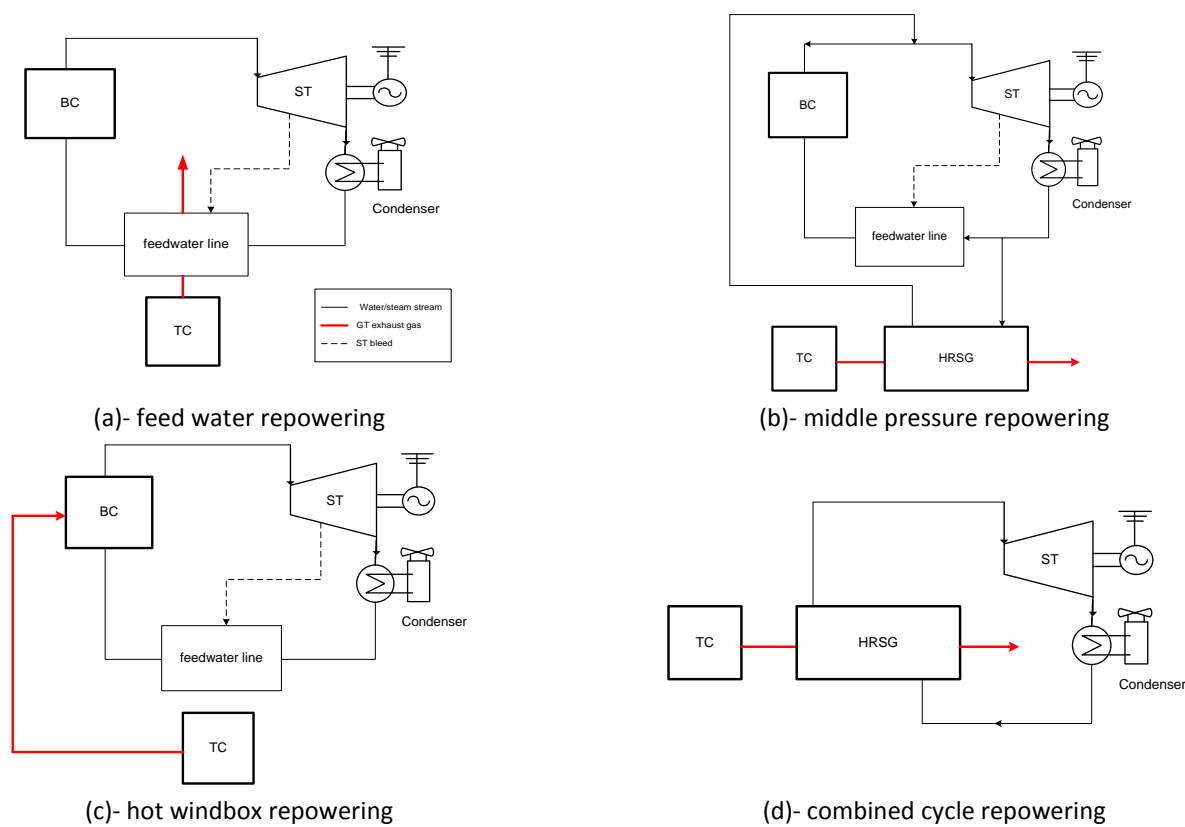


Figure 2: schematic of repowering options

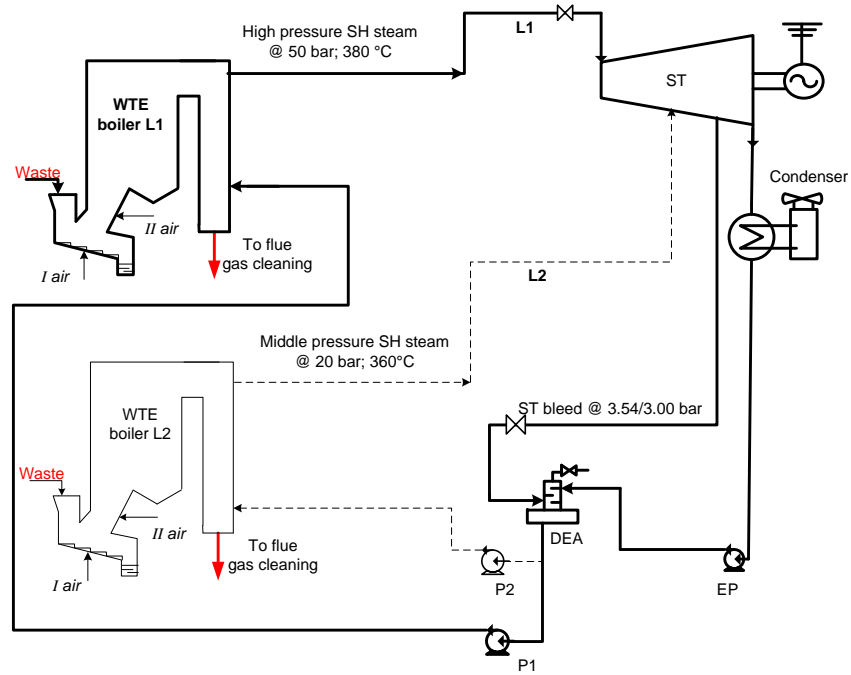


Figure 3: schematic of WTE power plant.

