The circular transition of the automotive sector in Italy: A system dynamics model

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Abstract: Air pollution and greenhouse gas emissions are one of the main problems impacting on climate change and society, resulting in issues for the environment and human health. These effects are mainly induced by transportation; indeed, most cars still use gasoline or diesel fuelled engines, which present several negative externalities such as emissions, pollution, noise, and fuel dependence. To reduce these impacts, many European countries have developed plans based on the circular economy paradigm and the electrification of cars to achieve the zero-greenhouse gas emission goal by 2050. However, this transition is complex due to several factors such as automotive supply chain re-design, impacts on employment, technological changes, mobility behaviours, and infrastructure development, especially in Italy, where the interdependence between electromobility and electricity production and distribution are slowing down this transition. Therefore, the purpose of this paper is to develop a system dynamics framework able to model the effects of the circular transition on automotive supply chains, by modelling production, re-manufacturing, and recycling activities for three different types of vehicles i.e., fuel, hybrid, and electric. Preliminary results of the model demonstrate that the circular transition of the automotive sector can bring to benefits in terms of reduction in raw material consumption and increasing in recycling rates.

Keywords: circular economy, system dynamics, electric vehicles.

I. INTRODUCTION

Air pollution and greenhouse gas emissions (GHG) are one of the main problems impacting on climate change and society, resulting in issues for the environment [1] and human health [2]. These effects are mainly induced by transportation [3-4], indeed, most cars still use gasoline or diesel fuelled engines, which present several negative externalities such as emissions, pollution, noise, and fuel dependence [5]. In this complex scenario charactered also by the global dimension of supply chains and an increasing and demanding world population [6], circular economy is considered a proper solution for reducing impacts of transportation [7]. Indeed, electric vehicles (EV) are considered a potential answer to reduce environmental and social impacts of transportation and contribute to face climate change issues [8]. Several countries and governments have developed specific policies to promote the circular transition of the automotive sector from traditional vehicles to electric ones by providing incentives or tax reductions [9]. EVs are gradually penetrating the European market, indeed there has been a steady increase in the number of new annually registrations, from 700 units in 2010 to about 1.325.000 units in 2020 [10]. However, apart from this encouraging numbers, the transition to EV is complex due to several factors such as the impact on the automotive supply chain re-design, effects on employment, technological changes, mobility behaviour, and infrastructure development [11]. Therefore, the purpose of this paper is to develop a System Dynamics (SD) model to capture the complexity of this transition. SD is a suitable method to investigate sustainable issues, it aims at understanding how and why the dynamic changes are generated and look for relevant strategies and policies to advance the system performance [12]. The SD framework models the automotive supply chain by including production, re-manufacturing, and recycling activities for three different types of motorizations i.e., fuel vehicles (FV), hybrid vehicles (HV) and EV. The model allows practitioners and decision makers to investigate and understand the effects of the EV transition on i) the automotive supply chain (re) design, and ii) resource consumption patterns in Italy. Indeed, Italy has been chosen due to its peculiar characteristics: i) the interdependence between electromobility and electricity production and distribution which are slowing down the EV transition, and ii) the worrying concentration levels of NOx, O3, PM10 and PM2.5 [13]. The paper is organized as follows; the next section presents the model development and validation. Section 3 shows the results of the model, and an in-depth discussion is provided. Finally, Section 4 focuses on conclusion and future outlook.

II. MODEL DEVELOPMENT AND VALIDATION

The model developed in this study aims at investigating the effects of the dynamic transition from traditional combustion engine vehicles to more sustainable options on automotive supply chains. It considers three different types of vehicles: FV, HV and EV.

