A multi-region representation of an automotive manufacturing plant with the TIMES energy model

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Abstract

Circular economy requires a material-specific and systemic approach in the design and management of production processes, as indicated in the European Commission Action Plan adopted in 2015 to promote global competitiveness, sustainable economic growth and create new jobs. This new approach implicates a more efficient use of resources within the entire production chain that aims to "close the loop" of the product life cycle. It promotes a self-regeneration that turns waste into resources. In this way, the recycling and reuse of recycled materials is constantly increasing and the demand for raw materials is decreasing, allowing waste to be contained. The concepts of the circular economy were applied to develop a two-region partial equilibrium model of an automotive manufacturing plant based on the ETSAP MARKAL-EFOM (TIMES) generator, aimed at identifying more efficient and sustainable configurations of the production system through a scenario analysis, taking into account energy recovery and recycling of plastic waste material from production processes as well as reducing CO_2 pollutant emissions. The multi-region approach allowed modelling two industrial units, the Assembly Unit and the Plastic Unit, as two different modelling "regions" with independent production of electricity, heat and cooling. Such "regions" are connected through unidirectional "trades" processes, i.e. the components produced in the Plastic Unit and he polypropylene waste, which represent a secondary input material. The model was calibrated based on real consumption data for the years 2015, 2016 and 2017 and optimized over a time horizon of ten years. Five medium-term evolutionary scenarios addressed energy and materials recovery and evaluated the feasibility of innovative technological solutions: photovoltaic, energy recovery from the molding process of polypropylene components, production of syngas from waste materials, recovery of polypropylene waste, use of pigmented polypropylene for bumper molding.

Introduction

The linear economy based on the "take-make-dispose" paradigm characterized the mass production of the industrial system of the nineteenth and twentieth centuries. This production system was one of the main causes of phenomena such as environmental pollution, the emission of greenhouse gases and the consequent climate change, also generating intense competition among States for the control of raw materials (Sauvè et al 2016). Over time, the world community has become aware of the increasingly reduced availability of resources, the volatility of the prices of natural resources and the instability of raw material supplies, the lost value of materials and products and the growing mass of waste. Since the 1970s there has been growing awareness among scientists and analysts of the need to link economic growth with sustainable development. In the last decade, a new economic system paradigm focused on a "circular economy" has emerged in order to take into account well-being, economic growth and safeguard of the environment (Loiseau et al 2016). The circular economy is aimed at reducing waste by better use of resources, considering waste itself as a resource which can reintroduced in the production cycle. This implies that the life cycle of products is extended in order to share resources, use recycled raw materials and produce energy from renewable sources. The European Commission adopted in 2015 an important European Action Plan for the Circular Economy (COM/2015/0614 final), that provides indications for sustainable economic development with increasingly fewer releases of carbon dioxide, a more efficient use of resources and higher competitiveness. The promotion of circular approach will require the activation of processes in which consumers, businesses, and local, regional and national authorities will have to be protagonists, with the active support of the European Union.

Several tools have been used to assess initiatives related to the circular economy in different scopes and at different scales. Some studies tried to create a complete overview of tools, methods and approaches through a review of literature and practices (Bocken et al 2019, Pieroni et al 2019, Rosa et al 2019). Kalmykova et al 2018 built a database on circular economy strategies, which summarizes the methods of circular economy implementation described in literature. Among the various available models and tools, material flow analysis (MFA) is one of the most widely accepted and utilized tools in the industrial-ecology discipline, that measures the input-output materials and examines the pathways and flux of each material flow within the whole system (Islam and Huda 2019). The SWOT (Strengths Weaknesses Opportunities Threats) analysis is a strategic planning instrument developed for business management to identify the external opportunities and threats as well as internal strengths and weaknesses of an organization and its environments. In particular, it was used to evaluate five strategies for integrating the recycling process based on the dismantling of plastic cases from LCD televisions in a commercial post-shredder recycling facility for waste electrical and electronic equipment plastics (Wagner et al 2019).

In order to implement circular economy practices in a leather industry for improving its sustainability, the "best worst method" was applied in the assessment process. It is a powerful and simple Multicriteria decision aid method based on pairwise comparison. Eight potential challenges to circular economy practices were determined and analysed with this tool (Moktadir, 2020). The Data Envelopment Analysis (DEA) model with undesirable input was applied to assess the efficiency of recycle treating and industrial waste reuse, including wastewater, waste gas and solid wastes in China. It represents an effective technique for measuring the relative efficiency of homogenous decision-making units, especially for complex production systems with multiple inputs and outputs (Li et al 2020). Life Cycle Assessment (LCA) is among the most powerful techniques to evaluate the sustainability of any technology. LCA computes all the inputs and outputs of a product, process, or service, the associated wastes, the impacts (on human health and on ecology), and interprets and communicates the results to the assessment throughout the life cycle of the products or processes under review (Boer et al 2020). As an example, the LCA was used to individuate the circular economy opportunities for small and medium-sized enterprises in the meat processing sector in order to reduce their environmental impacts. Four alternative scenarios for energy supply were developed with focus on photovoltaic and wind generation, the use of tallow, the use of biogas from anaerobic wastewater treatment ponds and the use of biomass. The obtained results were compared with the results of reference scenario (Colley et al 2020). The objectives of the circular economy, which correspond to those of the low carbon economy are: resource efficiency, sustainable development, access to clean water and social welfare. These objectives are more and more considered in a combined manner through the Nexus analyses, which takes into account the interconnections among several resources (energy, water, food, land and climate) in order to assess impacts and identify opportunities from a more holistic point of view (Brouwer et al 2018). For this purpose Brouwer et al proposed different types of models as, for example, the E3ME-FTT model, a macroeconomic simulation model (Lam et al 2018), the MAGNET model, Global computable general equilibrium model with an additional focus on agriculture (Boulanger P et al 2014), the CAPRI model, a Global agro-economic model (Himics et al 2019), the IMAGE model, a comprehensive integrated modelling framework of global environmental change (Stehfest et al 2014), the OSeMOSYS model, a systems cost optimisation model (Dhakouani A et al 2017) and the MAGPIE-LPjML model, a Global land use allocation model, coupled to grid-based dynamic vegetation model (Lotze-Campen et al 2008). Some modelling tools are used in an integrated way in order to discover behaviours of the system that otherwise would be difficult to identify. For this reason, for example, a network optimization model for the waste sector, OptiFlow, and the partial equilibrium energy systems model Balmorel were used together to analyse the role of the waste-to-energy co-optimizing waste management and energy systems at national scale. Moreover, the life cycle analysis was used to explore the potential climate impact of waste trade (Pizarro-Alonso, et al 2018).

