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MATERIAL FLOW ACCOUNTING: REVIEW AND APPLICATION IN THE ITALIAN GLASS INDUSTRY

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Abstract

This thesis presents a comprehensive exploration of material flow accounting (MFA) methodology within the context of the Italian glass industry, aiming to enhance our understanding of resource utilization, environmental impact, and sustainability. The thesis employs a systematic MFA framework to quantify and analyse material flows at various stages of the glass manufacturing lifecycle.

Specifically, a sub-methodology within material flow accounting is employed, the Economy Wide – Material Flow Accounting (EW-MFA), representing the entire economic system within a singular input-output process. This approach considers the complete inputs and outputs flows within this single framework, providing an understanding of the dynamic interactions within the broader economic context.

Through this lens the study delves into the intricate processes involved in glass production, from raw material extraction to end-of-life considerations; the thesis dissects the complexities of the glass industry, shedding light on patterns, trends, and potential areas for improvement.

The findings of this research not only contribute to the current body of knowledge on MFA methodology but also offer valuable insights for stakeholders in the glass industry in the Italian context. By critically assessing environmental implications, the study provides a basis for informed decision-making, promoting resource efficiency and sustainability. Additionally, the thesis explores the integration of MFA into glass recycling practices, paving the way for a more circular and environmentally responsible approach to glass production.

In conclusion, this research underscores the significance of material flow accounting as a tool for evaluating and advancing sustainable practices in the glass industry. By quantifying material flows and environmental impact, the study contributes to the ongoing discourse on industrial sustainability, offering a roadmap for future research and practical applications within the broader context of sustainable resource management.

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Research context and objectives of the study

The choice of the hosting location and company played a pivotal role in shaping the research context and objectives of this study. In my case, this involves the selection of Belgium, specifically Brussels, and the *EUabout* consulting company as the hosting environment. The research site provides a unique vantage point within the European Union offering a dynamic environment, facilitating access to key resources, expertise, and a network of professionals within the *EUabout* consulting company.

Through this collaborative effort, I have acquired new skills into the field of Economy-Wide Material Flow Accounting, including proficiency in data analysis, a deeper understanding of sustainability metrics and the ability to navigate the complexities of circular economy principles within the context of the glass industry. These acquired skills extend beyond the immediate scope of the thesis, positioning themselves as invaluable assets for my future endeavours.

The overall objective of my thesis project is to apply Economy-Wide Material Flow Accounting (EW-MFA) methodologies within the glass sector in Italy. The focus is on conducting an analysis towards quantifying material flows against the backdrop of circular economy principles and sustainability. This research aims to contribute valuable insights into the sustainable management of material resources within the glass industry.

It's crucial to recognize that my work is not an isolated effort but rather the initial step in a continuum. The insights generated from this research lay the groundwork for future studies, contributing to the ongoing discourse on sustainable practices within the glass industry and beyond.

In conclusion, the choice of hosting location, the objective of the thesis project, the acquisition of new skills, and the future application of these skills collectively shape the rich research context and objectives of this study. This endeavour marks not just the culmination of a thesis but the beginning of a trajectory contributing to the broader landscape of sustainable material management.

Chapter 1: Review of related work

1.1 Literature Review

In the realm of environmental accounting and sustainability research, the examination of material flows publications serves as essential for comprehending the previous achievement in understanding the complex interactions among the environment, economies, and material flows between them. At the beginning of this exploration lies one of the official documents result of a “Working Group on Environmental Information and Outlooks” (OECD, 2000), made whit the scope to contribute the OECD work programme on resource efficiency and on sustainable development. The paper introduces the foundational principles of material flow accounting but also sets the stage for an understanding of the EW-MFA methodology. Moreover, the paper delves into an international comparison of inflows and outflows. It presents the outcomes of a global research initiative aimed at constructing comprehensive physical accounts for each participating country within the OECD. It is important to note that these aspects are not directly relevant to the specific scope and objectives of my research.

