Bottom-up modelling of the Italian municipal waste generation: model set-up, validation and pathways towards 2040

Lidia Premoli Vilà[1], Andrea Trabucchi[1], Lorenzo Ferrè[1,2], Mario Grosso[2], Marco Borgarello[1], Giorgio Besagni[1,*]

[1]Ricerca sul Sistema Energetico - RSE S.p.A., Power System Development Department, via Rubattino 54, 20134, Milan, Italy

[2]Politecnico di Milano, Department of Civil and Environmental Engineering, P.zza L. da Vinci, 20133, Milan, Italy

[*] Corresponding author: Giorgio Besagni, giorgio.besagni@polimi.it.it, Ricerca sul Sistema Energetico - RSE S.p.A., Power System Development Department, via Rubattino 54, 20134 Milan, Italy

Abstract

The residential sector contributes to about 17% of the total waste generation in Italy. The main objectives set by the European and Italian governments regarding the waste sector include the promotion of reuse, recycling, and recovery, listed in order of importance; therefore, it is crucial to achieving, among others, a sufficient waste management capacity at the national level to accomplish such targets. In this context, a new approach to estimating and forecasting waste generation is introduced, based on bottom-up modelling to estimate the past and future Italian municipal waste generation. The modelling approach builds upon microdata describing the household expenditure behaviours supplied by the National Institute of Statistics. The assessment was carried out by dividing Italy into six macro-regions. The model was then validated by comparing the results with the historical aggregated official waste generation data. Lastly, a socio-demographic model has been applied to predict the trends of the various waste fractions due to the expected variation in the population, considering four different scenarios from 2019 to 2040. Results show the model's good performance, with relative errors below 5% at the national average concerning the historical data. The forecast of future trends gives a comprehensive picture of the effect of different waste management strategies.

Keywords bottom-up modelling; waste generation; residential sector; waste fractions; waste forecast.

Nomenclature

Abbreviations

ISTAT	*Istituto Nazionale di Statistica (National Institute of Statistics)*
BMT	Biological Mechanical Treatment
SC (RD)	Selective Collection
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale (Institute for Environmental Protection and Research)
ISMEA	Istituto di Servizi per il Mercato Agricolo Alimentare (institute for agricultural and food marketing services)
MW (RU)	Municipal Waste (Rifiuto Urbano)
WEEE (RAEE)	Waste of Electric and Electronic Equipment (Rifiuti di Apparecchiature Elettriche ed Elettroniche)
EU-28	European Union including 28 countries
EPR	Extended Producer Responsibility
DPR	Decreto del Presidente della Repubblica (Decree of the President of the Republic)
NIC	National consumer price Index for the whole community
HBS	Household Budget Survey

Symbols

GDP	Gross Domestic Product	€
$y_{x,yr}$	The generic expense for the x-product annualised to year yr	–
$\alpha_{x,yr,baseyear}$	NIC coefficient referred to product type x and year yr using the reference base "baseyear"	–
$Quantity_x$	Number of x-products inside the multipack packaging	–
$Unit\_of\_Measure_x$	Amount of x-product considered in the measurement	$kg, l, pc, etc.$
$Waste_{fr,x,q}$	Waste fraction-fr generated from product x reported at the q-quantity	g
$Coeff_{fr,x,z}$	Grams of fr-waste fraction generated per € spent in the z-macrozone, referred to the x-product	$\frac{g_{fr,x}}{€}$
$DomesticMeasurement_x$	Grams of fr-waste fraction generated per reference quantity (unit of measure), referred to the x-product	$\frac{g_{fr,x}}{UoM_{ref,x}}$
$ConsumerPrice_{x,z}$	Expenditure for the purchase of the x-product referred to reference quantity (unit of measure)	$\frac{€}{UoM_{ref,x}}$
$Nproducts_k$	Number of products within the k-expenditure item	–

$Coeff_{fr,k,z}$	Grams of fr-waste fraction generated per € spent in the z-macrozone, referred to the k-expenditure item	$\frac{g_{fr,k}}{€}$
$Waste_{fr,z,m,i}$	Waste fraction-fr produced monthly by i-household in the z-macrozone	$\frac{g}{month}$
$Expense_{k,z,i}$	Expense value declared by the i-household, belonging to z-macrozone, for k-item	€
c_i	Carryover coefficient related to i-household	–
$\%AVfr$	Percentage of food waste avoidable fraction	%
$Waste_{food,z,c,week}$	Food Waste produced weekly by c-component in the z-macroregion	$\frac{g}{pers * week}$
$Waste_{fr,z,yr}$	Total waste fraction-fr produced yearly in the z-macroregion	$\frac{g}{year}$
$Population_{z,yr}$	Total z-macroregion population in the yr-year	–
$Waste_{NF,r,yr}$	Non-forecastable fraction that is not collected by SC in r-region during yr-year	$\frac{g}{year}$
$Green_{r,yr}$	Green fraction that is collected by SC in r-region during yr-year	$\frac{g}{year}$
$Wood_{r,yr}$	Wood fraction that is collected by SC in r-region during yr-year	$\frac{g}{year}$
$Other_{fr,yr}$	Other fraction that is collected by SC in r-region during yr-year	$\frac{g}{year}$
$\%Diff_{r,yr}$	Percentage of SC in r-region during yr-year	%
$Weight_R$	Receipt weight	g
$Arrivals_{z,u}$	Total number of arrivals in the z-macroregion from the u-macroregion	$people$
$Share_{z,u}$	Share of arrivals in z-macroregion from the u-macroregion	–
$Ats_{z,u}$	Average time spent by people from the u-macroregion in z-macroregion	day
$Nhouseholds_{fr,z}$	Total number of households with a non-zero value for fr-fraction in the z-macroregion	–
$Nhouseholds_{HBS}$	Number of households recorded in the ISTAT HBS dataset	–
$Expenditure_{week,m,i}$	Average expenditure on food, alcohol and tobacco normally incurred in the Italian families	$\frac{€}{month}$
$Expenditure_{holiday,day,i}$	Average expenditure of Italians on holiday	$\frac{€}{day}$
$e_{\%}$	Relative error	–
N_{fr}	Total number of fr-fractions considered in the model	–

Subscripts

i	i-household
c	c-family component
yr	yr-year
95	Baseyear 1995 (NIC coefficients)
10	Baseyear 2010 (NIC coefficients)
15	Baseyear 2015 (NIC coefficients)

r	Region of the family component c
s	Sex of the family component c
a	The age group of the family component c
fr	fr-fraction type of waste
x	x-product
UoM	Unit of measure
ref	Reference, as it is in the consumer price dataset
q	q-quantity
z	z-macrozone
k	k-expense, HBS dataset item
m	m-month
week	In a week
food	Food waste
NF	Non-forecastable waste
R	Receipt waste
u	u-macroregion
HBS	Related to the ISTAT HBS dataset
tot	Total
Organic	Organic fraction
Cellulosic	Cellulosic fraction
Glass	Glass fraction
Metals	Metals fraction
Plastics	Plastics fraction
WEEE	Waste of Electric and Electronic Equipment fraction
Textile	Textile fraction
Selective	Selective fraction
Bulky	Bulky waste fraction
Rwf	Residual waste fraction
ISPRA	Related to the ISPRA dataset reference

1 Introduction

Industrialised countries have to deal with the issue of waste generation in a progressively challenging way, due to the constant increase in waste production, usually because of population increase and the improvement of living conditions, that lead to a rise in the production and consumption of goods; in particular, as far as the EU-28 countries are concerned, a high correlation can be found between the Gross Domestic Product (GDP) and the generation of waste (Eurostat 2020). Consequently, between 2010 and 2016, there has been a 3.0% increase (74.8 million tonnes) in total waste generation (European Environmental Agency 2019). Focusing on Municipal Solid Waste, there are clear signs of stabilisation in the growth, like Italy's case (ISTAT 2020), where some decoupling concerning the economic parameters is observed but still far from being consolidated. For example, a 2% growth in municipal waste generation was observed between 2017 and 2018, exceeding the value of 30 million tonnes in 2018 (ISPRA 2019). To deal with this issue, the European Commission adopted a series of Directives in the past few years to improve waste management and limit its impact on the environment. Directive (EU) 2018/851 (2018) has set some new challenging recycling targets: by 2025, at least 55% of municipal waste in weight must be recycled, raising this target to 60% and 65% by 2030 2035, respectively. Member states also have to selectively collect textile and hazardous waste generated by households by the end of 2024 and guarantee that the organic fraction is collected separately or recycled at the source by the end of 2023. Soon, as part of the European Green Deal (European Commission 2019), a new series of directives and regulations aimed at fostering the transition of member states toward a more sustainable economy are expected to be adopted (European Commission 2020).