In most cases the energy systems are analysed taking into account the supply and production of electricity and heat, mainly focusing on the following end-use sectors: Residential, Commercial, Industry, Agriculture and Transport (Cosmi et al 2009). Few studies use the TIMES model generator exclusively to analyse the Industry sector. In (Seck et al 2013)a technical energy model for non-energy intensive industry was developed by using TIMES, focusing the attention on food & drink sector in order to study its global energy efficiency and the potential for CO_2 emissions reduction.

This study focuses on the implementation of a model of the energy and materials system of an automotive industrial district (TIMES4CARS) using a partial equilibrium model based on the IEA-ETSAP TIMES[1] model generator. The TIMES4CARS is a two-region model (Assembly and Plastic units) that allows to explore the potentialities of the circular economy approach in a real case study. Moreover, best solutions to optimise base principles of the circular economy (sharing materials, valorisation of waste, electricity production from renewable sources, energy efficiency) are also evaluated through scenario analysis.

Methodology

The Integrated MARKAL-EFOM system (TIMES) is a widely used energy system model generator developed by the International Energy Agency (IEA) in the framework of the Energy Technology Systems Analysis Programme (ETSAP) im-

1. https://iea-etsap.org/index.php/etsap-tools/model-generators/times

plementing agreement (Loulou et al 2005). It is a bottom up energy optimisation model based on linear programming that provides a technology-rich basis for estimating energy dynamics over a medium and long-time horizon. It is demand driven and technology oriented, allowing to represent all the aspects related to energy system including emissions, materials and environmental damage.

The data input of the TIMES model consists of a detailed representation of existing and future technologies in terms of technical-economic and environmental parameters and technology turnover. This planning tool is utilized by numerous scientific communities worldwide to derive and study optimal energy-environmental scenarios at level of single communities, region, country or in a multi-regions approach, analysing in depth solutions for energy security, climate change mitigation and air pollution reduction (Di Leo et al 2015).

THE TIMES4CARS MODEL

The TIMES4CARS model was developed using the multi-region version of the TIMES model generator, which allows to characterize two industrial units, Assembly Unit (AU) and Plastic Unit (PU), as two different "regions". They are linked through unidirectional processes of "trades", which transfer all the components produced in the PU to the AU (Figure 1).

The production of cars in the AU represents the final demand that drives the model on the examined time horizon 2015-2025. It is divided into sub-periods of equal duration, having the main time unit coinciding with the single year. The reference year is 2015, i.e. the year to which the model is calibrated based on real data. The model is also calibrated to the years 2016 and 2017. The REMS (Reference System for Energy and Materials) includes, for both units, the primary energy supply (import of electricity and methane gas) and the transformations of primary energy into secondary energy (electricity production, heat and cooling or cold energy). As regards the Assembly Unit, the Press, Body, Paint and Assembly sectors are represented, as well as energy consumption in the General Services. Instead, as regards the PU, the molding line of plastic components and the bumper painting line are modelled. The optimization of the model had as objective the minimization of the system total cost to satisfy the production of three car models (CAR1, CAR2 and CAR3) already produced in the base year, in addition to the production of two other car models (CAR4 and CAR5) that are activated during the time horizon respectively starting from 2019 and from 2020. The total demand of cars is assumed to be constant over the 2018–2025 time horizon. The data input of the TIMES4CARS model is composed of a set of Templates (Excel sheets), which contain numerical data for the characterization of technologies, energy flows and material flows (Figure 2).

Six templates of the base model contain the definition of the technologies currently in use and the energy flows through technical and economic data. In particular, four templates refer to the AU and two templates to the PU. As regards the AU, it relates to the production of energy commodities (electricity, cold and heat), the supply of energy from the outside, the modelling of the four sectors (Press, Body, Paint and Assembly) and the representation of the infrastructure for the division of energy consumption into the four sectors. As concern the PU, the two templates are related to energy production (electricity, cold and heat) and the modelling of the molding and painting lines. The technology repository is a database of alternative technologies, existing and / or being tested, characterized by technical, economic and environmental parameters. It contains the alternative technological options available along the time horizon considered for electricity and heat production: Rankine cycle

