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ENERGY AND EXERGY ANALYSIS OF AN AROMATICS PLANT. IMPLEMENTATION OF TWO THERMAL ENERGY RECOVERY UNITS

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Abstract. The exergy analysis complementing a previous energy analysis, allows a deeper understanding of the implementation of energy efficiency procedures. As such, after an energy and exergy analysis of an aromatics plant from a refinery in the northern region of Portugal, the most important equipment components in terms of energy recovery measures were easily identified. Accordingly, besides several minor recommendations concerning the thermal efficiency of the plant, two main proposals for the exploitation of the wasted thermal energy, without affecting the chemical operation, were proposed. The first proposal is the application of an organic Rankine Cycle (ORC), fed by the wasted thermal energy released by two air coolers and a furnace, producing around 1.55 MW of electricity, corresponding to 59.1 % of the plant electricity needs. The second proposal is the application of a cogeneration unit producing 11.4 MW of electricity and 14 MW of thermal power. Considering only the implementation of the cogeneration, the energy efficiency of the aromatics plant would rise from 0.8 % to 7%, whereas the corresponding exergy efficiency would go from the present value of 65.6 % to 66.1 %. By combining the cogeneration with the ORC, the energy efficiency of the aromatics plant would rise to 8.1 % while the exergy efficiency would rise to 67 %.

Keywords: Energy efficiency, Exergy efficiency, Cogeneration, Organic Rankine, Aromatics

1. INTRODUCTION

1.1 General considerations

In oil refineries, a reasonable amount of energy is used for processing. The level of energy consumption can be represented by a special indicator, the amount of oil required for the refinery to meet its energetic needs. Currently, for oil refineries, the share of crude oil used for energy production is between 4% and 8%, depending on the level of their complexity (Ocic, 2015). Inefficient refineries can reduce their energy consumption by about 20-30% through the use of more efficient technologies and better energy solutions. This percentage is not small, considering the share of energy costs in total costs of crude oil processing; a refinery whose oil quota is 5% for its own energy consumption, has to operate 16 days per year to meet such needs (Ocic, 2015).

There has been a marked development of the petrochemical industry, driven by increased demand for high value-added products. This factor, coupled with the need to respond to an increasingly competitive global market and the obligation to respond to environmental compliance, increased the concern of the petrochemical industry towards increasing energy efficiency (Speight, 2011). This lead to studies on the recovery of flare gas energy (Comodi et al., 2016; Tahoumi et al., 2016), on the use of waste heat through Organic Rankine Cycles (Yu et al., 2016) and through the retrofitting of some refinery processes (Liu, et al., 2016).

An exergy balance of any equipment or process can says quite a lot about its potential in terms of the useful work that is being processed. The exergy destruction, or losses, is a quantitative measure of the process inefficiencies (Kotas, 1985). Therefore the exergy analysis represents a new light with respect to an energy-efficient target (Wall, 2002). Accordingly, exergy analysis, when used in conjunction with the mass conservation and energy laws, becomes an effective tool both to achieve an efficient use of energy with low environmental impact and high sustainability, and to provide optimal points of operation in the process and in systems design (Rivero and Koijer, 2003; Rivero et al., 2004; Wang et al., 2011).

The thermodynamic analysis of the separation systems, either through conventional basic approaches (Demirel, 2004), or through the use of commercial software (Demirel, 2006a, 2006b), has been oriented towards the petrochemical systems and to the biodiesel production (Nguyen and Demirel, 2010). The work that has been carried out in the analysis of the distillation processes is justified by the heavy energy burden the distillation processes impose upon the petrochemical and chemical industries (Demirel, 2013). There is consequently the need to improve the environmental and energy sustainability of these industries, being the main target the minimization of energy usage and waste formation through adequate process integration procedures (Klemes, 2014).

1.2 The aromatics plant

The Aromatics Plant (FAR) from the Matosinhos Refinery started its activity on May 1981. It can process 850,000 t per annum of reformate supplied by the Fuel Plant from the same refinery or from the Sines Refinery. It produces 440,000 t per annum of benzene, toluene, para-xylene, orto-xylen and solvents, Tab. 1.

Table 1. Annual production of FAR.

Product	Production (t/year)
Benzene	36000 - 50000
Toluene	129000 - 140000
Para-xylene	90000
Orto-xylene	30000
Solvents	35000