Many different studies have been performed to forecast future waste generation and,in the literature, a large number of methods can be found that address the topic in different ways; Table 1 synthetises the main approaches used in the past years to forecast MW generation in different countries:

Table 1: Overview of studies regarding MW generation forecast

Authors	Reference Country	Methodology
Smejkalová, Šomplák et al	Czech Republic	Time-series analysis
Abbasi and Hanandeh	Iran	SVM Model
Even Jr, Arberg et al.	USA	Descriptive statistical methods
Sha'Ato, Aboho et al.	Nigeria	Field survey
Denafas, Ruzgas et al.	Lithuania, Russia,	Regression Analysis

	Ukraine and Georgia	
Pan, Yu et al.	China	Correlation Analysis, Q-type clustering
Liu, Xue et al.	China	Statistical data analysis
Schiller, Raffiels et al.	Germany	Material flow model
Katsamaki, Willems et al.	Greece	Time-series analysis
Navarro-Esbrı, Diamadopoulos et al.	Spain and Greece	Time-series analysis
Abbasi, Abduli et al.	Iran	WT-SWM Model
Kumar, Subbaiah et al.	India	Neural Network Model

Differently from previous works, the method described in this paper is based on a bottom-up approach: in this type of approach the single parts of the model are designed in detail to be functional on their own and then combined together to define a complex system. Its main advantage with respects to other methodology is the fact that, thanks to its modular nature, the estimation precision at lower levels is higher. Also, the singular parts that compose the model are fully functional, meaning they can be re-used for the composition of new bottom-up models or to further expand previously existing ones. For instance, the FORECAST model developed by Fleiter, Rehfeldt et al. was firstly developed to study the energy efficiency potential and costs in the German basic material industry and later expanded to assess the impact of energy efficiency policies and long-term climate policy scenarios in the whole European Union.The model's primary input data are the detailed monthly expenses of the Italian population, expressed in €/month, which are used to estimate the total amount of municipal waste generated in the country. This can be achieved by multiplying the expenses by the value of the amount of waste generated per euro spent for each category of product and then actualising the results and using carryover coefficients, provided by the Italian Institute of Statistics (ISTAT), to estimate the annual waste generation. The advantage of this approach is that it is possible to perform some scenario analyses where the input information about demographic distribution, people's purchase behaviour, type of packaging materials, etc., can be easily changed, without involving macro-economic data (He, Reynolds et al. 2020). These simulations could also be used as inputs for optimisation models to impose constraints on the results, thus creating a hybrid model. In this way, it is possible to develop a model which is not based on historical time series of waste generation, that can be used instead just for validation purposes. Scenario analysis in this work could also consider the effects of policies, changes in people's behaviour.

This paper is structured as follows: Section 2 presents the modelling approach, validated and optimised in section 3 and applied in section 4 to investigate different scenarios. Finally, section 5 is devoted to the discussion and conclusions.

2 Model description

This Section describes the research methodology and the input data used. First, an overview of the model is given. The input data utilised are then described, followed by a third section explaining further data research; then, the urban waste production calculation procedure from micro-data on household expenses to country-layer values is presented.

2.1 Model overview

The waste management model is developed with a bottom-up approach aimed at determining the urban waste generation of the whole country from disaggregated data at the "bottom-layers" (i.e., at households' level); its structure can be further exploited to analyse the behavioural changes of consumers (at bottom-layer) effects on country-scale waste production. In Section 4, a scenario analysis is proposed, showing how different levels in the separate collection (SC) and food waste affect the municipal waste (MW) production, including the Italian population's socio-demographic growth. For all sorts of matter, variables regarding households' expenses are employed as input to calculate disaggregated data on MW produced for each household. Indeed, the high level of detail of the input data allows a complete disaggregation of the waste fraction generated. ISTAT data, described in Section 2.2, are exploited to estimate the quantity of each macro category of product, and then the type of waste-related are derived with the Italian Institute for Environmental Protection and Research (ISPRA) categorisation. The total MW produced from the Italian residential sector is then obtained by aggregating the carryover universe coefficient. The calculation procedure includes estimating the purchased product and the waste generated from the expenses. To summarise, the proposed model makes it possible to transform the household's money flows first into quantities of products purchased and then into the amount of waste generated. The model development procedure is organised as follows: 1) Input data pre-processing and significant variables selection; 2) Conversion of expenses into purchased products; 3) Conversion of purchased products into waste generated; 4) Validation of the model through a comparison with yearly data provided by ISPRA; 5) Optimisation of the model through the validation phase.

2.2 Input data

The bottom-up waste management model has been developed utilising the "Household budget survey" (HBS) dataset (ISTAT 2020) obtained and offered by ISTAT for three particular years: 2014, 2015, and 2016. The survey focuses on Italian households' monthly expenditures to purchase goods and services exclusively from household consumption. The employer's goods and services utilising wages and benefits, the estimated rentals of owner-occupied or free houses (imputed rentals) are also included. Moreover, this dataset represents the whole Italian population through a carryover universe coefficient assigned to each sample household, ISTAT. The representative sample comprises 16'804, 15'013, and 15'409 households for 2014, 2015, and 2016. The input variables, fully listed in Supplementary material S.1, can be divided into twelve services (e.g. food products, clothing, furniture, personal care goods, etc.). Then, seven macro-categories are identified: 1) Foodstuff; 2) Tobacco; 3) Clothing; 4) Furniture, appliances, and kitchen; 5) Removals and shipments; 6) Personal hygiene; 7) Other (Fuels, electronics, stationery, etc.).

The ISTAT dataset does not include information regarding consumers' prices of goods for the Italian population. This is needed to convert the ISTAT dataset values (i.e., services expenses for household consumption) into the number of purchased products (e.g., in kilograms, litres, units). These data are provided by municipalities, consumer associations, regions, etc. They have been collected to build up a single dataset that describes all ISTAT products, with the most recent values. It is worth mentioning that the consumer's prices significantly vary from Northern to Southern Italy and the social behaviours, the percentage of selective collection and the waste management infrastructure; thus, Italy has been subdivided into six macro-regions (Figure 1). The subdivision is defined as follows: Zone 1 - North-West: Aosta Valley, Piedmont, Lombardy, Liguria; Zone 2 - North-East: Trentino-Alto Adige, Veneto, Friuli-Venezia Giulia, Emilia-Romagna; Zone 3 - Centre: Tuscany, Umbria, Marche, Lazio; Zone 4 - South: Abruzzo, Molise, Campania, Apulia, Basilicata, Calabria; Zone 5 - Sicily; Zone 6 - Sardinia.

Figure 1. The six Italian macro-regions.

The references and the number of data collected for consumer prices are described in Supplementary material S.2. The majority of the values were related to "foodstuffs," and the municipalities that had made these data available are mainly located in the Centre-North of Italy. The data collected refer to different years; thus, public ISTAT data (ISTAT 2020) on consumer prices indexes for the whole national community (NIC) have been exploited to uniform the analyses. The NIC index measures the time-variation of the costs of a set of goods and services, representing actual household consumption in a specific year (ISTAT 2015), including the effect of inflation. In particular, the NIC index measures inflation at the level of the whole economic system, considering Italy as one big family of consumers, within which spending habits are very different (ISTAT 2015). Some types of urban wastes are not directly estimable from the HBS dataset (ISTAT 2020) (e.g., wood, cellulosic fraction, food, etc.); thus, ISPRA data (ISPRA 2019, ISPRA 2020), calculated as described in Supplementary material S.3, are exploited to estimate i) the non-forecastable waste fractions and ii) the selective collection not directly computable from the HBS dataset, as described in Section 2.4.4.2.

Moreover, the same data available from ISPRA (ISPRA 2020) will be utilised in the validation and optimisation process described in Section 3. Another waste fraction not directly computable from the HBS dataset is represented by tourism-related share, in terms of arrivals and departures, as described in Section 2.4.4.4. Indeed, tourism-related waste generation is not negligible, as stated by Wang et al.,

2021. For this matter, additional ISTAT surveys are exploited, namely the "*Accommodation capacity*" (ISTAT 2020) and the "*Movement of customers in accommodation establishments*" (ISTAT 2020) surveys. At the single municipality level, the first one quantifies the number of establishments, beds, bedrooms, and bathrooms for hotels and other establishments (ISTAT 2020). The second survey is carried out monthly and represents the primary source of information on domestic tourism available in Italy; it quantifies, for each municipality, the arrivals[1] and the presence[2] of customers according to the category and type of structure and according to the foreign country or Italian region of residence (ISTAT 2020).