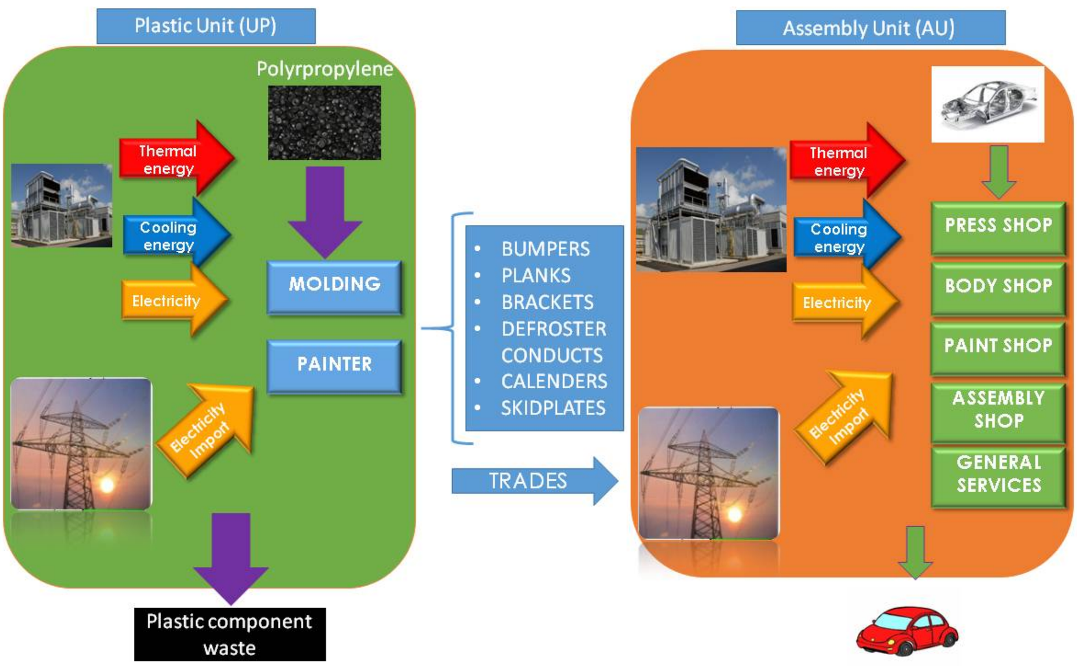

Figure 1. Representation of the two industrial units (PU and AU).

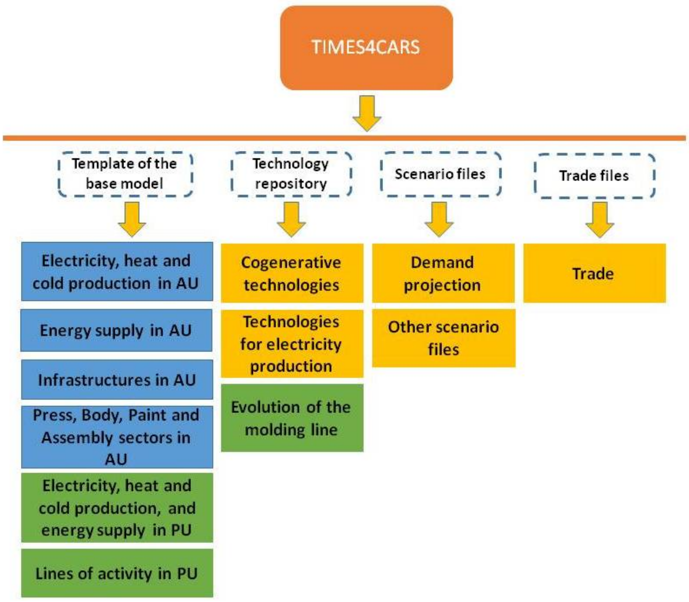

Figure 2. Data input of the TIMES4CARS model.

technologies having an organic fluid as the motor fluid, technologies for energy recovery obtainable from the plastic materials disposal through their gasification for syngas production and the characterization of the evolution of the molding line over the time horizon. Scenario files define the demand projection on the time horizon considered, the emission factors of air pollutants and exogenous constraints. Trade files define the transfer of the plastic components produced in the PU to the AU.

The reference energy system of the PU is schematized taking into account the existing trigenerator (production of electricity, heat and cooling energy), the molding processes of some plastic components and the painting for the bumpers (Figure 3).

The electricity and natural gas import are modelled through two processes, named respectively IMPELCUP and IMPMETUP characterized only by the output commodities, respectively electricity and natural gas, with a purchase cost. The trigeneration system is modelled through two processes: the CCHPMETPL00 co-generator powered by natural gas to produce electricity and heat, and the CCHTCOLPL00 compressor, powered by electricity to produce cold. Electricity and cold feed the processes that represent the molding lines of the Plastic Unit, modelled according to the plastic component produced and the type of car. The painting phase, relating only to the treatment of the bumpers, is modelled through different processes (depending on the cars models produced), powered by natural gas, electricity, heat and cold.

In Figure 4 the reference system of the materials of the PU is represented and it is delimited by the hatching in red, while externally the assembly processes that take place in the AU for the three types of cars produced in the base year are represented. The supply of three types of polypropylene (PP50,400 LCE, PP50,20RNERO and PP65,40) is modelled through three supply processes (MINPP50400, MINPP50R and MINPP654). The three types of polypropylene feed the molding processes from which are the main plastic components (Bumpers, Conducted Defroster, Planks, Skidplates, Calenders, Brackets) depending on the type of car produced and scraps of plastic components are produced. The scraps are currently disposed of and not recycled. All the plastic components produced by the molding are sent directly to the AU through the Trade processes, with the exception of the bumpers, which are sent for painting.

The Reference Energy System of the AU is more complex than that of the PU, due to wider extension of the unit and the higher number of processes used. It takes into account both the energy production and supply (Figure 5) and the four sectors in which cars are built starting from the virgin body. The RES includes the import of gas and electricity, and the two processes CCHPMET01 and CCHTCOL01 which model trigeneration, which produces heat (INDHET), electricity (INDELC) and cooling energy (INDCOL).