The FAR is composed by the following units:
- Un 0100 – The pre distillation unit, where the input reformate is separated into three cuts:
- Un 0200 – The Arosolvan unit, using a liquid-liquid extraction process combined with distillation, and producing benzene and toluene;
- Un 0300 – The Parex unit for para-xylene extraction;
- Un 0400 – The Isomar unit for para-xylene an orto-xylene extraction;
- Un 0500 – The Solvent unit for the extraction of a wide range of solvents.
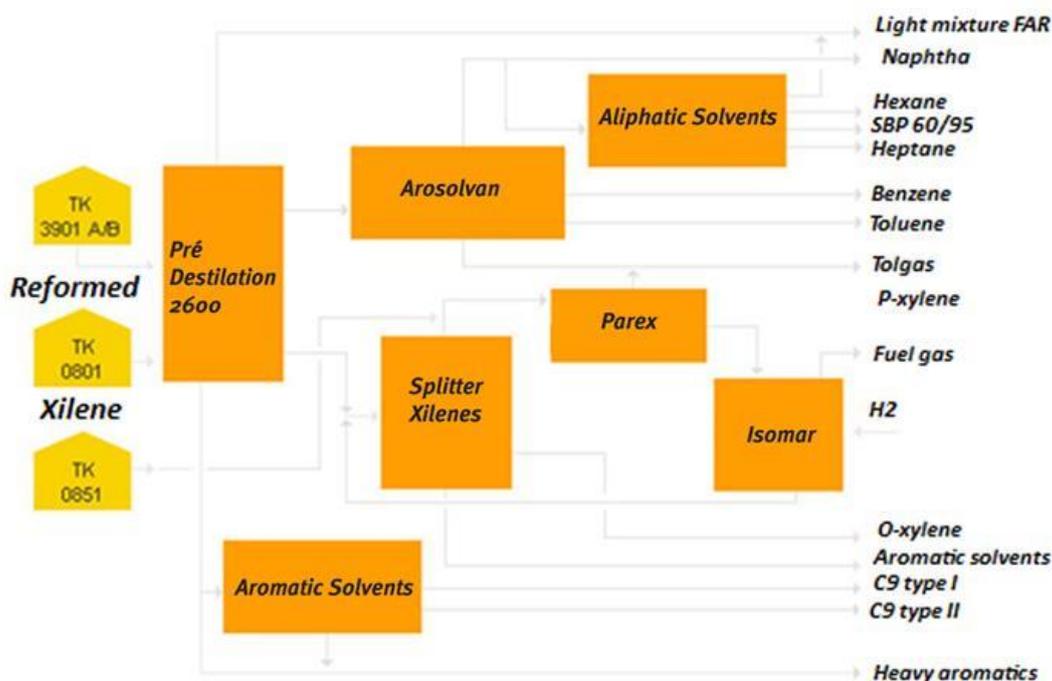

Figure 1. The subunits that compose the aromatics plant (FAR).

There is also a complementary unit for nitrogen production in order to assure the operational safety of the plant and the products quality. The composition of the aromatics plant is schematically presented on Fig. 1.

2. OVERALL ENERGY AND EXERGY ANALYSIS

In order to find out situations where the exploitation of energy wastes and losses could improve the energetic performance of the plant in its present operating layout, it was performed an overall energy balance of the plant. In the second step, the energy analysis was complemented by an exergy analysis, looking at the qualities of the several energy forms that were handled in the process (Vilarinho et al., 2016; Vilarinho et al., 2017).

From the energy and exergy analysis, the calculated energy and exergy efficiencies are respectively 0.81% and 65.9%. The presented energy and exergy balances for the aromatics plant show that, even not considering the potential changes on the chemistry of the process, by only analyzing the energy losses and the corresponding exergy destructions, there is a huge potential for the energy utilization, through the adequate conversion of the rejected thermal energy.