2.3 Data aggregation and completion

First of all, among the HBS dataset (ISTAT 2020), the expenses directly related to the waste generation are identified: among 1264 expenses items, 213 have been determined to be significant; furthermore, by cross-referencing the microdata with the ISTAT questionnaire, 857 products included were identified within the expenses mentioned above. Further information is proposed in Supplementary material S.1. To associate each item selected from the ISTAT microdata (ISTAT 2020), a consumer price value, the municipal dataset described in Section 2.2, and Supplementary material S.2 have been exploited. However, municipalities' data are provided for different years. Thus, all values are elaborated to be referred to the same year using the NIC coefficients already described in Section 2.2. By identifying to which category of the NIC dataset every item in municipal datasets belongs, it is possible to carry out the conversion as follows:

$If, 1995, \leq yr < 2010:$

$$y_{x,2010} = y_{x,yr} \times \frac{\alpha_{x,2010,95}}{\alpha_{x,yr,95}} \quad (1)$$

$$y_{x,2015} = y_{x,2010} \times \frac{\alpha_{x,2015,10}}{\alpha_{x,2010,10}} \quad (2)$$

$If\ 2010 \leq yr < 2015:$

$$y_{x,2015} = y_{x,yr} \times \frac{\alpha_{x,2015,10}}{\alpha_{x,2010,10}} \quad (3)$$

$If\ yr > 2015:$

$$y_{x,2015} = y_{x,yr} \times \frac{\alpha_{x,2015,15}}{\alpha_{x,yr,15}} \quad (4)$$

[1] Number of clients arrived who checked-in during the period considered, broken down by foreign country or Italian region of residence ISTAT. (2020). "Scheda standard di qualità - Movimento dei clienti negli esercizi ricettivi." Retrieved 19/11, 2020, from https://www.istat.it/it/archivio/216332.

[2] Number of nights spent by clients in the accommodation facilities during the period considered ibid.

The α values represent NIC coefficients, provided concerning reference *base years* (95,10,15 referring to the year 1995, 2010 and 2015, respectively), and they are utilised to refer the product prices *y* at year *yr* to the reference year 2015, unifying the dataset and allowing to aggregate different municipalities values belonging to the same macro-regions presented in Figure 1. Moreover, the municipality dataset values are aggregated to reflect the categories extracted from the HBS dataset. A total of 540 items were found. There is some lack of data, especially in the southern regions and islands, limiting the model's accuracy but not invalidating it. To overcome the lack of data obtained by geographical macro-area, the national average has been assumed, where consumer price value was missing. The additional data have been researched in the following order: Data collected by Growth for Knowledge (GFK) surveys (GFK 2019); data extracted from the Eurostat database, the statistical office of the European Union (EUROSTAT 2015); ISMEA (the Italian institute for agricultural and food marketing services), that provides information, insurance, financial services credit and financial guarantees for agricultural enterprises and their associated forms, to promote market information and transparency (ISMEA); Statista website in which is possible to find statistics, consumer survey results and industry studies from over 22'500 sources on over 60'000 topics on the internet's statistics database (STATISTA 2020); the dataset made available by the "Monopoly and Customs Agency" (Dogane 2020) for tobacco, since it is subject to a state of monopoly. Lastly, the consumer prices for all 857 items within the HBS extract have been set, disaggregated by the Italian macro-regions. The number of purchased products need to be further converted into the quantity of waste produced. However, the lack of data on waste generated by a single product is a critical issue of this work. Thus domestic measurements, surveys carried out by Ricerca sul Sistema Energetico SpA, and reference works (Caporaso 2019) have been exploited to build up a second additional dataset for the purpose. In particular, from the primary reference (Caporaso 2019), the values generated for 121 products have been found, broken down in the following way: 107 foodstuffs, ten personal hygiene, three furniture, appliances, and kitchen.

Conversely, 1253 values have been found from the surveys performed by Ricerca sul Sistema Energetico SpA and from some additional domestic measurements carried out during the model development; these values are divided into the macro-categories as follows: 846 foodstuffs, 133 clothing, 45 furniture, appliances and kitchen, 78 personal hygiene, 144 other, and seven tobacco. The overall measurements have been employed within the model, maintaining the sub-categories' disaggregation to consider as many types of packaging as possible for each product. For each product, the unit of measure is reported and whether it can be purchased as a single-pack or multipack so that the packaging fee is allocated to every single component; moreover, all elements generated are reported together with their relative class of waste and weight. During this dataset's construction, some external information was used for the average weight of some products, their density, or the percentage of residues they contain; the complete list of this information can be found in Supplementary material S.4.

Moreover, a comparison on single-pack and multipack elements has been carried out, later described in section 2.4.1, unifying the units of measurement for each product and resulting in coefficients for the conversion from product purchased to waste for 679 goods, broken down in the following way: 352 foodstuffs, 115 clothing, five tobacco, 33 furniture, appliances and kitchen, 69 personal hygiene and 105 others. For additional estimations of the amount of packaging (cellulose fraction and plastics), five calculation functions have been defined to assess the weight of the packaging relative to a specific object, receiving as input height, width, length, and type of packaging; in particular, these functions have been set for five small appliances, five small objects, four large household appliances, two items of furniture and three books. These functions are further described in Supplementary material S.5. The use of these five functions made it possible to estimate the plastic and cellulosic packaging of 187 products, broken down as follows: 24 large household appliances, 66 small objects, 56 small appliances, 23 Items of furniture, and 18 books. Additional assumptions have been defined for calculating bulky waste, Waste of Electric and Electronic Equipment (WEEE), and textile fraction. Indeed, the difficulty in recovering their measurements and the problems in defining their frequency of disposal required a simplification: it was thus assumed that, for each bulky product (e.g., furniture, appliance, big object), electronic component (e.g., personal PC, headphones, tablet) or item of clothing purchased, one is disposed of. Two hundred three products were obtained, divided into 115 clothing, 50 WEEE, and 38 bulky waste. For further information and the complete list of references, refer to Supplementary material S.4. Finally, all results have been aggregated in a single dataset, including the products needed to develop the model.

2.4 Model calculation procedure

In this Section, the calculation procedure for the total annual production of waste generated from the whole residential sector is described in each phase.

2.4.1 Pre-processing

All input datasets, including the additional ones built following the procedure described in section 2.3, should refer to the same year. Thus, as previously done in Section 2.3, the NIC coefficients have been exploited to bring the expenses from 2015 to the reference year of the different input datasets (e.g., the input HBS datasets are referred to years 2014, 2015, and 2016). The following equations rule this operation:

$If\ yr < 2015:$

$$y_{x,yr} = y_{x,2015} \times \frac{\alpha_{x,yr,10}}{\alpha_{x,2015,10}} \tag{5}$$

$if\ yr > 2015$:

$$y_{x,yr} = y_{x,2015} \times \frac{\alpha_{x,yr,15}}{\alpha_{x,2015,15}} \tag{6}$$

Thus, the aggregated input dataset composed of consumer prices is referred to the same year of the ISTAT input dataset, unifying the calculations. It is noted that the Italian macro-regions will still disaggregate the data.

Secondly, an analysis of single-pack or multipack purchased products has been carried out, as previously mentioned in section 2.3. In particular, for each product, in case of discrepancy between quantity (i.e., set to 1 if single-pack, >1 if multipack) or the unit of measure (e.g., kilograms, litres, pieces), two conversions are performed as follows:

$If\ Quantity_x \neq Quantity_{x_{ref}}$:

$$Waste_{fr,x,q_{ref}} = Waste_{fr,x,q} \times \frac{Quantity_{x,ref}}{Quantity_x} \tag{7}$$

$If\ Unit\_of\_Measure_x \neq Unit\_of\_Measure_{ref}$:

$$Waste_{fr,x,UoM_{ref}} = Waste_{fr,x,UoM} \times \frac{Unit\_of\_Measure_{x,ref}}{Unit\_of\_Measure_x} \tag{8}$$

These conversions are implemented to unify the measure units (i.e., the reference quantity) to the consumer price dataset (referred to as *ref* in the equations). Indeed, it is crucial to have the exact reference quantities of both the consumer prices' dataset and the domestic measurements' dataset to perform the conversions described in section 2.4.2.