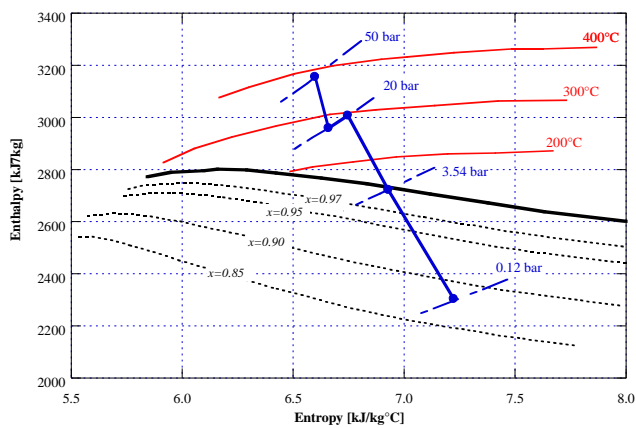


Figure 4: h-s diagram showing Design steam expansion line

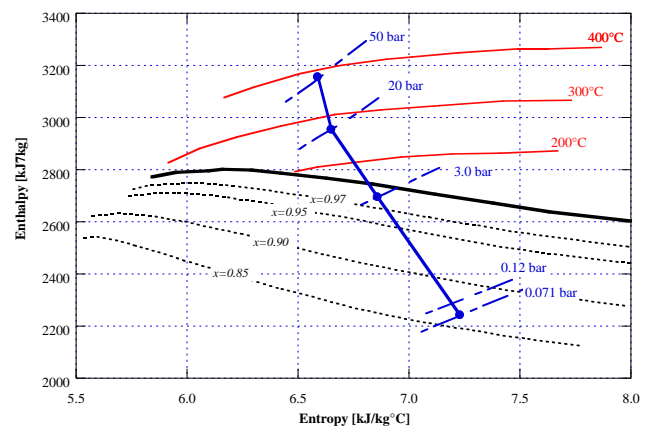


Figure 5: h-s diagram showing Off-design steam expansion line

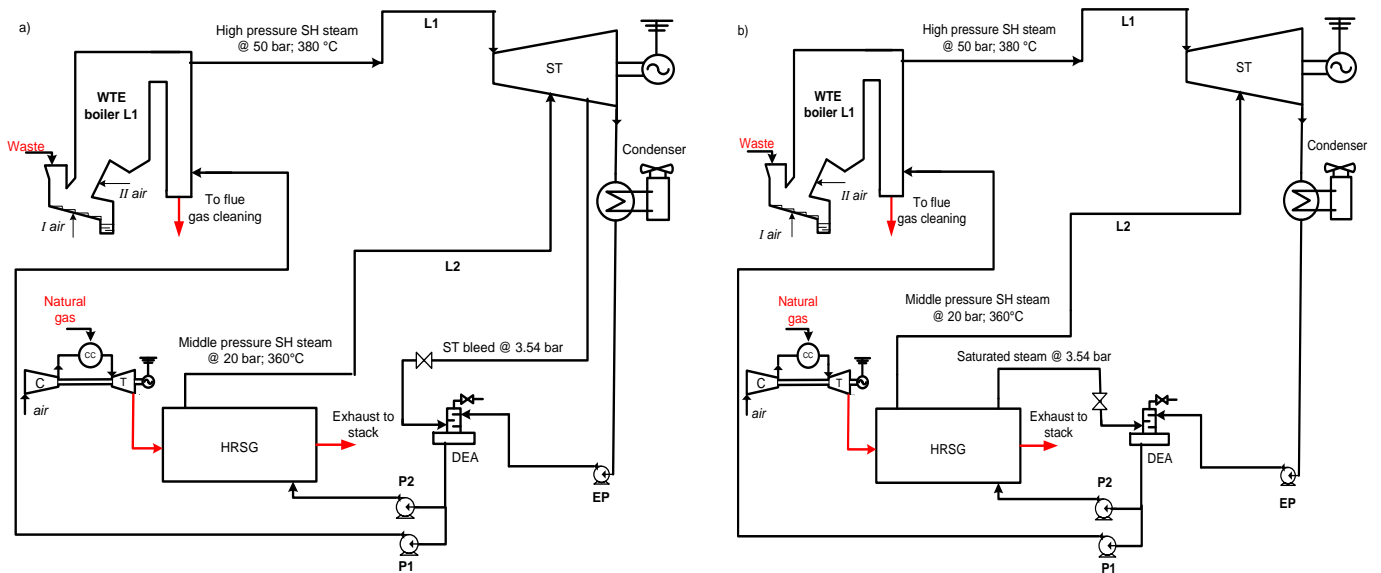