From the Sankey and Grassmann diagrams, Fig. 2, it is clear that bigger energy losses come from the condensers, 26 %, followed by the air coolers, the furnaces and heat exchangers, with 15.6 %, 14.8 % e 3.1 % of the unit global losses, respectively.
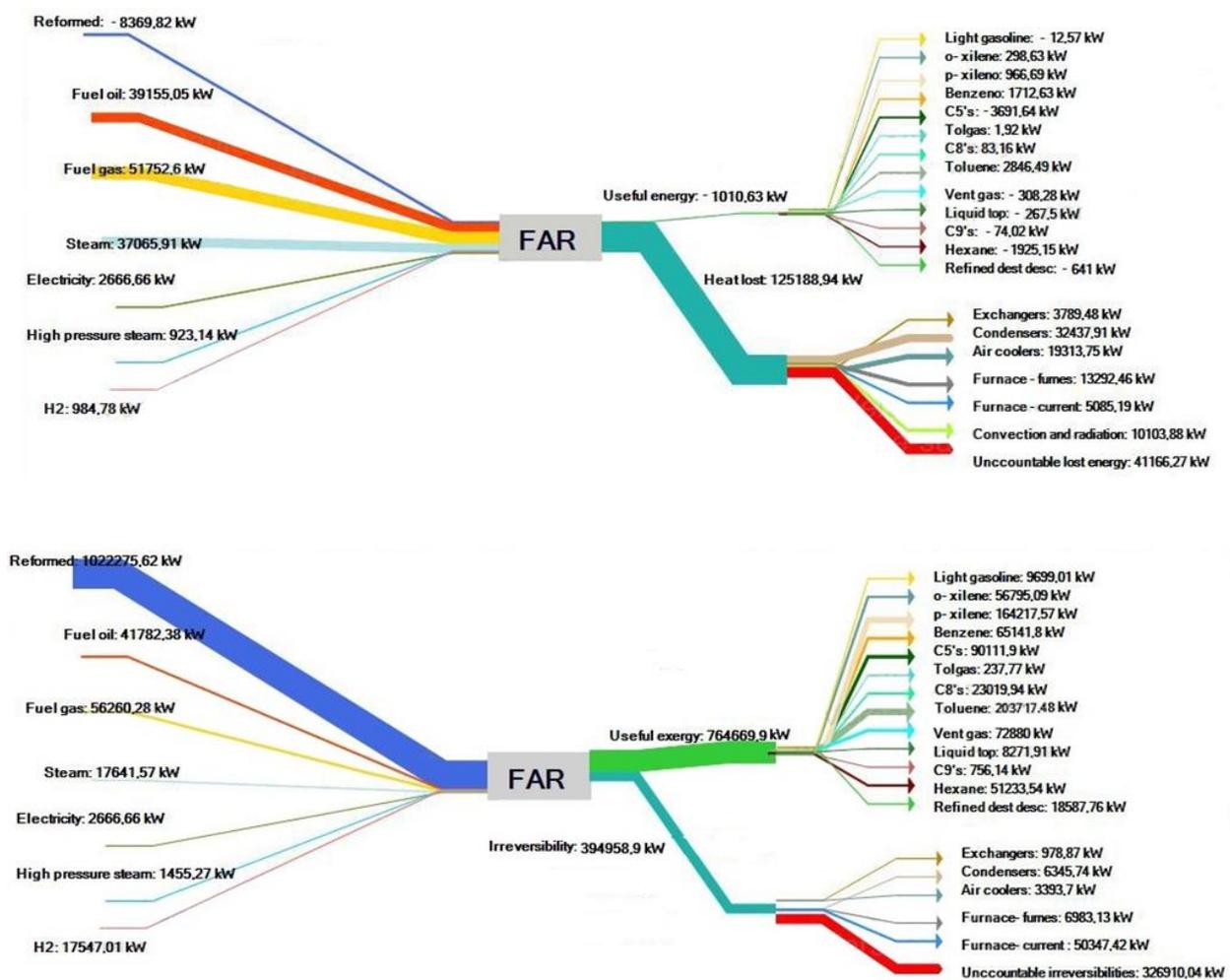

Figure 2. Sankey and Grassmann diagrams.

In the next figures, Figs. 3 and 4 are presented thermal losses and irreversibilities of the main component sets of the aromatics plant (FAR).
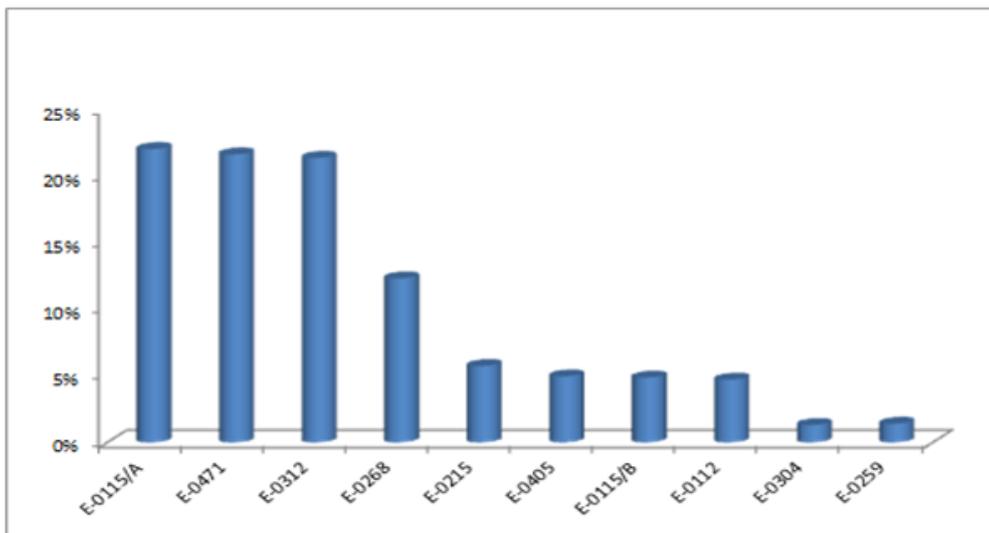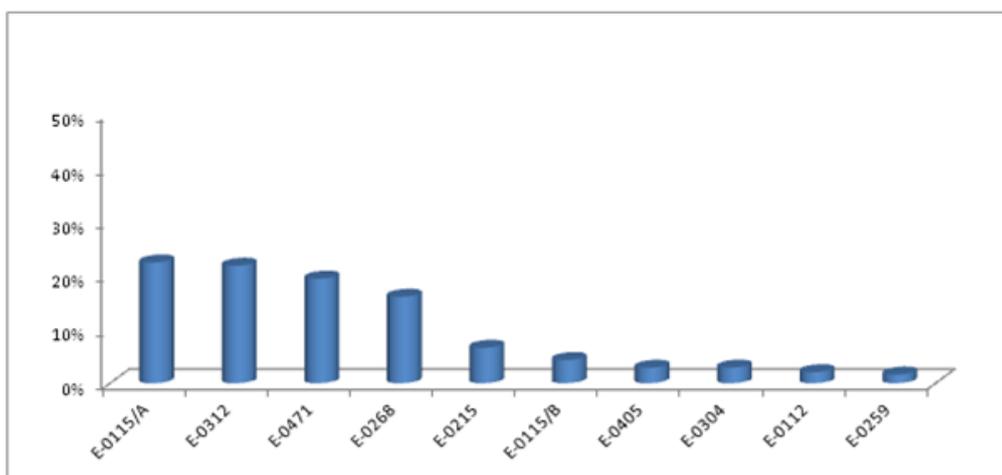
Figure 3. Thermal losses distribution in the FAR.