The other relevant publication for my study is the Volume I of the guide entitled “Measuring material flows and resource productivity” (OECD, 2008) that serves as a foundational resource, elucidating the nuances of how materials traverse economic systems and how environmental impacts are intricately linked to these movements at the different MFA levels. Moreover, the detailed description of indicators in the final segment of the publication becomes an elucidating link between the material flow accounting methodology and quantifiable environmental impact measures of material flows.

To obtain a comprehensive explanation of the specific applied methodology, the EW-MFA, the guide named “Economy-wide material flow accounts and derived indicators” (Eurostat, 2001) delve into its complexities, shedding light on its relevance and utility in comprehending material flows within an entire economy. This comprehensive overview, derived from the Eurostat's insights, becomes instrumental in laying the groundwork for subsequent discussions on the significance of EW-MFA and its role in providing a holistic perspective on resource use and environmental impacts. Furthermore, this guide complements the theoretical foundations with practical insights related to data sourcing and the application of the methodology, serving as a valuable resource for researchers navigating the challenges of implementing EW-MFA.

Lasty, the most recent iteration of the preceding publication from Eurostat, “Economy-wide material flow accounts – Handbook” (Eurostat, 2018), serves as the most updated version about the topic with numerous direct references to the previous publication already mentioned. However, important adjustments have been made to align with new environmental norms and regulations, and certain terminologies from previous guides have undergone revision. First, this version encompasses a comprehensive summary of all the conceptual foundations underlying the Economy-Wide Material Flow Analysis (EW-MFA) methodology. Moreover, it plays a crucial role by explicating the steps, the sources, and some potential complications that may arise during data research and compilation. Ultimately, the publication offers clear representations and examples on how to present data, along with the official questionnaire to be exhibited. This manual ensures a comprehensive understanding of the methodology, making it an indispensable resource for researchers and practitioners engaged in EW-MFA studies.

1.2 Software Review

In the realm of Material Fow Analysis, the range of software applications play a central role facilitating the systematic examination, collection and visualization of data both with the representation of all the relevant flows and their interactions within a given or defined system. The landscape of MFA software tools is examined along with an examination of their key features, functions, and suitability for use in sustainable resource management. The software review, an important component of this thesis, attempts to give a description of the tools that are out there and to identify important software solutions that improve Material Flow Analysis's effectiveness and open the door to better decision-making in the pursuit of sustainable resource use.

In detail, the first set of tools, only available with a purchased licence, encompass the **INOSIM**[1]**,IPOLOG**[2] and **VIS TABLE**[3] software. They stand out as a robust and versatile material flow analysis software. Their adaptability and scalability make them a tool of choice for entities ranging from medium-sized enterprises to major international corporations, navigating complex domains such as bulk chemicals and pharmaceuticals. This set of tools not only facilitates the simulation and evaluation of process alternatives but also excels in identifying bottlenecks, assessing uncertainties, and understanding dependencies. Moreover, these tools contribute significantly to cost reduction and efficiency enhancement. They enable right-sizing of processes, thereby reducing investment costs, and assist in implementing optimized processes, leading to operational cost savings. In addition to their prowess in material flow analysis, these tools extend their capabilities through the integration with Excel that enhances data analysis and reporting capabilities, providing a comprehensive solution. The tools' visualization capabilities empower users to comprehend and share simulation results seamlessly, promoting collaboration and communication within the industrial landscape.

Completing the review, there are two freeware software known as **STAN**[4] (Cencic & Rechberger, 2008) and **OMAT**[5], specifically designed for the Economy Wide-Material Flow Accounting, a wide range method derived from the MFA that will be further investigated and applied in the thesis. However, the first software STAN, one of the most prominent software in the realm of environmental accounting, excels in conducting thorough Substance Flow Analyses placing a heightened emphasis on assessing the environmental impacts associated with material inputs and outputs. This comprehensive approach ensures a detailed understanding of the life cycle of materials. With its user-friendly interface and robust analytical capabilities, STAN allows users to scrutinize the intricate connections between economic activities and their ecological consequences in a broader perspective, resulting particularly helpful aiding decision-makers in crafting sustainable strategies and policies.