2.4.2 **Conversions of expenses into waste**

The core of the developed model relies on converting the representative sample's expenses stated by the HBS dataset (ISTAT 2020) into the amount of waste generated, first through transforming costs into purchased products. For every single product inside the datasets (i.e., the 857 items identified), the following calculation is performed:

$$Coeff_{fr,x,z} = \frac{DomesticMeasurement_x}{ConsumerPrice_{x,z}} \tag{9}$$

In this way, the coefficient $Coeff_{fr,x,z}\left[\frac{g_{fr,x}}{€}\right]$ for each z-Italian macrozone, the generated fr-waste fraction from the expenditure related to the x-product, as stated in the HBS dataset, allows estimating. However, first, the products' totality must be reduced and associated with the macro-categories related to the HBS dataset. Then, the values of products belonging to the same macro-category (i.e., the 213 selected expenses from the HBS dataset) are added together and divided by the number of products within the expenditure item themselves, obtaining a coefficients' matrix referring to the 213 selected expenditures, as described in section 2.3, with the disaggregation in the Italian macro zones.

$$Coeff_{fr,k,z} = \frac{\sum_{x=1}^{Nproducts_k} Coeff_{fr,x,z}}{Nproducts_k} \tag{10}$$

The conversion coefficient calculation for each of the expenditure items allows to define the total production of each waste fraction generated monthly by each representative household, and to aggregate it by a waste fraction, as follows:

$$Waste_{fr,k,z,m,i} = Expense_{k,z,m,i} \times coeff_{fr,k,z} \tag{11}$$

$$Waste_{fr,z,m,i} = \sum_{k=1}^{213} Waste_{fr,k,z,m,i} \tag{12}$$

2.4.3 **Annualisation and aggregation process**

All values obtained through the conversion process applied to the HBS data must be transformed from monthly to annual. The average monthly generation of any waste fraction is annualised for the *i*-

household and then aggregated at the country-level through the carryover coefficient c_i, provided by HBS ISTAT dataset, as follows:

$$Waste_{fr,z,yr,i} = \sum_{m=1}^{12} Waste_{fr,z,m,i} \tag{13}$$

$$Waste_{fr,z,yr} = \sum_{i=1}^{Nhouseholds_{HBS,z}} Waste_{fr,z,yr,i} \times c_{i,yr} \tag{14}$$

The carryover coefficient is the specific i-household and yr-year in which the analysis takes place.

2.4.4 Estimation of wastes not directly quantified from the HBS input

Some waste fractions cannot be directly estimated through the conversion described in section 2.4.2. Indeed, four types of wastes are added with ad-hoc equations to complete the model, taking into account the following items: 1) Food waste; 2) Non-forecastable fractions (e.g., green fraction, wood, street sweeping, construction and demolition waste); 3) Receipts; 4) Tourism-related.

2.4.4.1 Food wastes estimate

To consider the share of organic waste deriving from the Italian households' food waste, the estimates provided by the REDUCE Project (Giordano et al. 2019, Grosso et al. 2019) have been exploited. The total food waste produced yearly by Italian households are calculated as follows:

$$Waste_{food,z,c,yr} = Waste_{food,z,i,week} \times \frac{100\%}{\%AVfr} \times \frac{365}{7} \tag{15}$$

$$Waste_{food,z,yr} = Waste_{food,z,i,yr} \times Population_{food,z,yr} \tag{16}$$

In particular, the terms $Waste_{food,z,i,week}\left[\frac{g}{pers*week}\right]$. Furthermore, $\%AVfr[\%]$ are extrapolated from the reference (Giordano et al. 2019, Grosso et al. 2019) to estimate the total yearly food waste produced in the *z-macroregion*.

2.4.4.2 Non-forecastable fractions estimation

As described in Supplementary material S.3, some waste fractions cannot be directly estimated from the household's expenses. Moreover, the correct selective collection (SC) share does not represent the totality (i.e., 100%) of these fractions' total waste generation. Estimating how much of these fractions are not recycled will be crucial for calculating the residual waste (Edjabou et al., 2021). The separate collection coefficient for each region, provided by ISPRA data (ISPRA 2019, ISPRA 2020) described in Section 2.2, is exploited to estimate the non-forecastable fractions, and then the results of the regions belonging to the same macrozone are grouped, as follows:

$$Waste_{NF,r,yr} = \left(Green_{r,yr} + Wood_{r,yr} + Other_{r,yr}\right) \times \frac{100\% - \%Diff_{r,yr}}{\%Diff_{r,yr}} \tag{17}$$

$$Waste_{NF,z,yr} = \sum_{r=1}^{Regions_z} Waste_{NF,r,yr} \tag{18}$$

2.4.4.3 **Waste coming from receipts**

Concerning the other quantities of waste taken into account by the model, the amount of refuse from the receipts is undoubted of minor relevance; however, it should also be considered for the sake of completeness. For this purpose, the yearly number of generated receipts, obtained by the reference report (Censis 2010) and summarised in Table 3, were utilised to estimate the related waste as follows:

$$Waste_{R,c,yr} = \left(60{,}7\% \times \frac{365}{7} + 26{,}8\% \times 365 + 10.0\% \times \frac{365}{12} + 2{,}2\% \times 12 + 0{,}3\% \times \frac{365}{50}\right) \times Weight_R \tag{19}$$

$$Waste_{R,z,yr} = Waste_{R,c,yr} \times Population_{R,z,yr} \tag{20}$$

The yearly production of receipt waste for a single person $Waste_{R,c,yr}\left[\frac{g}{pers*year}\right]$ is calculated taking into account average shopping frequency provided by reference (Censis 2010) (i.e. the Italian distribution of shopping frequency as *once a week*, *once a day*, *once every 10-15 days*, *once a month* or *less than once a month*) and the average weight of a single receipt $Weight_R[g]$, measured to be $1\,\frac{g_{waste}}{receipt}$.

2.4.4.4 **Tourism-related waste generation estimate**

The waste generated from tourism-related matter is estimated by exploiting the ISTAT references (ISTAT 2020, ISTAT 2020) described in Section 2.2. The data are first aggregated by macro-regions and values of the average time spent, and the number of arrivals, net of the number of people who leave, in the *z-macroregion* are derived as follows:

$$ATs_{z,u} = \frac{Arrivals_{z,u}}{Presences_{z,u}} \tag{21}$$

$$Arrivals_{net_z} = Arrivals_{tot_z} - \sum_{u=1}^{n_z} Arrivals_{u,z} \tag{22}$$

$$ATs_z = \frac{\left(\sum_{u=1}^{n_z} ATs_{z,u}\ \right) + ATs_{z,foreigncountry} - ATs_{z,z}}{n_z - 1 + 1} \tag{23}$$

The number of people represented by the arrivals will contribute to waste generation, particularly organic fraction, cellulosic fraction, glass, plastics, metals, and residual waste fraction. First, the yearly waste fraction generation calculated from eq. (14) is exploited to estimate the per capita generation of each waste fraction, considering the number of households that recorded a non-zero value:

$$Waste_{fr,c,yr} = \frac{Waste_{fr,z,i}}{N_{households_{fr,z}}} \times \frac{1}{365} \tag{24}$$

Then, a higher average daily expenditure has been assumed for holidays compared to weekdays, through a coefficient calculated by the ratio between the average spending on weekdays and the average spending on holydays, derived by references (ISTAT 2020) and (ISTAT 2020), respectively; then, the related waste on holydays has been calculated:

$$Waste_{holiday_{fr,c,yr}} = Waste_{fr,c,yr} \times \frac{Expenditure_{week_{m,i}} \times \frac{12}{365}}{Expenditure_{holiday_{day,i}}} \tag{25}$$

Finally, the total waste generated by tourism is calculated as follows:

$$Waste_{tourism_{fr,z,yr}} = Waste_{holiday_{fr,c,yr}} \times Arrivals_{net_z} \times ATs_z \tag{26}$$

2.4.5 **Total waste generation**

All the equations mentioned above are aggregated by fractions set by the ISPRA dataset (ISPRA 2020) to perform the model's validation and calibration. Thus, the total waste generation will be presented for the following categories:

Organic fraction:

$$Waste_{tot,Organic,z,yr} = Waste_{Organic,z,yr} + Waste_{food,z,yr} + Waste_{tourism_{Organic,z,yr}} \tag{27}$$

Cellulosic fraction:

$$Waste_{tot,Cellulosic,z,yr} = Waste_{Cellulosic,z,yr} + Waste_{tourism_{Cellulosic,z,yr}} \tag{28}$$

Glass:

$$Waste_{tot,Glass,z,yr} = Waste_{Glass,z,yr} + Waste_{tourism_{Glass,z,yr}} \tag{29}$$