Figure 4. Irreversibilities distribution in the FAR.

Table 2. Identification of the equipment referred in Figs. 2 and 3.

Equipment	Unit
E-0115/A – Air cooler	UN-0100
E-0471 - Condenser	UN-0400
E-0312 - Condenser	UN-0300
E-0268 - Condenser	UN-0200
E-0215 - Cooler	UN-0200
E-0405 - Heat Exchanger	UN-0400
E-0115/B – Air cooler	UN-0100
E-0112– Cooler	UN-0100
E-0304 - Heat Exchanger	UN-0300
E-0259 - Heat Exchanger	UN-0200

Based on the hierarchy of energy losses and irreversibilities it was then possible to define a distribution of equipment components with more relevance for a prospective exploitation of the thermal energy wastes. Equipment with larger thermal losses are E-0115/A, E-0471, E-0312 and E-0268. However, in terms of irreversibilities the most important are E-0115/A, E-0312, E-0471 and E-0268. This clearly demonstrates that bigger thermal energy losses do not mean better possibilities of waste thermal energy exploitation. It is the weight of the exergy destruction that matters, i.e., the combination of the amount of wasted thermal energy and its corresponding temperature level. To choose equipment that

can be picked up the irreversibility losses must be combined with the practical and economic viability of the suggested interventions.

3. STUDIED SOLUTIONS

Two main solutions were studied, the application of two Organic Rankine Cycles (ORC) for electricity production and the application of a cogeneration system. Concerning the ORC's, one of the cycles would replace the air cooled heat exchangers E-0115A e E-0115B while the other ORC would use the wasted heat from the furnace H-0301.

For the ORC replacing the air cooled heat exchangers E-0115A/B that liberate 12 MW thermal energy in the 140 to 200 ºC range, it is possible to generate between 1500 to 1750 kWe, using a Turboden 22 HR SPLIT ORC system operating with an electrical efficiency of 14 %. For the exploitation of the thermal energy wasted in the exhaust gases from furnace H-0301, available at about 346 °C, a Turboden 6 HR system was considered. Assuming, in this last situation, that the exhaust gases leaving the ORC heat exchanger are at 150 ºC, an electric efficiency of 20 % can be obtained, and the output electrical power will be 319 kW. Both ORC systems can produce around 1555 kW which is equivalent to 59.1 % of the electricity needs of the Aromatics Plant.

The other scenario was the replacement of the furnace H-0301 by a twin fuel, fuel gas and fuel oil, cogeneration system. The proposed solution was a Wärtsilä system, reference 12V46GD, producing 11 MW of electricity, with an electric efficiency of 45.3 % and also about 14 MW of thermal energy. For the economic analysis of this solution three operating conditions were chosen, exclusively fuel oil fueled, exclusively fuel gas fueled, or a combination of both, Tab. 3. For the electricity selling prices two values were chosen, 0.09 €/kWh and 0.13 €/kWh. The cogeneration system had a cost of 1 M€/MW and the annual maintenance cost was assumed as 1.5% of the investment on equipment (Camus and Eusébio, 2017). The electricity production of this cogeneration system, 11384 kW, comprises the electricity needs of the Aromatics Plant, leading to an excess of 8717 kW to be sold. On the other end, considering that this system produces 14 MW of thermal energy, the thermal energy needs of the Aromatics Plant will be supplied at 74%. In the economic evaluation of this system the remaining thermal needs of 5 MW were also taken into account.

Table 3. Fuel costs for the cogeneration Wärtsilä 12V46GD operation.

Fuel cost	Cogeneration (Fuel oil)	Cogeneration (Fuel gas)	Conventional proportions
(€/h)	1801	1054	1562

Table 4. Costs and profits per hour of the cogeneration system.

Cogeneration Wärtsilä 12V46GD		
	Coefficients	(€/h)
Fuel Oil	Fuel cost	1801
	Cost of 5 MW $_{thermal}$ production with fuel gas	232
	Power purchase savings	373
	Sale energy profits (0.09 €/kWh)	785
	Sale energy profits (0.13 €/kWh)	1133
Fuel gas	Fuel cost	1054
	Cost of 5 MW $_{thermal}$ production with fuel gas	232
	Power purchase savings	373
	Sale energy profits (0.09 €/kWh)	785
	Sale energy profits (0.13 €/kWh)	1133
Fuel oil + fuel gas	Fuel cost	1562
	Cost of 5 MW $_{thermal}$ production with fuel gas	232
	Power purchase savings	373
	Sale energy profits (0.09 €/kWh)	785
	Sale energy profits (0.13 €/kWh)	1133

Looking at Tab. 3 it is clear that if the cogeneration is fed only with fuel gas, the feeding cost will be close to half the fuel oil feeding cost, whereas if a combined fuel feeding solution is adopted by taking into account the conventional H-0301 furnace feeding rates, 68 % (w/w) of fuel oil and 32 % (w/w) of fuel gas, the corresponding hourly cost will be of 1562 €.