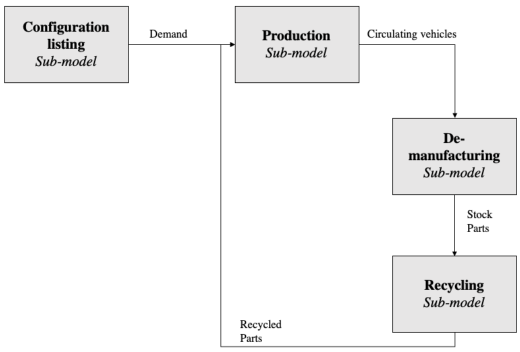

Fig. 1. SD Model structure and links between sub-models

The SD model is composed of four main sub-models as depicted in Figure 1: i) the configurations listing, ii) the production, iii) the de-manufacturing, and iv) the recycling sub-models. The configuration listing sub-model simulates the demand trends and withdrawals of FV, HV and EV and uses this data as an input for the production sub-model. Then the withdrawn vehicles are decomposed into four main components: i) mechatronics, ii) metal parts, iii) composites parts and iv) batteries. All these materials are inspected in the de-manufacturing sub-model in order to evaluate their condition and then according to their status are recovered (recycling sub-model) or sent to the landfill. The recycled material flow for each component is then re-entered into the production sub-model. The model has been developed by using years as unit of analysis.

A. Configuration listing sub-model

Figure 2 depicts the configuration listing sub-model. It has been built starting from the study developed by [14], that explained the dynamics regulating vehicle configurations in the price list. The elimination rate of each type of motorization is defined as the number of vehicle configurations removed from the market list in a period of a year. Every year a fraction of the listed configurations is checked for potential obsolescence, and a percentage of these vehicles is removed from the market list, while the others are restyled. Listing rates represent the listing of new configurations and are related to the R&D department. The FV_listing_rate is set to zero, as suggested by [14], this means that no new FVs will be introduced in the market. HV listing rate is proportional to the FV elimination rate and the EV listing rate is proportional to the FV and to the HV elimination rates. FV_HV_factor and FV_EV_factor manage the substitution of eliminated FV models with new HV or EV ones and represent the proportion of HV and EV upon which the automotive industry is investing. Both parameters have a value between 0 and 1 and their sum is always 1. This means that when FV_HV_factor is greater than FV_EV_factor, the R&D department is more focused on new HV development, otherwise the company is more focused on new EV development. The Configuration listing sub-model also includes an event called "FV elimination policy", whose purpose is to suppress FV configurations from the market in a given moment during the simulation. The FV_elimination_year parameter determines when this occurs and in this context is set to 10 years. Indeed, European countries are evaluating the possibility to ban FV selling from 2035. While some countries such as Denmark and Netherlands are expected to introduce such a ban earlier, in 2030. Therefore, this functionality of the model allows the analysis of national regulatory policies and their impacts on the automotive supply chain as well as on the market.

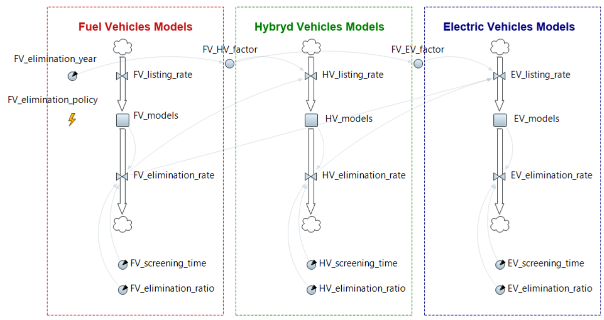

Fig. 2. Configuration listing sub-model

B. Production plant sub-model

The production sub-model is the heart of the SD framework and is connected to the other sub-models. Indeed, it uses the demand patterns generated in the configuration sub-model as an input and its outputs in terms of circulating vehicles are used as an input for the de-manufacturing and recycling sub-models. The production sub-model consists of three different production processes (one for each type of vehicle), which present the same SD structure, Figure 3, for example, depicts the EV production process. The aggregate EV demand (EV_demand) and the related raw material demands (M_EV_order, B_EV_order, MP_EV_order, C_EV_order) are the dynamic variables that drive the production of the EV. Particularly, the EV demand is calculated in the configuration listing sub-model and then divided into four raw material demands, one for each component (i.e., mechatronics, metal parts, composites parts and batteries), through the evaluation of weight fraction parameters. The model calculates the necessary quantity of raw materials with the aim of matching vehicles demand. The required components are then collected into their related stocks

(M_EV_inventory, B_EV_inventory MP_EV_inventory and C_EV_inventory). Each component comes from two possible sources: i) the recycled flow, which is the primary resource, and/or ii) the external supplier, which, if necessary, complements the raw material order. The different components are then assembled and transformed into final vehicles (EV_circulating stock).