Dummy technologies (SHAREHET00, SHARECOL00, SHAREELC00) are used to characterize the energy vectors produced and imported on the basis of their subsequent use (HET030 –

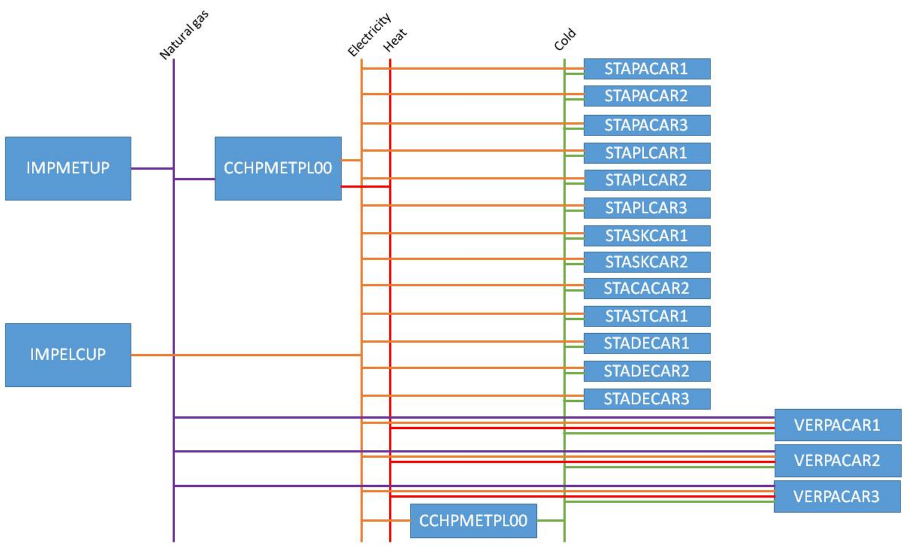

Figure 3. Reference energy system of the PU.

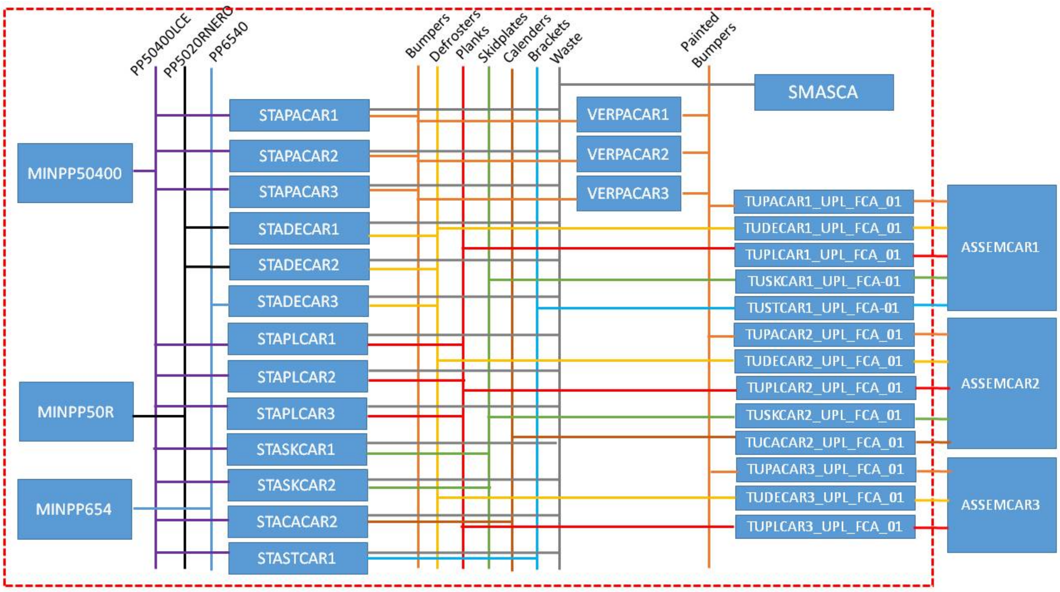

Figure 4. Reference system of Materials of the PU.

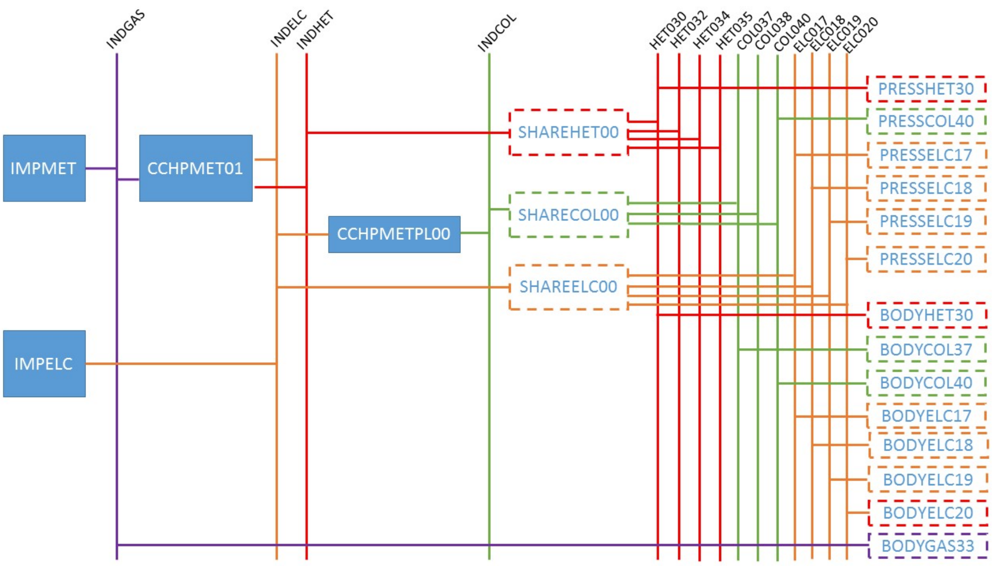

Figure 5. Reference Energy system of the Assembly Unit – energy supply side.