Table 4 shows the hourly costs and profits for this cogeneration plant. The next figures present the financial evolution of the cogeneration system investment project for the six scenarios under consideration.
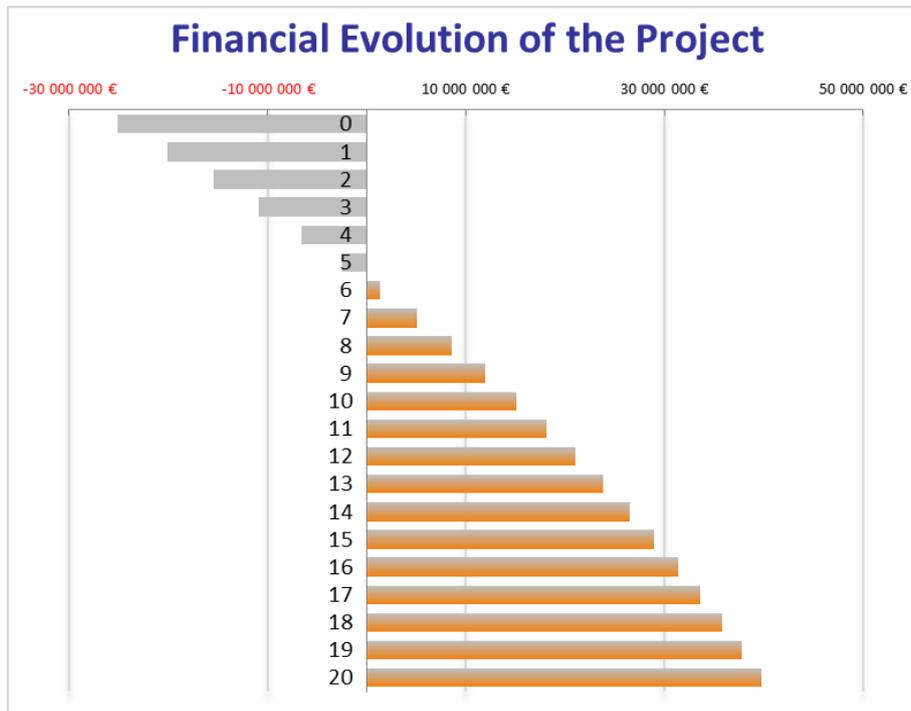

Figure 5. Financial evolution of the cogeneration system investment project, working with fuel oil and with price of electricity sale to the grid of 0.09 €/kWh.
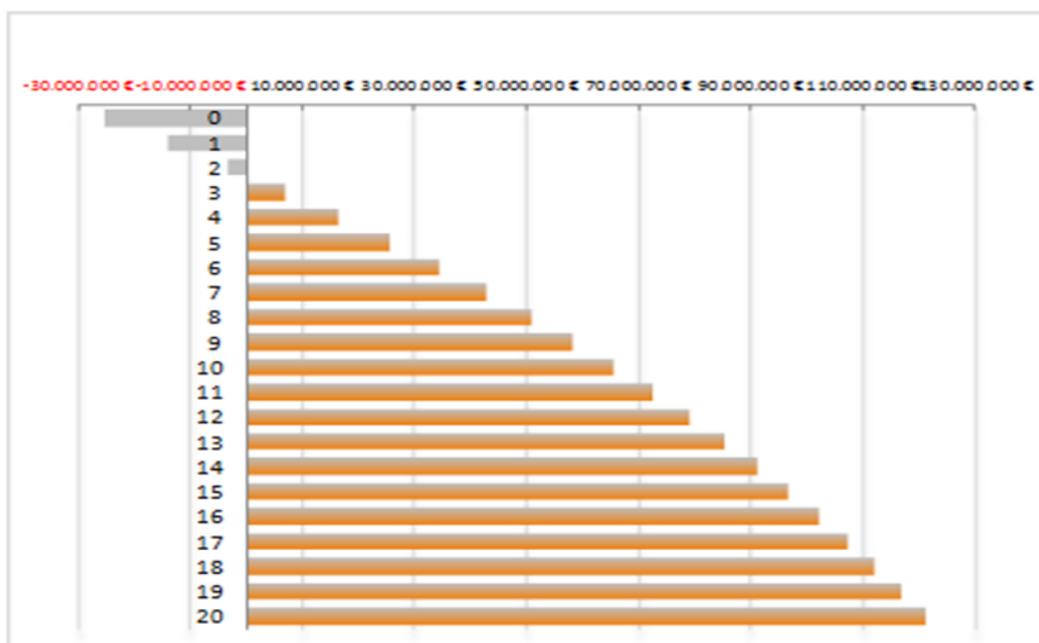