Metals:

$$Waste_{tot,Metals,z,yr} = Waste_{Metals,z,yr} + Waste_{tourism_{Metals,z,yr}} \quad (30)$$

Plastics:

$$Waste_{tot,Plastics,z,yr} = Waste_{Plastics,z,yr} + Waste_{tourism_{Platics,z,yr}} \quad (31)$$

WEEE:

$$Waste_{tot,WEEE,z,yr} = Waste_{WEEE,z,yr} \quad (32)$$

Textile fraction:

$$Waste_{tot,Textile,z,yr} = Waste_{Textile,z,yr} \quad (33)$$

Selective fraction:

$$Waste_{tot,Selective,z,yr} = Waste_{Selective,z,yr} \quad (34)$$

Bulky waste:

$$Waste_{tot,Bulky,z,yr} = Waste_{Bulky,z,yr} \quad (35)$$

Residual waste fraction:

$$Waste_{tot,Rwf,z,yr} = Waste_{Ndf,z,yr} + Waste_{NF,z,yr} + Waste_{tourism_{Ndf,z,yr}} \quad (36)$$

Finally, the **total waste generated** can be further aggregated as follows:

$$Waste_{tot,z,yr} = \sum_{fr=1}^{N_{fr}} Waste_{tot,fr,z,yr} \quad (37)$$

3 Model validation and optimisation

Applying Eqs. (5-37) to the HBS dataset, the developed model can be validated by comparing the results with the data available in the ISPRA dataset (ISPRA 2019, ISPRA 2020), described in section 2.2. For each total waste fraction generation and macrozone, the following equation is applied to calculate the relative error:

$$e_{\%,fr,z,yr} = \frac{Waste_{tot,fr,z,yr} - Waste_{tot,fr,z,yr,ISPRA}}{Waste_{tot,fr,z,yr,ISPRA}} \quad (38)$$

A first estimation shows error values too large to validate the model developed—however, a general check on total waste generation estimation, applying eq. (37) and reported in Table 2, shows significant correctness of the model itself.

Table 2. Relative errors of the total MW generation estimated by the model concerning ISPRA's values (ISPRA 2020).

Zone	2014	2015	2016

1	Model estimation [ton/year]	8,069,121	8,391,569	8,861,776
	ISPRA value [ton/year]	7,659,243	7,621,696	7,985,314
	Relative error	5.35%	10.10%	10.98%
2	Model estimation [ton/year]	6,503,802	6,346,667	6,146,463
	ISPRA value [ton/year]	6,113,187	6,097,577	6,187,222
	Relative error	6.39%	4.09%	-0.66%
3	Model estimation [ton/year]	6,209,489	5,979,400	6,031,970
	ISPRA value [ton/year]	6,611,031	6,555,161	6,723,137
	Relative error	-6.07%	-8.78%	-10.28%
4	Model estimation [ton/year]	5,636,801	5,629,922	6,068,821
	ISPRA value [ton/year]	6,202,300	6,180,092	6,484,875
	Relative error	-9.12%	-8.90%	-6.42%
5	Model estimation [ton/year]	2,099,704	2,118,584	2,075,490
	ISPRA value [ton/year]	2,340,935	2,350,191	2,379,290
	Relative error	-10.30%	-9.85%	-12.77%
6	Model estimation [ton/year]	744,298	731,358	785,710
	ISPRA value [ton/year]	725,024	719,624	783,385
	Relative error	2.66%	1.63%	0.30%
Italy	Model estimation [ton/year]	29,263,215	29,197,501	29,970,230
	ISPRA value [ton/year]	29,651,721	29,524,341	30,543,223
	Relative error	-1.31%	-1.11%	-1.88%

Even if Table 2 shows error values within an acceptable error range (i.e., ±15%), an optimisation procedure is required to improve the disaggregated results further. However, it should be noted that a value of 100% selective collection cannot be reached. Thus, it has to be assumed that part of the fractions that should be collected as SC is instead disposed of together with non-differentiated fractions, in different proportions according to the Italian macro zones. To subdivide the values of the differentiated fractions to balance the errors, the following parameters and equations have been defined:

Coeff$_{fr,z,yr}$: Coefficient initially assumed to be equal to 10% and then modified to split the values of the selective collection and non-differentiated collection balancing the errors.

Residue $_{for,z,yr}$: Part of the fr-waste fraction that is put together with the residual waste fraction.

For fr ≠ Residual waste fraction:

$$Residue_{fr,z,yr} = \left(Waste_{tot,fr,z,yr} - Waste_{tot,fr,z,yr,ISPRA}\right) \times coeff_{fr,z,yr} \quad (39)$$

SCeff$_{fr,z,yr}$: Part of the fr-waste fraction considered that is assumed to be collected through the SC.

For fr ≠ Residual waste fraction:

$$SCeff_{fr,z,yr} = Waste_{fr,z,yr} - Residue_{fr,z,yr}; \qquad (40)$$

For fr = Residual waste fraction, and frac = Organic fraction, Cellulosic fraction, Glass, Metals, Plastics, WEEE, Textile fraction, Selective fraction, Bulky waste:

$$SCeff_{fr,z,yr} = Waste_{fr,z,yr} + \sum_{fraz} Residue_{frac,z,yr}; \qquad (41)$$

Goal$_{fr,z,yr}$: Relative error of each fr-waste fraction calculated concerning the correspondent value published by ISPRA. To be acceptable, its value must be between Up$_{limit}$ and Down$_{limit}$.

$$Goal_{fr,z,yr} = \frac{\left(SCeff_{fr,z,yr} - Waste_{fr,z,yr,ISPRA}\right)}{Waste_{fr,z,yr,ISPRA}}; \qquad (42)$$

Up$_{limit}$: Maximum value of the relative error admitted: 15%.

Down$_{limit}$: Minimum value of the relative error admitted: -15%.

Finally, the optimisation equation is defined to reduce to zero the Goal$_{Residualwastefraction,z,yr}$, by modifying the Coeff$_{fr,z,yr}$ of each fraction. The optimisation is carried out for all fractions simultaneously, and it has some constraints to which it must withstand, that they can be represented as follows:

$$Down_{limit} \leq Goal_{fr,z,yr} \leq UP_{limit} \ \ \forall \, fr \in SC \qquad (43)$$

Subsequently, eq. (38) has been applied for the final validation. Results are shown in Table 3 for the reference year 2016.

Table 3. Results of the model validation in the reference year 2016, part 1. Elaboration (ISPRA, 2020, ISTAT, 2020).

	2016	**Organic fraction [ton/yr]**	**Cellulosic fraction [ton/yr]**	**Glass [ton/yr]**	**Metals [ton/yr]**	**Plastics [ton/yr]**	**WEEE [ton/yr]**	**Textile fraction [ton/yr]**	**Selective fraction [ton/yr]**	**Bulky waste [ton/yr]**	**Residual waste fraction [ton/yr]**
Zone 1	Model estimation	1,240,127	1,041,880	695,074	97,930	452,439	82,763	46,185	16,825	375,890	3,590,346
	ISPRA value	1,100,722	914,693	617,713	91,471	405,493	73,775	42,839	15,493	334,257	3,166,542
	Relative error	12.66%	13.90%	12.52%	7.06%	11.58%	12.18%	7.81%	8.60%	12.46%	13.38%
Zone 2	Model estimation	999,763	753,454	488,689	97,868	344,000	65,013	32,422	15,859	203,565	2,200,341
	ISPRA value	973,085	822,777	472,589	94,730	323,653	61,813	31,462	15,233	195,680	2,250,710
	Relative error	2.74%	-8.43%	3.41%	3.31%	6.29%	5.18%	3.05%	4.11%	4.03%	-2.24%
Zone 3	Model estimation	891,375	701,651	331,134	49,683	178,618	44,404	21,622	6,844	131,804	3,045,097
	ISPRA value	998,773	793,592	368,891	54,713	197,381	48,406	23,677	7,527	145,875	3,454,562
	Relative error	-10.75%	-11.59%	-10.24%	-9.19%	-9.51%	-8.27%	-8.68%	-9.07%	-9.65%	-11.85%
Zone 4	Model estimation	1,056,369	464,770	271,430	35,129	225,381	30,020	26,637	3,710	152,380	3,361,489
	ISPRA value	1,156,736	515,174	288,559	38,297	242,271	32,846	28,721	3,925	166,035	3,570,807
	Relative error	-8.68%	-9.78%	-5.94%	-8.27%	-6.97%	-8.60%	-7.26%	-5.46%	-8.22%	-5.86%
Zone 5	Model estimation	105,743	85,245	37,246	3,225	23,072	6,821	3,442	293	14,894	2,010,781
	ISPRA value	113,303	93,016	40,424	3,472	25,282	7,522	3,739	312	16,165	2,002,496
	Relative error	-6.67%	-8.35%	-7.86%	-7.10%	-8.74%	-9.33%	-7.95%	-6.04%	-7.86%	0.41%
Zone 6	Model estimation	194,067	81,882	65,350	10,749	40,556	9,908	2,939	1,448	15,449	282,528
	ISPRA value	188,572	79,691	64,272	10,459	39,957	10,473	2,888	1,389	15,102	289,747
	Relative error	2.91%	2.75%	1,68%	2,77%	1,50%	-5.40%	1.76%	4.21%	2.30%	-2.49%
Italy	Model estimation	4,487,443	3,128,882	1,888,923	294,584	1,264,067	238,930	133,247	44,979	893,983	14,490,583
	ISPRA value	4,531,192	3,218,943	1,852,449	293,142	1,234,037	234,836	133,327	43,878	873,113	14,734,864
	Relative error	-0.97%	-2.80%	1.97%	0.49%	2.43%	1.74%	-0.06%	2.51%	2.39%	-1.66%