Space heating; HET032 – Technological Heat Steam; HET034 – Technological Heat for Water – Continuous; HET035 – Technological Heat for Water – Seasonal; COL037: Water cooling – Continuous; COL038: Water cooling – Seasonal; COL040: Space cooling; ELC017: Thermo-ventilation; ELC018: Lighting; ELC019: Driving force; ELC020: Compressed Air.

The four sectors (Press, Body, Paint and Assembly) are considered as "black-boxes" placed in series with each other. Energy consumption and the bodies from the previous sector represent the input for each sector, whereas the treated bodies by the sector represent the output. The final sector is the Assembly shop, in which the bodies from the Paint sector, the plastic components produced in the PU, and the energy carriers are the input whereas the output is represented by cars (end use demand of the model).

DEFINITION OF SCENARIOS

The scenario analysis allows analysing the evolution of both the energy system and the production system related to the PU and the AU under specific exogenous constraints. The introduction of exogenous constraints allows to identify different evolutions of the production system over the considered time horizon and to compare trends with the results obtained in the reference scenario.

The '*Business-As-Usual scenario*' is the reference scenario which represents the evolution of the current energy and productive system of the two units in order to satisfy the final demand over the time horizon 2015–2025. Among the basic assumptions, energy consumption for the four sectors of the AU an energy saving of 4 % has been assumed for each two-year period starting from 2019. Besides the purchase costs of electricity and natural gas are considered constant over the time horizon.

Two types of alternative scenarios were identified for a total number of five scenarios depending on whether they focus on the energy aspects or those relating to plastic materials.

The *energy scenarios* are:

- The '*photovoltaic scenario*' is based on the introduction of photovoltaic systems both on the PU and on the AU in order to satisfy a part of electricity consumption such as lighting. As regards the AU, it is assumed to use a photovoltaic system characterized by a peak power of 1.2 MWp and 1,300 operating hours per year with an electricity production of 1,560,000 kWh per year. This plant requires a surface of photovoltaic panels equal to 12,000 m^2 which should be placed on the roof of the plant. The installation of a photovoltaic plant characterized by a peak power of 0.6 MWp is supposed for the PU. Assuming the same operating hours of the system to be installed on the AU (1,300 hours per year), it is estimated a production of 780,000 kWh per year which require a surface area of photovoltaic panels equal to 6,000 m^2.
- The '*energy recovery scenario*' assesses the economic feasibility and the effects in terms of energy of the introduction of Organic Rankine Cycle technologies for the energy recovery in the molding processes. The cases in which the additional heat source consists of a solar collector, a geothermal probe or a biomass boiler were also examined.
- In the '*syngas production scenario*', a pyrogasification technology coupled to an internal combustion engine is introduced into the energy system of both the AU and the PU, assuming an investment cost of 4,000 Meuro/GW). Three types of syngas are hypothesized on the basis of different concentrations in moles of polypropylene (20 %, 40 % and 60 %) mixed with municipal solid waste. Furthermore, it has been assumed that the cost of transporting municipal solid waste to be mixed with polypropylene is negligible.

The scenarios related to the *Plastic materials* are:

- The '*pigmented scenario*' assesses the convenience of using pigmented polypropylene during the molding phase. Pigmented polypropylene is a particular material with intrinsic proprieties such as to avoid the painting of the plastic components, but it is characterized by a higher procurement cost compared to the polypropylene usually used. Furthermore, the cost of pigmented polypropylene waste is higher than that of polypropylene waste currently in use. Therefore, this scenario permits to evaluate the system's response to the introduction of the pigmented polypropylene for molding the bumpers, quantifying the energy savings and the reduction of pollutant emissions into the atmosphere.
- The '*recycling scenario*' assesses the convenience of the recycling system taking into account the investment costs and the quantities of waste produced in the PU. It is assumed that all waste deriving from the molding process of the bumpers and the defroster conducts is recovered through a process that models the shredding system.

Results

BAU SCENARIO

The optimal solution obtained for the BAU scenario is characterised by a total system cost of 70.16 MEuro, of which 28.79 MEuro are related to the PU and 41.37 MEuro to the AU. Starting from 2019 the current cogeneration systems are replaced by two steam turbines with bleed and cogeneration condenser for both two Units characterized by higher efficiencies (0.38) than those existing in the base year (0.25). As concern the AU, natural gas consumption by cogeneration technologies decreases from 1.68 PJ in 2017 to 1.27 PJ in 2025. This reduction of 25 % is due to a greater efficiency of the new steam turbines with bleed and to a lower demand of electricity and heat resulting from the efficiency of the production processes. The latter factor also results in reduction of energy consumption per car from 2017 to 2025. In fact, as it is evident in Figure 6, electricity, heat and cold consumption per car decrease respectively by 9 %, 10 % and 8 % in 2025 compared to 2017.