Figure 6. Financial evolution of the cogeneration system investment project, working with fuel gas and with price of electricity sale to the grid of 0.09 €/kWh.
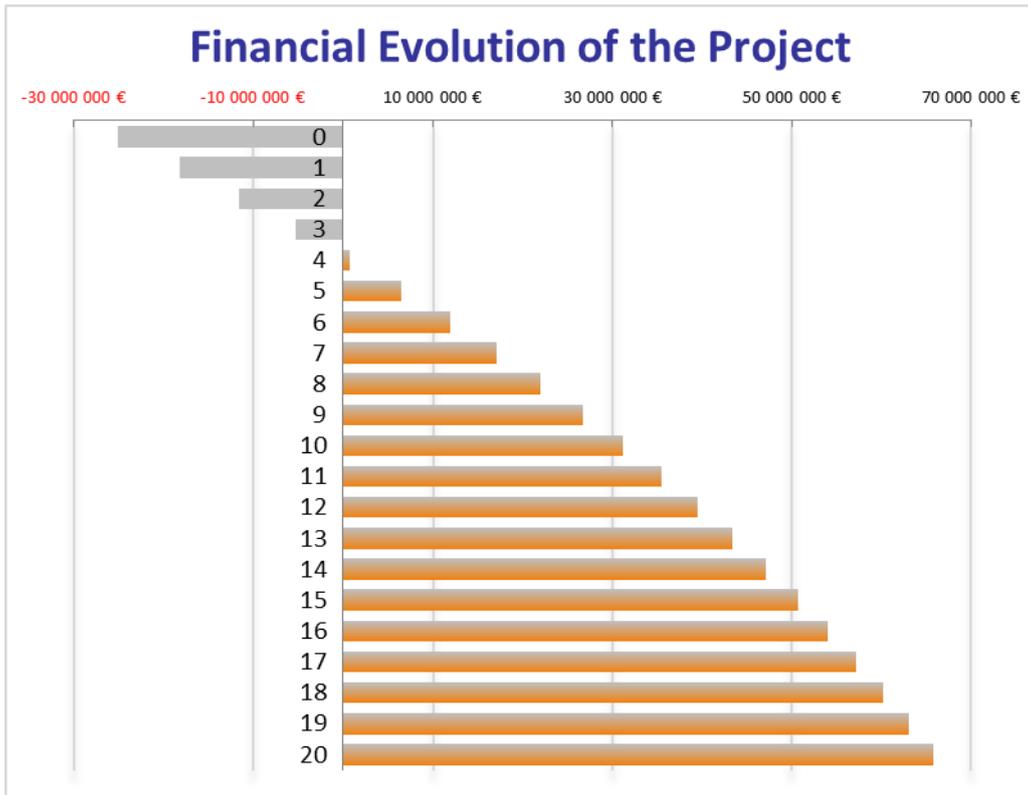
Figure 7. Financial evolution of the cogeneration system investment project, working with fuel oil and fuel gas with price of electricity sale to the grid of 0.09 €/kWh.
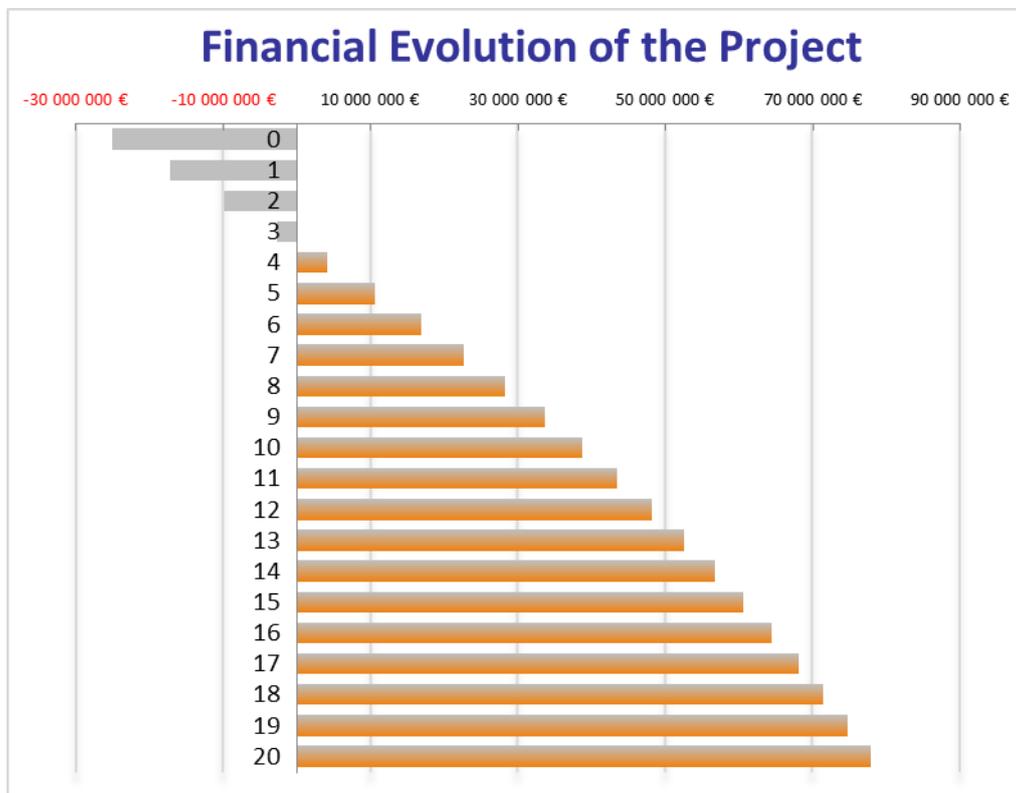