4 Italian MW generation forecast

In this Section, the developed model is utilised to forecast the future MW production in Italy from 2019 to 2040. For this purpose, an aggregated ISTAT dataset is employed, and a socio-demographic model is provided by the reference activity carried out by Besagni et al. 2021.

4.1 Additional dataset and sub-models

The ISTAT datasets referred to the Household Budget Survey (ISTAT 2020), to the Aspects of Daily Life (ISTAT 2020), and Household Energy Consumption (ISTAT 2017) are aggregated with ad-hoc statistical methods (Besagni et al. 2021), providing a single aggregated ISTAT dataset as input to the developed waste generation model. Then, the model has been further validated and optimised by applying the procedure described in section 3; the validation of the aggregated ISTAT dataset is presented in Supplementary material S.6. Moreover, the socio-demographic model, developed by (Besagni et al. 2021), extends the carryover coefficients associated with each representative sample household of the dataset without changing the sample itself and allows to take into account the changes in the population growth and to perform scenario analyses. However, the primary assumption for its application has to be introduced: the aggregated ISTAT dataset variables taken as input (e.g., the spending habits, types of products' packaging) remain constant in the forecasting calculations. Besides, to forecast the MW generation for the next twenty years, the estimations of the production of the waste fractions, discussed in section 2.4.4, and the optimisation coefficient, presented in section 3, need to be corrected for each year; in this context, a linear regression model has been applied for each of the following items to be estimated: non-forecastable waste, receipt waste, tourism-related waste, and optimisation coefficients. Further details on linear regression models applied are reported in Supplementary material S.7.

4.2 Methods and scenarios

The baseline case has been defined during the validation procedure, described in Supplementary material S.6. The evolution of separate collections in the different macro-regions and the food waste in the years of the analysis is considered defining the different scenarios. In contrast, all other waste fraction production and coefficients are calculated following the methodologies and linear regression models described in section 2 and Supplementary material S.7, respectively. In particular, four scenarios are investigated:

Scenario 0: zero growth, values blocked at those of the last year available, i.e., 2018.

Scenario 1: current scenario, small but sustained growth in the SC percentage and a slight decrease in food waste.

Scenario 2: pessimistic scenario, a decrease in separate waste collection and a substantial increase in food waste.

Scenario 3: more optimistic scenario, significant growth in the SC percentage, especially in central and southern Italy, and great attention to food waste, i.e., substantial reductions over the years.

Complete information about SC and food waste percentages set for the four defined scenarios are provided in Table 4.

Table 4. SC percentage growth in the year concerning year$_{yr}$ concerning year$_{yr-1}$ and food waste trends in the four different scenarios.

	Food waste			**%SC year$_{yr}$**							
				0-30%	**30%-40%**	**40%-50%**	**50-60%**	**60%-70%**	**70%-80%**	**80-90%**	**90%-100%**
Scenario 0	Constant food waste	0%	yearly	0%	0%	0%	0%	0%	0%	0%	0%
Scenario 1	A slight decrease in food waste	-1%	yearly	2.00%	1.50%	1.00%	0.50%	0.30%	0.10%	0.05%	0.01%
Scenario 2	Increase in food waste	3%	yearly	-1.00%	-1.50%	-2.00%	-2.50%	-2.00%	-3.00%	-4.00%	-5.00%
Scenario 3	Significant decrease in food waste	-5%	yearly	4.00%	3.50%	3.00%	2.50%	2.00%	1.50%	0.75%	0.25%

The equations applied for the forecasting calculations are described in Supplementary material S.7, for all considered fractions, listed in section 2.4.

4.3 Results and discussion

The results of the above-described scenarios regarding the most critical waste fractions are displayed in Figure 2-Figure 5. The other estimated waste typologies trends are presented in Supplementary material S.8. Outcomes are presented subdivided by fractions and macro-regions to highlight how different SC and food waste percentages will impact the Italian MW generation. As shown in Figure 2-Figure 5, all the fractions' estimated behaviour is similar in the different macro-areas. As far as the organic fraction is concerned (Figure 2), its generation decreases for Scenario 2 due to the drastic decrease over the years of the different collection percentages, inversely to Scenario 1. In Scenario 0, the age remains almost constant, increasing or slightly decreasing according to the macro-region population's development. Finally, in Scenario 3, for the areas with an already high level of separate collection percentage, the organic fraction production decreases since the effect of food waste reduction is dominant; otherwise, i.e., in macro-zones 3, 4, and 5, there will be an initial growth followed by a slight decrease. Focusing the attention on the other fractions of separate waste collection, i.e. cellulosic fraction (Figure 3), glass (Supplementary material S.8), metals (Supplementary material S.8), plastics (Figure 4), WEEE (Supplementary material S.8), the textile fraction (Supplementary material S.8), the selective fraction (Supplementary material S.8) and bulky waste (Supplementary material S.8), it can be observed that, unless there are some inaccuracies in macro-zone six due to the poverty of data relating to Sardinia, the trend in waste generation is the same for each fraction in each zone. Scenario 3 shows very strong growth due to a considerable increase in recycling attention; Scenario 1 shows lighter growth, Scenario 0 shows almost constant growth, mainly influenced by demographic development. Conversely, Scenario 2 shows a significant decrease for its assumptions on the increase of food waste and at the same time the decrease of SC percentage; this indeed leads to significant growth of the residual waste fraction generation, as shown in Figure 5 (Scenario 2), while it decreases in its generation over the years for Scenario 0, Scenario 1 and Scenario 3, with and inversely proportional trend with respect to all other waste fractions taken into account. It should be noticed that even for the most optimistic scenario (Scenario 3) in macro-zone 1 and in macro-zone 2 the decreasing trend reaches a technical plateau limit due to both the demographic dimension of the population and unavoidable residual waste fraction for each family; this limit will likely occur for the other waste fractions and macro-zones as well.