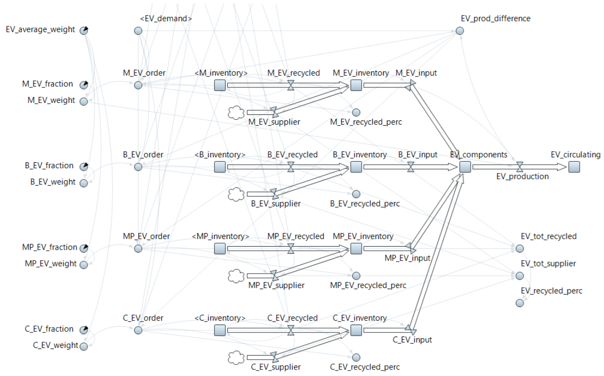

Fig. 3. Production sub-model for EV

C. *De-manufacturing sub-model*

Another important part of the SD framework is the de-manufacturing sub-model. Here, old vehicles are withdrawn from the respective circulating stock, converted into components mass, and sorted in the correct material flow: mechatronics, metal parts, batteries, and composites.

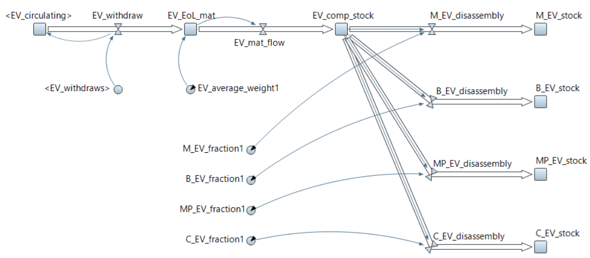

Fig. 4. De-manufacturing sub-model for EV

As mentioned above, the percentage of withdrawn vehicles is calculated in the configuration listing sub-model. Similarly, to the production sub-model, the de-manufacturing one presents three different flows, one for each type of vehicles. Also in this case, these processes present the same SD structure with some peculiar parameters such as the average weight and the fraction of the total weight for each type of materials which are customized according to the type of vehicle. Figure 4 shows details related to the EV de-manufacturing process. The withdrawal parameter is modelled by evaluating the circulating vehicles' percentages 10 years earlier, indeed the average life of a vehicle is set to 10 years. In this way, the aging of vehicles is considered. Each withdrawn vehicle is ideally converted in mass, and this is then divided into the four material categories by using the weight fraction parameters.

D. *Recycling sub-model*

Once the material is sorted into the correct stock, it is then moved to the recycling area, as illustrated in Figure 5, which depicts the mechatronics recycling process. Even in this case, the recycling sub-model presents four processes, one for each component, and all have the same SD structure. Then the stacked components are tested with a quality control which checks their status and, according to it, components are destined to the proper flow: good quality components are ready to be reused, repaired, or recycled, while low quality pieces are considered waste. The fraction parameters of each component type (M_FV_good_fraction, M_HV_good_fraction, M_EV_good_fraction in the mechatronics example of Figure 5) are used to distinguish and separate them. Their initial and final values, shown in TABLE 1, were set as assumptions from European statistics regarding currents standards and future targets [15]. Their positive trend over the simulation time is related to the technological improvement of these recovery processes.. Moreover, the model includes a parameter called the "Recycling Improvement Factor" (RIF), which can be used to conduct scenarios analyses. The standard value of RIF is set to 1, which corresponds to a "realistic scenario", in which the company can achieve the recycling rates presented in TABLE 1. If the RIF parameter is set to a value less than 1, a "pessimistic scenario" is described in which the company can achieve lower recycling rates.