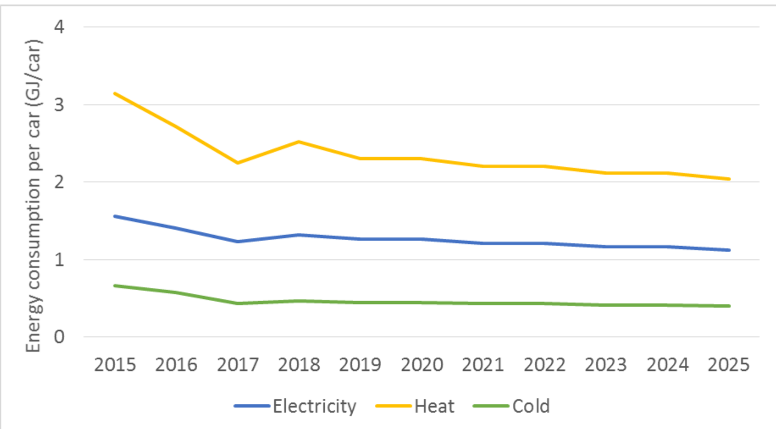

Figure 6. Energy consumption per car (GJ/car) – AU.

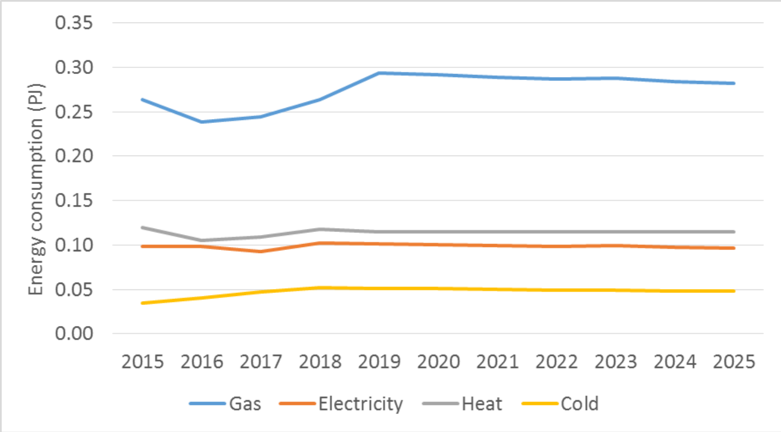

Figure 7. Energy consumption (PJ) – PU.

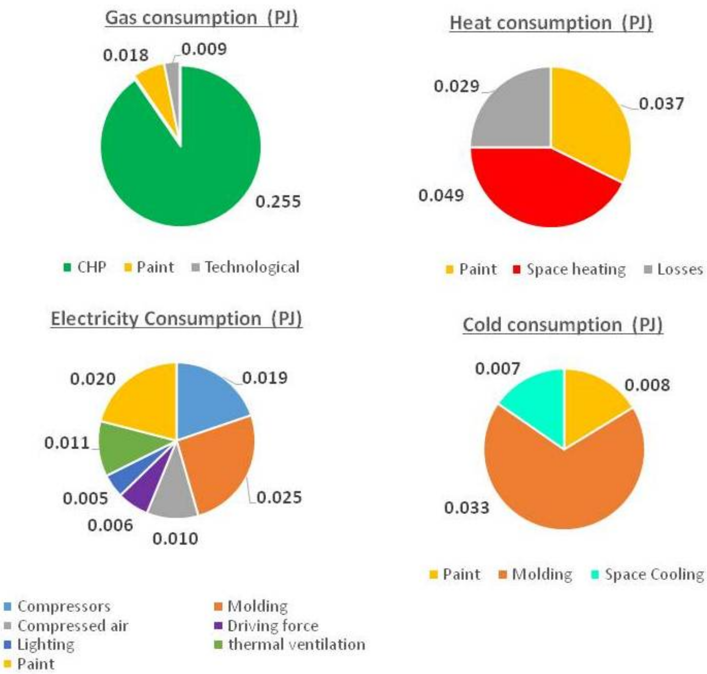

Figure 8. Breakdown of energy consumption by 2025 by use (PJ) – PU.

As concern the PU, gas, electricity, heat and cold consumption by type of use are almost constant over the entire time horizon (Figure 7), because it has been assumed that the total number of cars produced on the time horizon is constant.

In Figure 8 the breakdown of energy consumption by use is shown for 2025. It is possible to observe that the highest consumption of natural gas (0.255 PJ) are related to co-generation of heat and electricity. As concern heat consumption, the three typologies of use are more comparable, observing a value of losses of 0.029 PJ. Electricity and cold consumption for molding are the highest values (respectively 0.025 and 0.033 PJ) for these typologies of energy sources.

The consumption of polypropylene PP50,400LCE and PP50,20RNERO is almost constant starting from 2018, whereas the consumption of polypropylene PP65,40 is zeroed starting from 2019, because a model is no longer produced. In Figure 9 the number of painted bumpers is reported for each model of car on the time horizon. Starting from 2020 for each year, all the bumpers are painted, consuming 0.020 PJ of electricity, 0.037 PJ of heat, 0.018 PJ of natural gas and 0.008 PJ of cold. The paint process produces 0.12 ton of carbon dioxide and 0.18 kton of volatile organic compounds (VOC).

PHOTOVOLTAIC SCENARIO

The constraint on the electricity production from photovoltaic systems implies an increase of the system total cost compared to that of the reference system. In particular, the total cost increases by 1.2 % for the AU and by 0.8 % for the PU. The photovoltaic system is characterized by an investment cost of 1,800 Euro/kW. The electricity production from the pho-

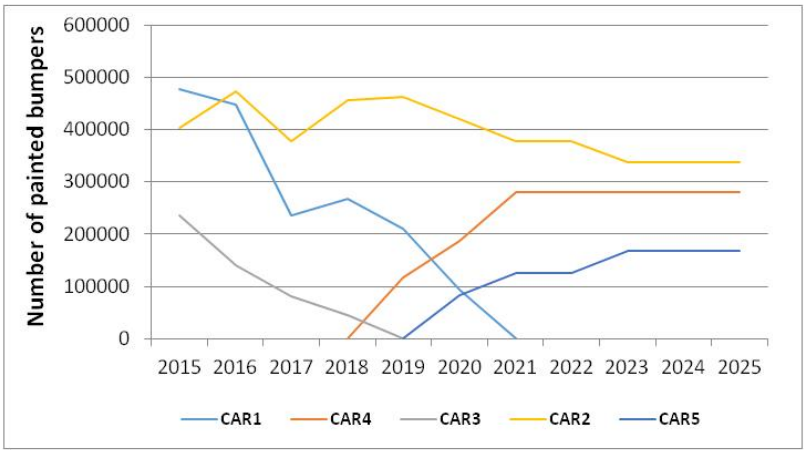

Figure 9. Number of painted bumpers for each car.