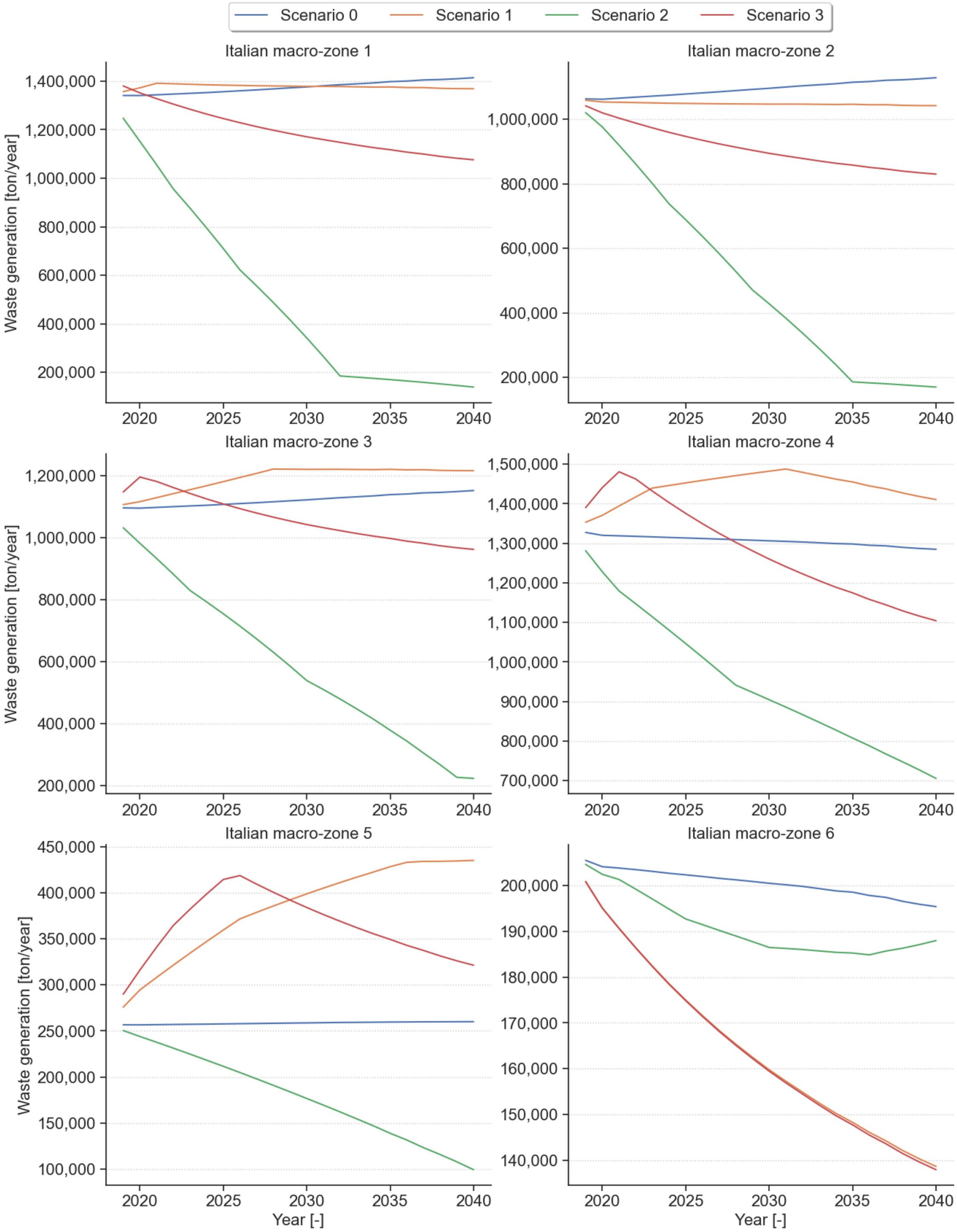

Figure 2. Results of organic fraction generation's forecast from 2019 to 2040 in Italy

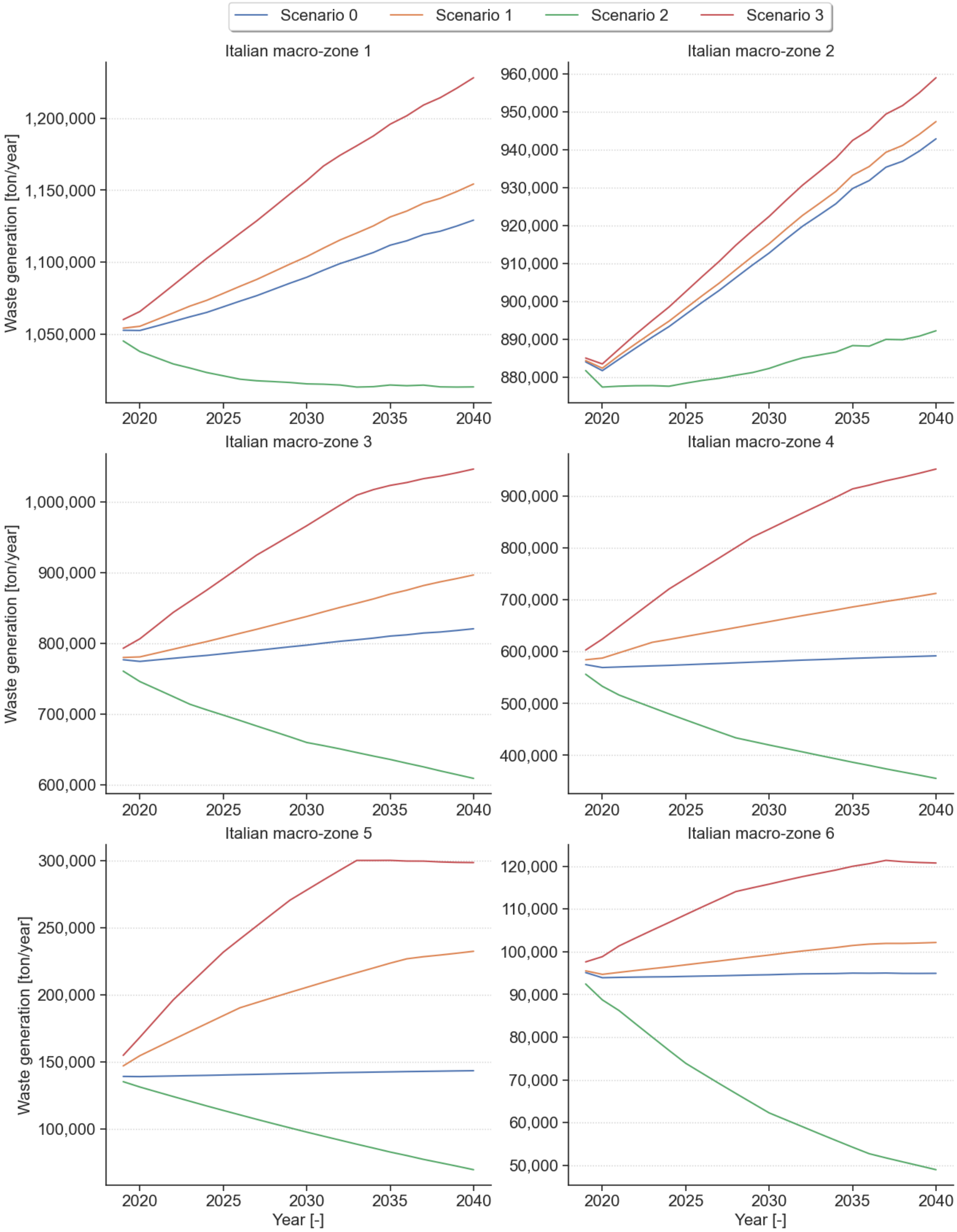

Figure 3. Results of cellulosic fraction generation’s forecast from 2019 to 2040 in Italy.