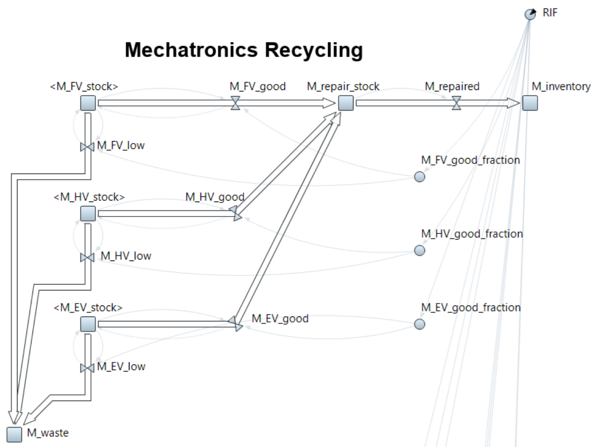

Fig. 5. Recycling sub-model for mechatronic parts

On the contrary, if the RIF is greater than 1, an "optimistic scenario" is obtained, with recycling rates higher than the realistic scenario. This RIF parameter represents the technological development, indeed if RIF is greater than 1, it means that new or more efficient technologies allow companies to increase their recycling rates. Therefore, this parameter allows the framework to take into consideration the technological impact on recycling activities. Many studies have confirmed the importance of technological advancement and its related impacts on sustainability performance [16-17]. Following the de-manufacturing process, good quality components are collected in a common container, submitted to the necessary operations, and finally sent to the respective inventory. The model doesn’t describe the various manufacturing operations necessary to recycle components, it simply distinguishes between pieces that can be reused or repaired from those that are considered waste. Only batteries have a third option. Indeed, medium quality batteries are stock in another container and sold to external companies.

TABLE 1

RECYCLING RATES BY TYPE OF VEHICLE AND MATERIAL COMPONENT AT THE BEGINNING AND AT THE END OF THE SIMULATION

* FV percentage values are hypothetical and will not be reached during the simulation, due to the effects of the FV elimination policy

		2020	2060
Mechatronics	FV	80%	95%*
	HV	85%	95%
	EV	90%	95%
Metal Parts	FV	90%	95%*
	HV	90%	95%
	EV	90%	95%
Batteries	HV	80%	90%
	EV	80%	90%
Composites	FV	70%	90%*
	HV	70%	90%
	EV	80%	90%

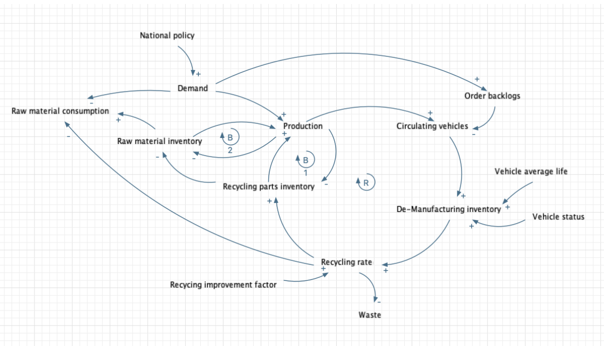

Fig. 6. Causal loop diagram for the EV system

To conclude Figure 6 depicts the casual loop diagram for EV system. Three different feedback loops are visible within the system, two balancing loops (B1 and B2) and one reinforcing loop (R). The reinforcing loop is composed by production, circulating vehicles, de-manufacturing inventory, recycling rate and recycling inventory. It represents a behaviour in which if the production increases also the circulating vehicles increases, and therefore there would be more available parts for de-manufacturing and recycling activities. This results in an increasing number of recycled parts which can be used as an input for the production at the expense of raw materials. In the procurement process, the system behaves in such a way that if the recycling parts inventory increases, then compliance with production orders increases, but this increase in production orders influences the decreasing inventory of recycling parts (B2). The same behaviour can be seen in the interactions between raw material inventory and production (B2).

E. Validation

The simulation is performed using AnyLogic software. The model validation is conducted through a structure and behaviour validity test [18] by analysing the effects of demand pattern on the circulating vehicles. The vehicle total demand is modelled by assuming a positive trend over the years. Figure 7 shows the trends of the aggregate vehicle demand and the individual demands, one for each type of vehicles. These are the output data obtained from the simulation of the configuration listing sub-model. The FV elimination policy, which is set to occur after 10 years, implicates that from 2030 the FV production will be stopped and therefore it is possible to see a resulting increasing in HV and EV demands.