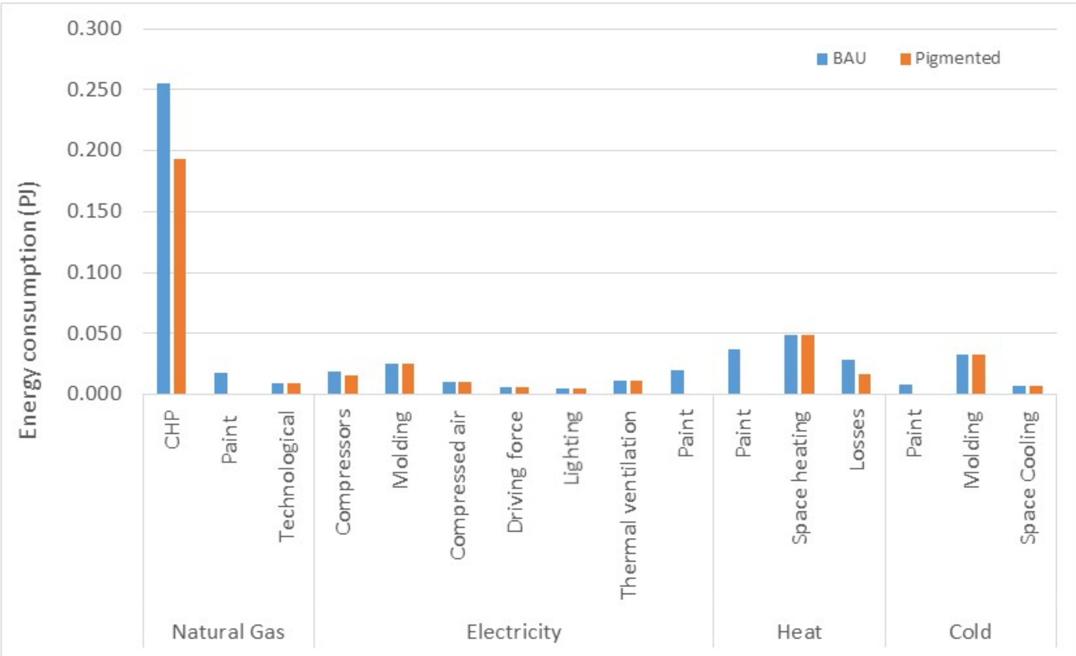

Figure 10. Energy consumption by use – year 2025.

tovoltaic systems installed on the two Units implies a lower amount of electricity produced by the tri-generator system and therefore a lower natural gas consumption. Starting from 2019 the installed capacity of the new steam turbine with bleed and cogeneration condenser is equal to 21.75 MW compared to 21.83 MW of the BAU scenario for AU. The electricity production from photovoltaic sources implies a lower natural gas consumption of 1.2 % and 2.8 % respectively for the AU and PU respect to the BAU scenario results. CO_2 emissions also drop by 1.1 % and 2.6 % respectively for the AU and PU.

PIGMENTED SCENARIO

The use of pigmented material for bumpers molding leads to an increase of the system total cost (+1.2 %) compared to that of the BAU scenario. In particular, the total cost of the PU increases by 3 %, whereas there are no changes as regards the total cost of the AU. Bypassing the painting process, the use of pigmented material reduces the natural gas purchase (-30.4 % in 2025 compared to the BAU scenario). In fact, electricity, cold, natural gas and heat consumptions related to painting process are zero, and as a consequence natural gas for cogeneration system, heat losses and electricity used in compressors for cold production are reduced respectively 24 %, 43 % and 16 % compared to the BAU scenario (Figure 10).

The reduction of fuel consumption translates into a lower release of all pollutants into the atmosphere related to combustion processes with a reduction that reaches 40 % in 2025. On the other hand, process emissions of both CO_2 and VOC are completely cut.

RECYCLING SCENARIO

In the absence of constraints on the reuse of plastic components scraps, taking into account the investment cost of the recycling system (estimated at 60 Euro/kg), the quantities of plastic components scraps and disposal costs, the model suggests the disposal of the scraps as the optimal solution in terms of cost. It prefers this solution to shredding and subsequent reuse of plastic waste. In order to assess the convenience of the plastic waste recycling system, a sensitivity analysis was carried out by imposing gradually decreasing investment costs starting from a value equal to 60 Euro/kg. Figure 11 shows the obtained results with the sensitivity analysis, where the investment cost is 60 Euro/kg for the Recycling_1 scenario, 30 Euro/kg for the Recycling_2 scenario, 20 Euro/kg for the Recycling_3 scenario, 15 Euro/kg for the Recycling_4 scenario and 10 Euro/kg for the Recycling_5 scenario.

The sensitivity analysis highlights that the investment respect to the BAU scenario can be convenient when the cost is of 10 Euro/kg (Recycling_5 scenario), that is when the total system cost is lower than system total cost of the BAU scenario.