Figure 8. Financial evolution of the cogeneration system investment project, working with fuel oil and with price of electricity sale to the grid of 0.13 €/kWh.
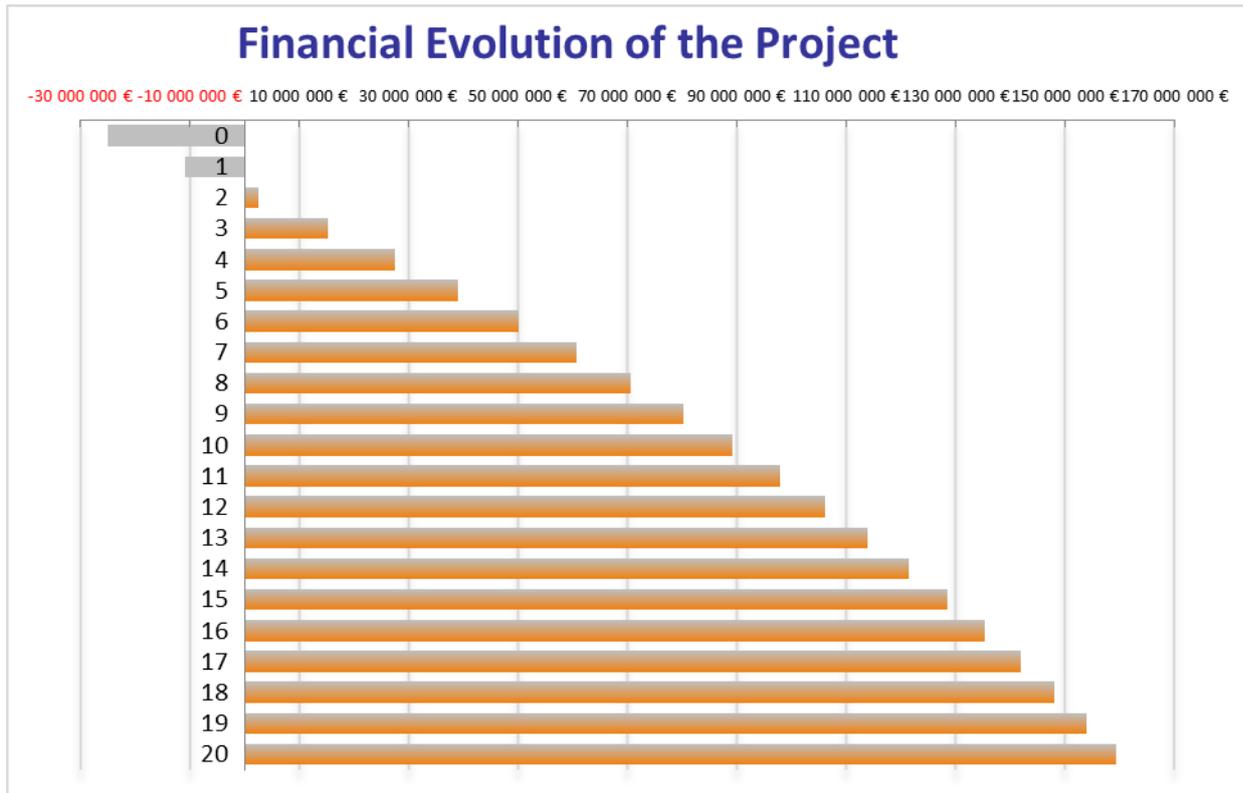
Figure 9. Financial evolution of the cogeneration system investment project, working with fuel gas and with price of electricity sale to the grid of 0.13 €/kWh.
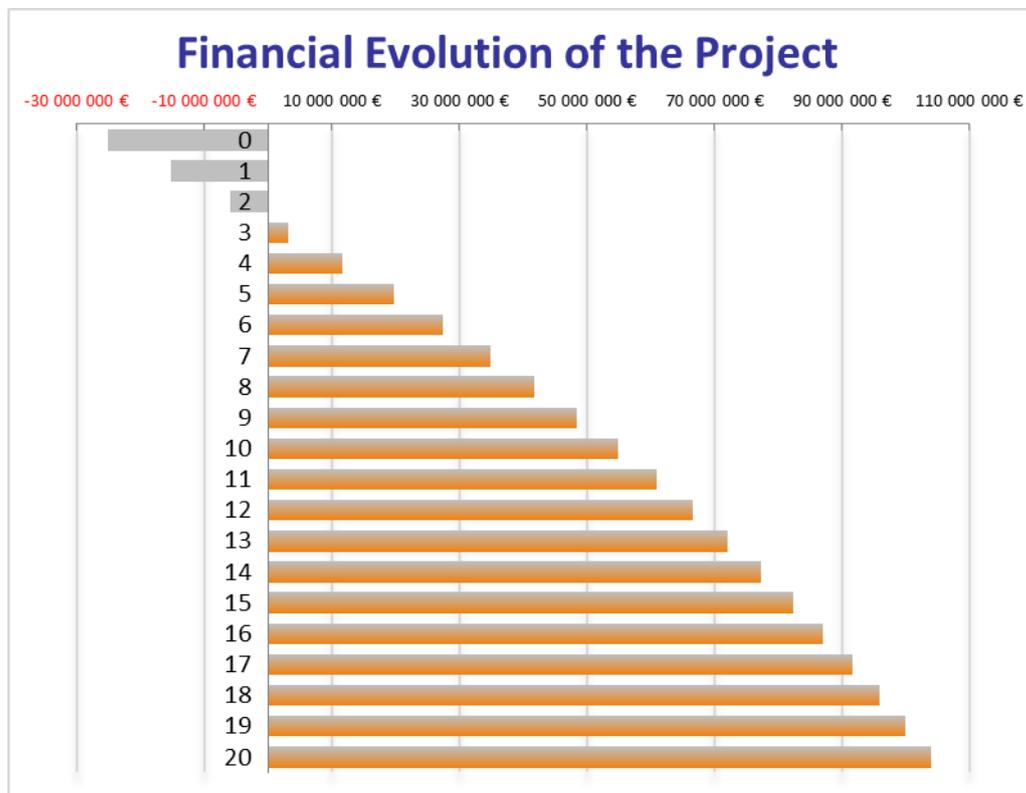