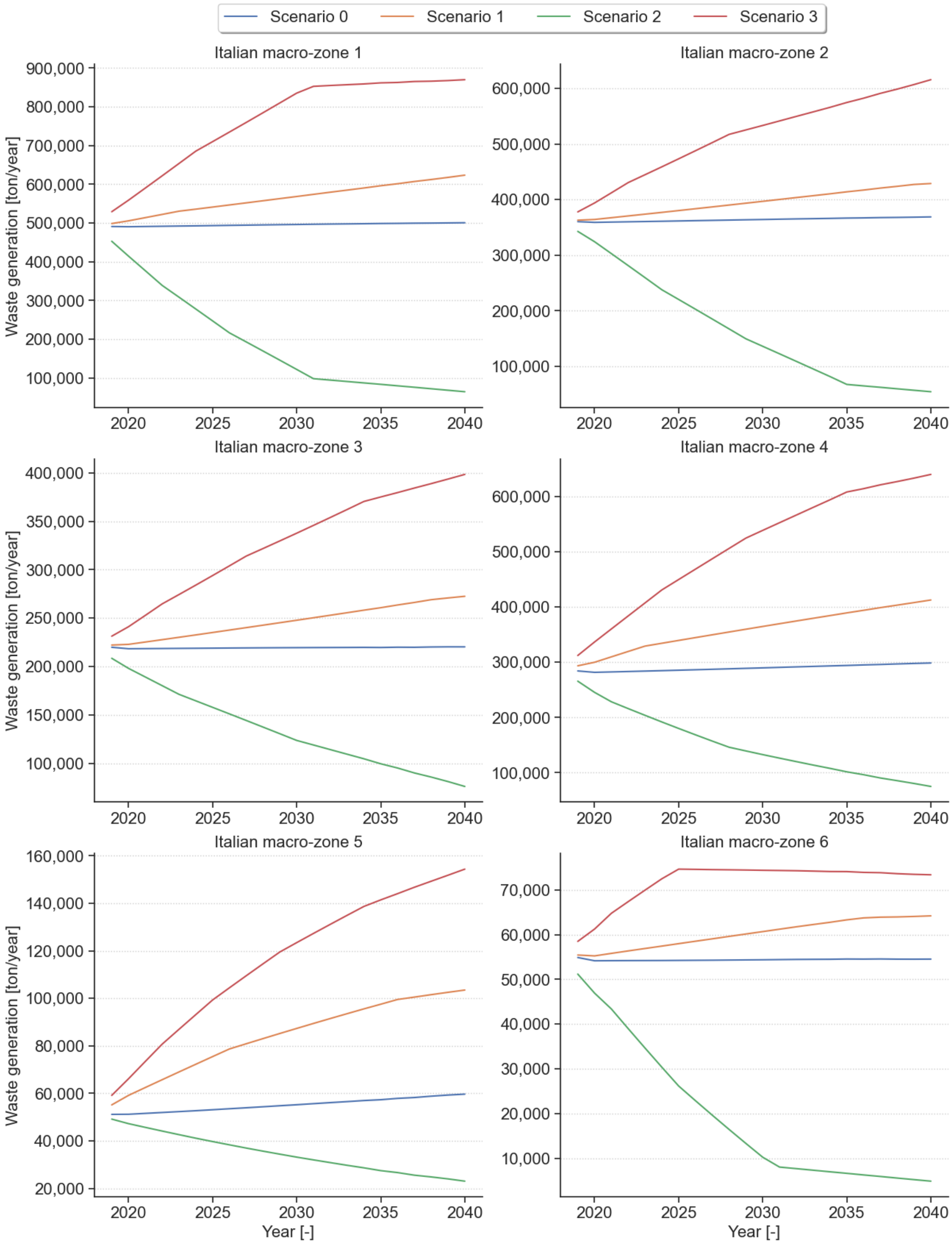

Figure 4. Results of plastics generation's forecast from 2019 to 2040 in Italy.

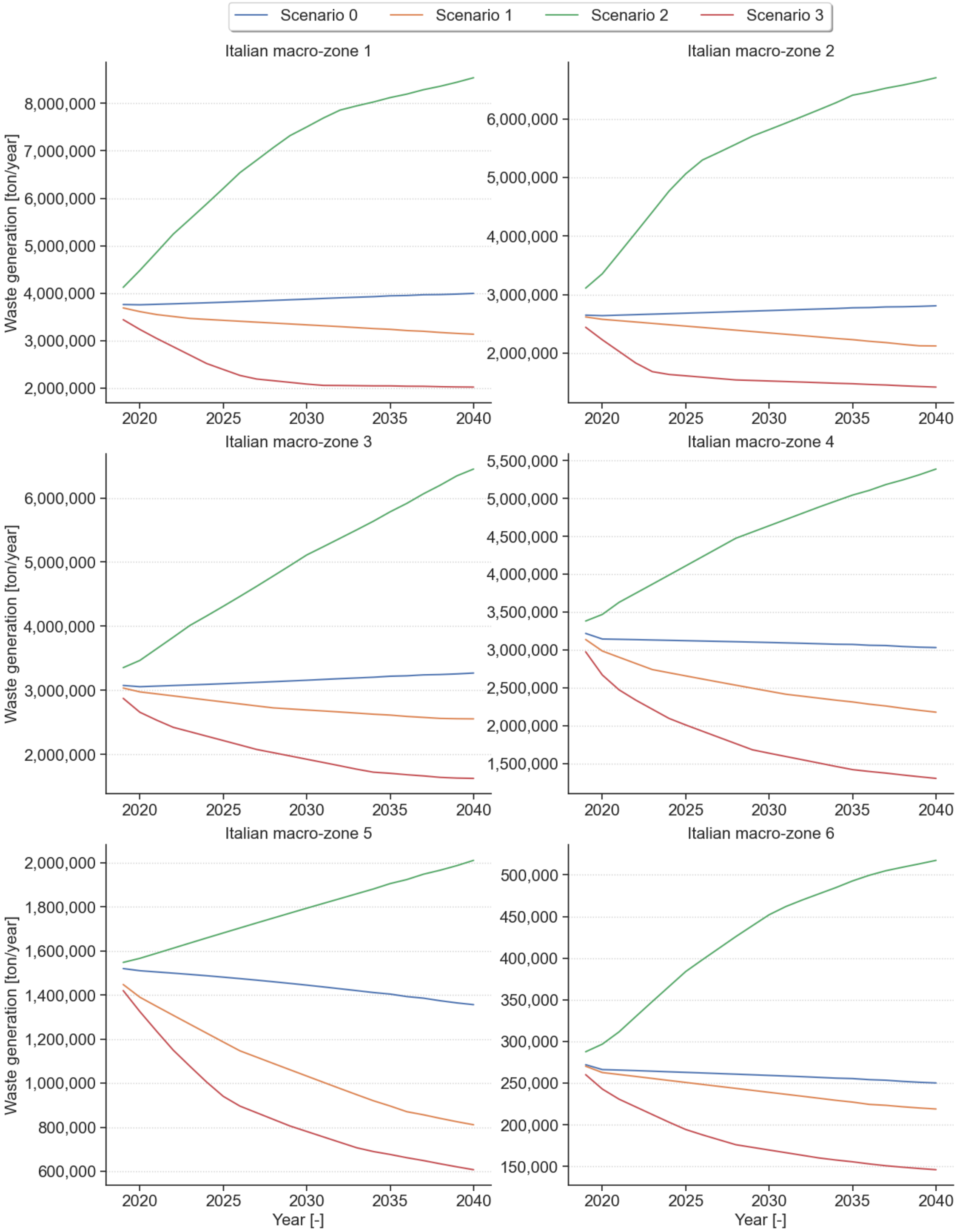

Figure 5. Results of residual waste fraction generation's forecast from 2019 to 2040 in Italy.

5 Conclusions and outlooks

5.1 Conclusions

Reducing the amount of generated waste is one of the primary objectives at the Italian and European levels. This paper contributes to understanding municipal waste generation by developing a novel bottom-up modelling approach to estimate current and future waste generation in disaggregated terms. The model was validated and optimised by comparing the results with the official ISPRA datasets (ISPRA 2020). Finally, the model has been employed to investigate the municipality waste generation in future years, considering four different scenarios. The socio-demographic variables that accompany the input and characterise the final user remain directly associable; these parameters allow to describe the end-users behaviours and link them to the values of waste generated. However, the methodology has some limitations since it fails to estimate the quantities of the waste directly related to the collection of wood, construction and demolition waste, road sweeping for recovery, tourism, food waste, and other fractions, as well as not being able to separate bulky waste going to disposal from bulky waste going to recovery. Nevertheless, the validation and optimisation procedures show positive results, with relative errors below 5% at the national average and between ±15% at the macro-regional level.

5.2 Outlooks

The developed model, aiming at estimating the municipal waste generation, should be further improved in future research activities: the aggregated ISTAT dataset allows the integration of the MW generation model into a broader bottom-up model to tackle the residential sector consumptions declined in energy, transportation, waste, expenses. For instance, the integration with the MOIRAE model to estimate the energy consumptions of the residential sector with a similar dataset as input (Besagni et al. 2020) and extended with economic analysis (Besagni et al. 2021) should be taken into account; the proposed modelling methodology could be applied to other sectors (e.g. the industrial sector), in order to include the whole country's waste generation; the estimation of MW generation from the end-users side may be coupled to the waste management side (i.e. collection schemes, and treatment and disposal facilities) to forecast the effects on increasing SC fraction or decreasing food waste concerning the evolution of the waste management infrastructure (e.g. composting plants, incinerators, landfill) and thus to analyse the saturation of such systems. The idea is to have a comprehensive modleing approach, at the bottom-layer to consider all the energy and energy-raleated and aterial needs. To this end, we are planning to (i) deploy extensive surveys, to Italian households, to have more detailed insights and improve the model performances (this activity will take one year of work), (ii) implement ad-hoc monitoring of Italian households. This bottom-up view is also of peculiar importance within the currect framework and regulations. E.g., the legislative proposals Clean Energy Package, the recast of the Renewable Energy Directive (RED II) and the recast of the Internal Market for Electricity Directive (IEM), which endorsed “prosumers” as new key-role-players in the energy system. According to the provisions of the Directives mentioned above, “energy communities” are legal entities whose members may share the produced energy internally. Hense, the above-describe “supply-side” is characterised by an increasing share of decentralised energy sources having households at their core, acting in the production, storage, consumption, supply and distribution of electricity and renewable energy. Thus, bottom-up modleing approaches might be a betst fit to also model the behaviour spectrum at the household layer.

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