ENERGY RECOVERY SCENARIO

The Energy Recovery Scenario aims to verify the economic feasibility and energy savings obtainable from the introduction of Rankine cycle technologies with organic fluid (ORC) as the driving fluid in the molding process. Several optimization runs were carried out by competing the molding processes equipped with a system for energy recovery with the existing molding processes. The analysis of results shows that the system prefers not to use Organic Rankine cycle technologies for energy recovery in the molding phase due to the high investment costs (0.1 Euro/KWh in the case of integration with the solar source estimated on the basis of the Levelized Energy Cost). If the model is forced by the imposition of an exogenous constraint to use the Rankine cycle technologies, than it prefers to activate those not integrated with a renewable source. In this case an electricity and cooling savings of 30 % are obtained for 2025 in the molding process compared to the BAU scenario. These savings translate into a lower electricity production by the steam turbine (-9 %) and a lower import of natural gas (8 %) by 2025 compared to the BAU scenario. The compressors for cold production show also a 17 % reduction in electricity consumption by 2025. As concern the environmental parameters, CO_2 emissions reduction reaches 9 % in 2025 compared to the BAU scenario. However, there are no changes in the production and consumption of heat. Further optimization runs have shown that Organic Rankine cycle technologies with energy recovery are competitive, if the assumed investment cost is 0.0001 Euro/KWh.

SYNGAS PRODUCTION SCENARIO

In the Syngas production scenario, the feasibility of using a pyrogasification technology coupled with an internal combustion engine for electricity production is assessed using only polypropylene waste produced in the PU. The pyrogasification technology is put in competition both with the technologies already existing in the base year and with those included in the Technology repository. Two cases were analyzed: in the first case the pyrogasification technology is assumed to be available for the AU and in the second case it is available for the PU. In both cases the model prefers to use the syngas type 3 (60 % of moles concentration of polypropylene) and the System total cost decreases by 3 % compared to that of the BAU scenario. Both for the AU and PU a pyrogasification technology is activated from 2019 with a capacity of 0.035 MW. It permits an annual electricity production of $0.7*10^{-3}$ PJ. In the case of activation of the pyrogasification technology in the AU there is a reduction of natural gas consumption of 0.1 % compared to the BAU scenario, whereas in the PU the reduction of natural gas consumption is of 0.7 %.

Conclusions

This work was useful to verify the feasibility of modelling a specific industrial district for cars production using the TIMES energy modelling platform. It represents one of the first successful applications of the ETSAP-TIMES model generator to

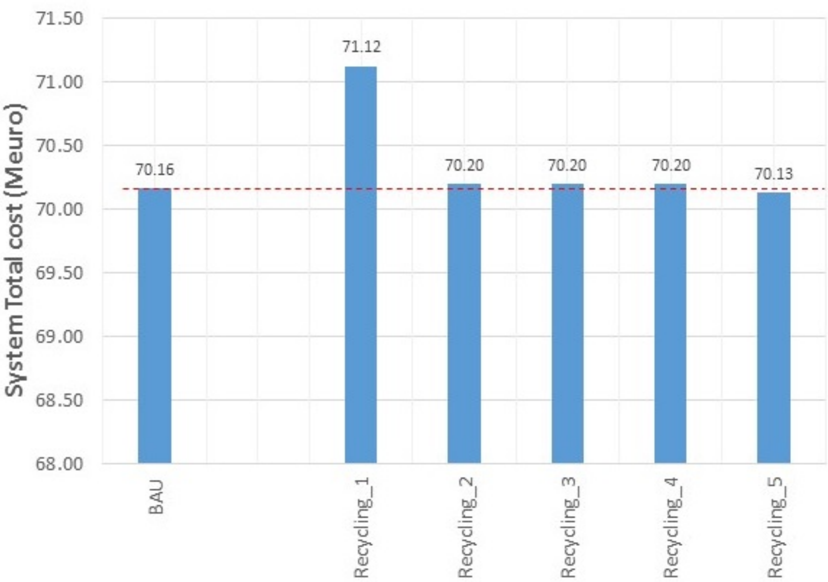

Figure 11. Sensitivity analysis.

an industrial district. Moreover, it showed the advantages in implementing such a models in order to evaluate the possible implementation of measures based on the principles of the circular economy. The obtained results suggested to introduce steam turbines with bleed and cogeneration condenser in order to replace the current systems of electricity and heat production for both the two analyzed industrial units. The scenario analysis highlighted the impact of the implemented measures in economic, environmental and energy saving terms. As concern the energy measures, the introduction of photovoltaic panels for both industrial units lead to a reduction of natural gas consumption and consequently a reduction of CO_2 emissions although the total cost of the system increases, due to the investments in new technologies. A 30 % saving of electricity and cooling energy consumption were also obtained with the introduction of Rankine cycle technologies with organic fluid (ORC) as the driving fluid in the molding process, but the investment costs are too high to be implemented. Instead, the use of a pyrogasification technology coupled with an internal combustion engine for electricity production is economically convenient for both the production units although the polypropylene wastes used are not excessive as well as the production of electricity is not high. The replacement of the polypropylene currently in use with the pigmented polypropylene entails a significant reduction of energy consumption and CO_2 emissions from combustion into the atmosphere and the elimination of emissions from the painting process. On the basis of the quantities of waste currently produced in the Plastic Unit, the sensitivity analysis indicated that the recycling system is convenient from an economic point of view if the investment cost of the shredding system is equal to 10 Euro/kg. The implementation of the TIMES energy model at industrial level can be a good tool for industrial management to make the most appropriate choices in terms of sustainability that take into account environmental and economic aspects.

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