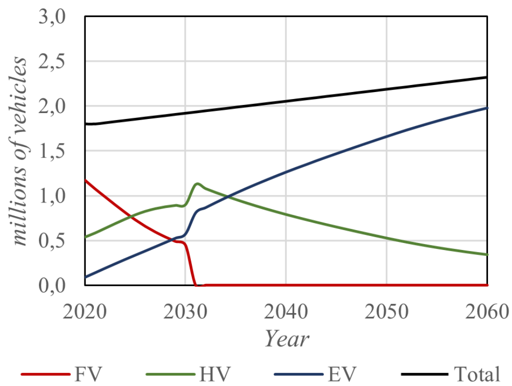

Fig. 7. Vehicle demand trend

By considering the trends of the latest years and the guidelines imposed by European Commission to accelerate the transition towards the electric mobility, the circulating FVs are supposed to decrease until they disappear from the streets as a result of the FV elimination policy. HVs are supposed to have a positive trend in the first period of the simulation, then they should start to decrease due to the growing market share of EVs. Indeed, these are supposed to increase over the entire considered period. In general, the simulation results follow the expectations and behaviours of the real system. Figure 8 shows the aggregate circulating vehicle trends and individual trends for each type of vehicle, while Figure 9 illustrates percentage trends. FVs have a steady decline, covering only 30% of the fleet in 2040 and disappearing completely in 2058. HVs increase steadily for the first 20 years of the simulation, reaching 40% of the total circulating vehicles in 2040. Thereafter they have a gradual decline, bringing them to 28% of total vehicles at the end of the simulation. The number of circulating EVs increases over the years, from 3% in 2025 to 72% in 2060.

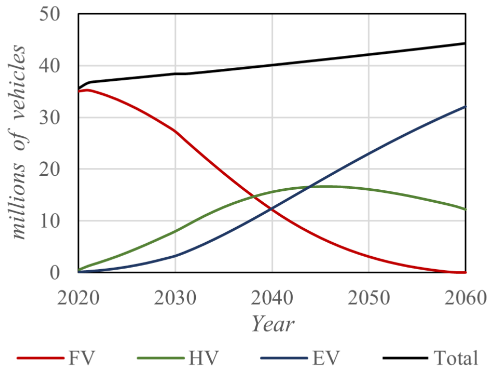

Fig. 8. Circulating vehicle fleet in Italy

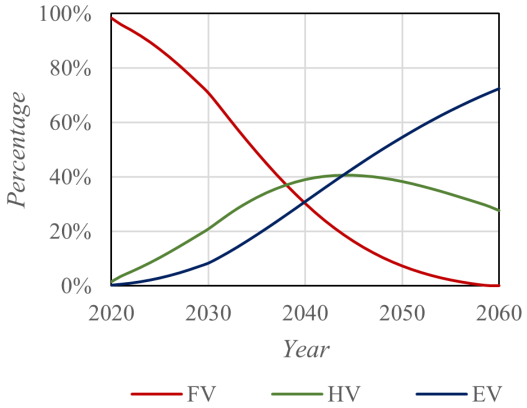

Fig. 9. Percentages of circulating vehicle types

III. Results and Discussion

To analyse the model results, it has been chosen a time window of 40 years, from 2020 to 2060 to evaluate both medium and long terms dynamics of the model. Due to the absence of stochastic variables, the results are fixed for every set of parameters. Consequently, one single simulation run has been developed for each scenario. Figure 10 depicts a scenario analysis based on the RIF parameter variation over time and its effects on virgin raw material consumptions. As described in Section 2, RIF determines the efficiency of recycling percentages as a result of the technological advancement. Four different scenarios have been created to analyse the impact of this parameter. The first scenario is called the “realistic scenario” and presents an RIF set to 1, the second scenario is the “pessimistic” one, which presents a RIF value of 0.7, the third scenario is the “optimistic” one, where RIF is set to 1.3. These three scenarios are then compared to a fourth case in which there is no improvement in the recycling technologies (RIF=0). Figure 11 depicts the related raw material reductions’ percentages resulting from the scenarios analysis. On a first look it might appear that RIF has a little influence on the virgin raw material consumption, but as clearly depicted in Figure 11, the technological development allows companies increasing their recycling rate and therefore it is clearly evident a reduction in virgin raw material consumption and raw material dependence, especially in a long-term view. Indeed, even in the pessimistic scenarios, the virgin raw material consumption decreased by 16% in 2060.