Figure 6: schematic of WTE middle pressure repowering options: Case A (a) and Case B (b)

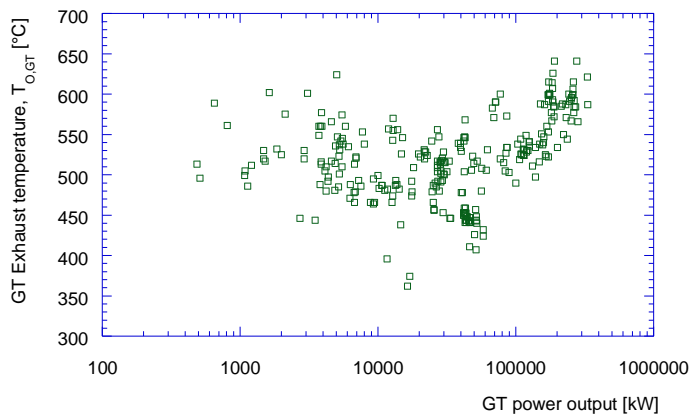


Figure 7: GT commercial units exhaust temperature values versus power output.

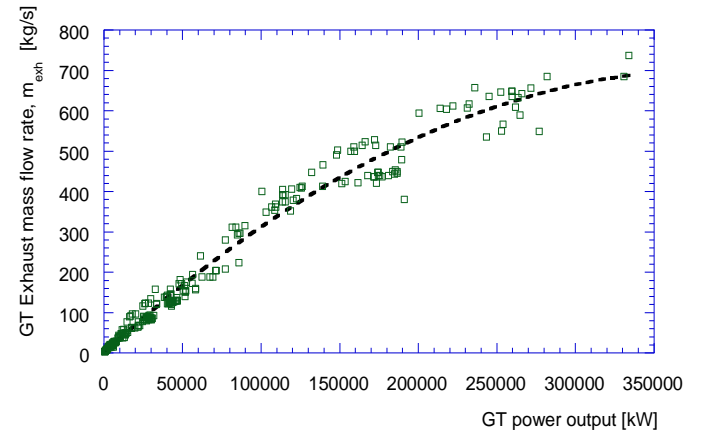


Figure 8: GT commercial units exhaust mass flow rate values versus power output.