Figure 10. Financial evolution of the cogeneration system investment project, working with fuel oil and fuel gas and with price of electricity sale to the grid of 0.13 €/kWh.

The return of investment is not attractive when using only fuel oil because the investment will only be paid after six years. However either using only fuel gas or the conventional mixture of fuel oil and fuel gas, the corresponding return periods will be better, around 4 or four years. Although this analysis is still rather simple and a deeper study should be recommended it is quite clear the importance of this solution, even for the rather conservative price for electricity sale of 0.09 €/kWh. The values for the net added value (NAV) are quite attractive. For an investment of 25 M€ a value of NAV of 40 M€ is obtained while a value of 121 M€ is obtained when the fuel is exclusively the fuel gas. The internal rate of return goes from 20 % for the least favorable situation to the 47 % for the most favorable situation.

When considering an electricity selling price of 0.13 €/kWh all the three considered situations are acceptable, four years of investment return when using fuel oil, three years for the fuel oil fuel gas combination and two years for the exclusive consumption of fuel gas.

Further calculations demonstrate (Vilarinho, 2015) that the energy efficiency of the Aromatics Plant using only this cogeneration system would raise from the 0.8 % (Vilarinho et al., 2016; Vilarinho et al., 2017) to 7 %, whereas combining this cogeneration with the ORC's, it would take the energy efficiency to 8 %. As far as the exergy efficiency is concerned, the actual value of 65.9 % would suffer a small increase to 66.1 % (Vilarinho, 2015). This small increase is explained because the relatively high value of the original exergy efficiency is due to the fact that the aromatic separation process undergoing in the plant results in the increase of the exergy value of the separated aromatics when compared with them in the original mixture (Vilarinho et al., 2016; Vilarinho et al., 2017). Using the cogeneration plant plus the ORC's under consideration the exergy efficiency would go towards 67 %, Tab. 5.

Table 5. Comparison of the energy and exergy efficiencies found for the Aromatics Plant (AP), with the Cogeneration and ORC investments

	AP	AP + cogeneration	AP + cogeneration + ORC
Energy efficiency	0.81 %	7 %	8.1 %
Exergy efficiency	65.9 %	66.1 %	67.0 %

4. CONCLUSIONS

As a main consequence of the energy and exergy analysis of an Aromatic Production Plant, some important suggestions were proposed:
– Implementation of an ORC to exploit the thermal energy wasted in air coolers;
– Implementation of an ORC to exploit the thermal energy wasted from the combustion products of the furnaces;
– Implementation of a cogeneration unit producing 11 MW of electrical and 14 MW of thermal energy.

The implementation of the ORC solutions would be non-intrusive because they would simply take profit from the actual situation, by exploiting the large thermal energy wastes available for the production of electricity. By its turn, the implementation of the cogeneration unit would be intrusive as the main furnace of the plant would be replaced. Through the application of the cogeneration, the energy efficiency of the Aromatics Plant would increase from the present 0.8 % to 7 %, whereas the exergy efficiency would increase from 65.9 % to 66.1 %.

The combination of this cogeneration plant with the ORC exploiting the thermal energy wasted from the air coolers would result in the best solution, leading to a further increase of the Aromatics Plant energy efficiency to wards 8.1% and the corresponding exergy efficiency towards 67 %.

5. ACKNOWLEDGEMENTS

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