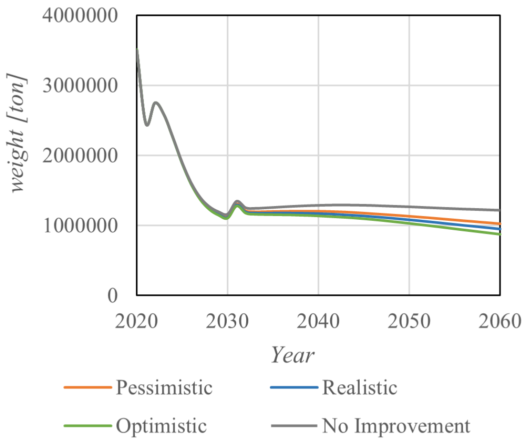

Fig. 10. Circulating vehicle fleet in Italy

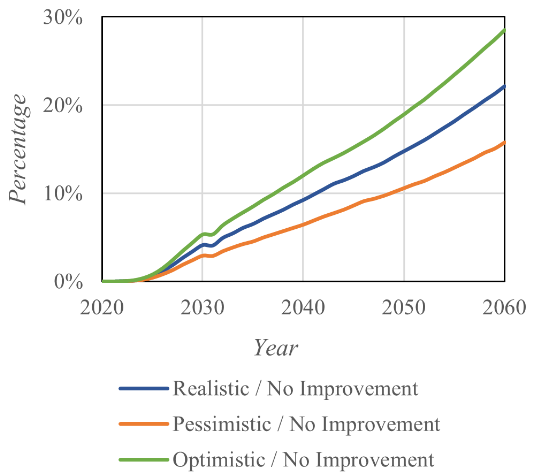

Fig. 11. Percentual reduction of consumptions compared to the no improvement scenario

The realistic and optimistic scenarios present a decrease in virgin raw material consumptions by 22% and 28% respectively. This analysis is aligned with other studies which highlight the importance of implementing innovative technologies to support companies reducing their environmental impact [19]. However, it is also fundamental to highlight the double effects of innovative technologies, indeed, several studies have warned about the effects of new technologies which can drastically transform the labour market resulting in many working activities being automated, and therefore creating less employment than the previous industrial revolutions. Indeed, EV does stand to significantly reduce the number of manufacturing jobs available in the automotive field. This is primarily because there are fewer moving parts in electric cars and no engines. Assembly of the required components is highly automated, demanding less maintenance and replacement parts. Another point of reflection is that Italy presents many suppliers which provide parts for the FV production, therefore, the transition to the EV needs to include the redesign of supply chain activities as well as the management of the workforce which need to be trained and re-distributed along the EV supply chains. Another effect of the recycling technologic improvements is the consequently reduction of waste produced.

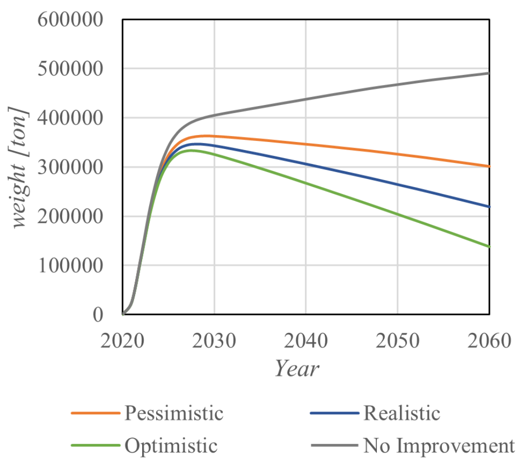

Fig. 12. Total wastes in the different scenarios

Figure 12 and Figure 13 show the trend of the waste material produced, and the waste reduction by considering the overmentioned scenarios which are deepened upon the variation of RIF parameter. Figure 13 clearly shows that even in the pessimistic scenario, companies can reduce waste production by 40%. This can generate a positive impact on the environment and at the same time an economic advantage for companies which can reduce disposal costs and their dependence to virgin raw material by re-using materials which were previously considered waste. This latter point is of particular importance in the today complex world, in which global events such as pandemics, socio-economic issues and climate change are causing shortages of several components for the automotive sector (i.e., chip, steel, energy). Therefore, companies need to increase their resiliency by facing these crises with a long-term perspective and by trying to re-adapt their processes in the light of the circular economy benefits. Figure 14 show the consumption trends of new batteries with RIF parameter set to 1. It illustrates a reduction in virgin raw materials consumptions, thanks to the growing relevance of the de-manufacturing cycle during the simulation. Specifically, the increase of the HV and EV demand could cause serious production problems if the manufacturing sector is not supported by an efficient de-manufacturing and re-manufacturing system.