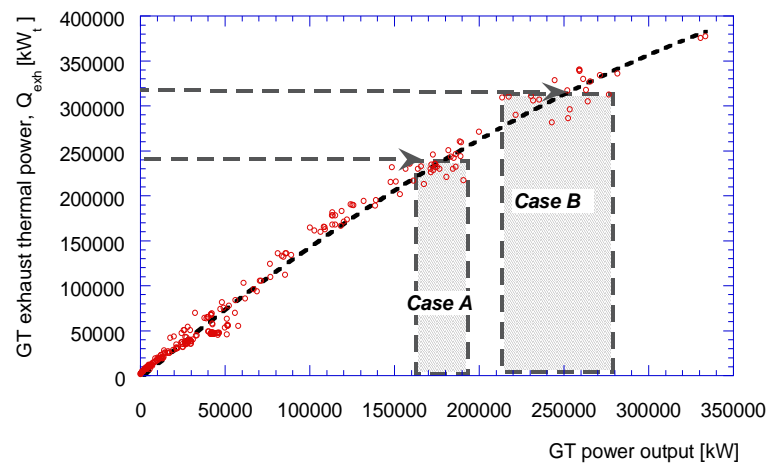


Figure 9: GT commercial units discharged heat values versus power output.

TABLES

Table 1: comparison of on-design and off-design WTE operation

	L1+L2 design	L1 off-design
Total waste input capacity [MW <sub>i</sub> ]	106	78.5
Waste LHV [kJ/kg]	12622	12622
L1 pressure [bar]	50	50
L1 steam temperature [°C]	380	380
L2 pressure [bar]	20	-
L2 steam temperature [°C]	360	-
L1 steam mass flow rate [kg/s]	24.05	24.05
L2 steam mass flow rate [kg/s]	9.04	-
ST bleed to feed DEA[bar]	3.54	3.00
DEA set point operating pressure [bar]	2	2
Steam mass flow rate for DEA[kg/s]	3.81	3.20
Condenser pressure [bar]	0.12	0.07
Outlet steam quality [-]	0.88	0.86
WTE exhaust temperature [°C]	174	174
Power output [MW]	24.9	19.7
Electric efficiency [-]	0.235	0.251

Table 2: Selected Gas Turbines performance data.

Repowering solution	CASE A		CASE B	
GT#	GT1	GT2	GT3	GT4
manufacturer and model	KAWASAKI GPB180D	GE LM2500PH	SIEMENS SGT-600	GE LM2500+PK
Gas Turbine power output ( $P_{GT}$ ) [kW]	17493	19250	21068	27851
Fuel inlet to Gas Turbine ( $F_{NG}$ ) [kW <sub>i</sub> ]	52962	55028	65762	73669
GT electric efficiency [-]	0.33	0.35	0.32	0.38
Gas Turbine Outlet Temperature [°C]	544	526	520	502
Exhaust gas mass flow rate [kg/s]	58	62	77	84
Exhaust thermal power [kW <sub>i</sub> ]	27040	27733	33957	35456



Table 3: Case A and Case B WTE middle pressure repowering results.

	CASE A		CASE B	
GT unit	GT1	GT2	GT3	GT4
Steam Turbine power output [kW]	24846	24846	26208	26208
ST power increase vs. WTE stand-alone off-design [kW]	5169	5169	6531	6531
WTE+GT Power output, $P_{WTE+GT}$ [kW]	42339	44096	47276	54059
First law efficiency, $\eta_I$ [-]	0.32	0.33	0.33	0.36
Separate generation efficiency, $\eta_\theta$ [-]	0.28	0.29	0.28	0.31
HRSR recovery effectiveness, $\varepsilon$ [-]	0.70	0.68	0.76	0.73
Input fuel capacity ratio, $F_{NG}/F_W$ [-]	0.67	0.70	0.84	0.94
Natural Gas Synergy Index, $SI_{NG}$ [-]	0.43	0.44	0.42	0.47
Waste Synergy Index, $SI_W$ [-]	0.26	0.27	0.26	0.30
MF Synergy Index, $SI$ [-]	0.14	0.13	0.16	0.14
Power output allocated to natural gas, $P'_{NG}$ (Approach #1) [kW]	16948	18159	15601	26521
Power output allocated to waste, $P'_W$ (Approach #1) [kW]	25391	25937	31675	27538
Power output allocated to natural gas, $P'_{NG}$ (Approach #2) [kW]	22360	23513	27186	32175
Power output allocated to waste, $P'_W$ (Approach #2) [kW]	19979	20583	20090	21884