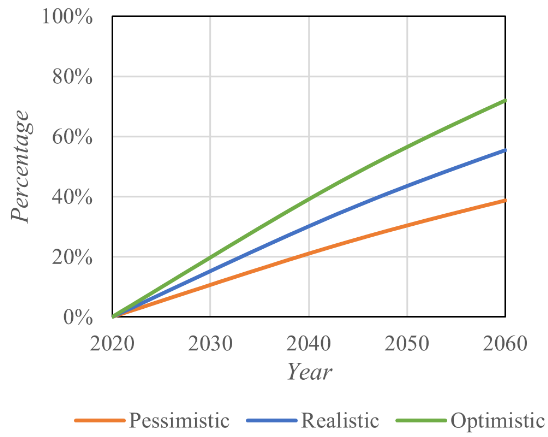

Fig. 13. Reduction of the total waste

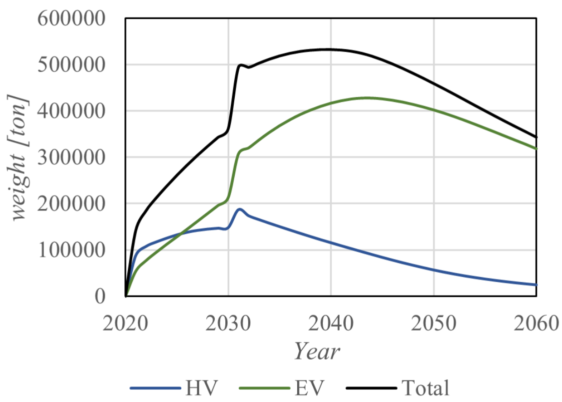

Fig. 14. New batteries consumption

Finally, Figure 15 shows the trends of the circulating vehicle percentages by varying the FV elimination policy and RIF set to 1 in order to evaluate the impact of the national policies on the Italian market and on the circulating fleet. Three scenarios have been designed: FV elimination policy is applied i) after 10 years (in 2030, solid lines), ii) after 15 years (dashed lines) or iii) after 20 years (dotted lines). In all scenarios, it is evident the decreasing of FVs and the consequently EVs increasing. This can generate additional benefits for the environment and society by reducing CO2 and GHS emissions as well as noise as a result of EV introduction.

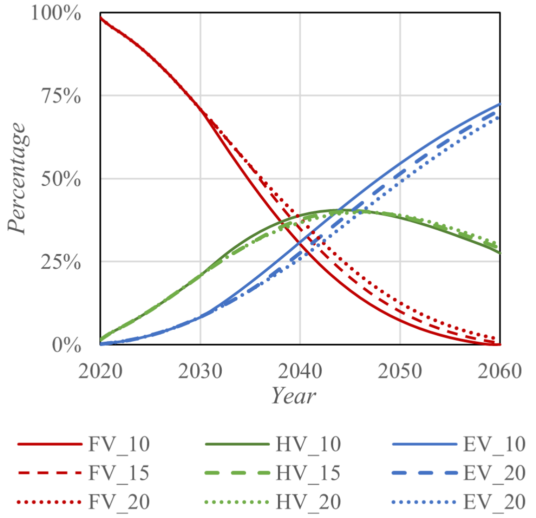

Fig. 15. Circulating vehicles percentage trends

IV. Conclusions

In this paper, a SD framework has been developed to analyse the effects of the circular transition on the automotive sector as well as on the environment. The SD framework consists of four sub-models which can analyse: i) demand patterns, ii) vehicles circulating, iii) raw material consumptions, iv) waste production and v) the effects of national policies for three different types of vehicles (FV, HV and EV). The results show that by implementing a circular economy strategy in the automotive sector, companies can increase environmental and economic performances as well as competitiveness. Indeed, in the today complex world in which supply chains are depended upon political, social, environmental, economic, and global phenomena, companies need to reduce their dependences and re-adapt their processes to increase resilience. Certainly, our model presents some limitations, indeed it strictly focuses on the resource production and consumptions and efficiency concepts. In the future, we plan to improve the SD framework by including a more holistic perspective. We are working to introduce both the economic and social dimensions of sustainability to quantitatively demonstrate the economic benefits resulting from a circular strategy as well as to investigate the positive and negative effects of the circular and technological revolution emerging from the EVs transition on employment. To do this, we will integrate an agent-based model to our existing framework to better capture social behaviours.

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