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[1] https://www.inosim.com/material-flow-analysis/

[2] https://www.ipolog.ai/en/optimization-areas/material-flow-planning/

[3] https://www.vistable.com/software/material-flow-planning-software/

[4] https://www.stan2web.net/

[5] https://metabolismofcities.org/projects/omat/

The final software to undertake an EW-MFA is known as OMAT, appears as a software solution that meets the special objectives of Material Flow Analysis researchers. Its flexibility in dataset saving, practical logistics support, collaborative work environment, and seamless dataset sharing capabilities position OMAT as a valuable tool for advancing the efficiency and effectiveness of MFA research.

Chapter 2: Conceptual Foundation of Material Flow Analysis

2.1 Material Flow Analysis and Accounting

The material flow analysis and accounting (MFA) is a methodology born in the 1980 in different laboratories around the world and then became a structured academic discipline in the 1990 and early 2000s. The awareness of its industrial relevance has increased over the last years and it will be considered among the most used tools to assess and enhance material flows in the optic of the climate change. The value of this methodology has been increased also for the increment availability and quality of medium-long term data allowing increasingly reliable past trends analysis. For these reasons, nowadays, there are institutions as the International Society for Industrial Ecology (ISIE) that has a section called Socio-Economic Metabolism (SEM) that organises researchers in this topic.

In general, MFA offers an in-depth knowledge of a variety of interconnected processes and flows, and the analyses can be useful in identifying intriguing insights, challenges and to analyse the relationships between material flows, human activities and environmental changes. In addition, its output can also serve as a starting point for the creation of official statistics and the derivation of indicators for the advancement of sustainability transition.

The conceptual background is rooted in the recognition that the industrial system, along with its associated social interactions, is intricately linked to the surrounding environment via material and energy flows as showed in **Figure 1** (Eurostat, 2018, p. 16). This connection gives rise to a comprehensive and interconnected system, where the interdependence between critical factors within each subsystem is unmistakable.

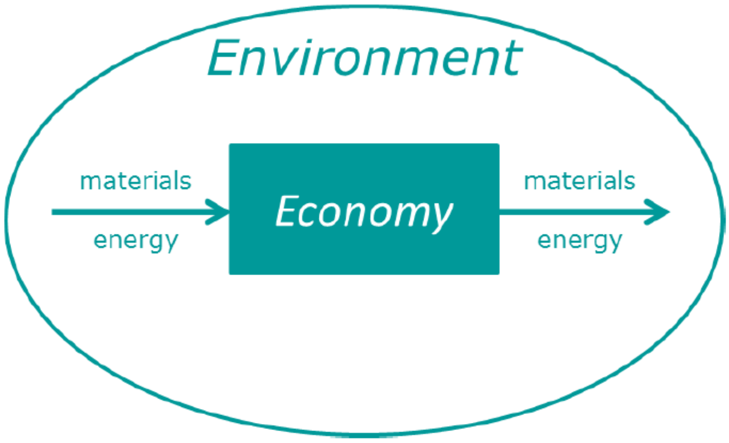

Figure 1. Physical exchange between economy/society and environment

It may reveal not just the types and quantities of natural resources coming into the economy, but also what happens to materials as they move inside and outside of the economy, and how this relates to resource productivity and environmental load. It also allows you to analyse an industry, region or country environmental impact from its economic operations and estimate how material-intensive its economy is.

The relationship between the economy and the environment is well presented within an exploded view showed in the **Figure 2** (Eurostat, 2001, p. 11) below. The *economy sphere* is divided into the national economy and the rest of the world (in the national accounting sense) while the *environmental sphere* is represented by the national environment and the ecosystem that belongs to rest of the world. The economic territory, as delineated in the System of National Accounts, corresponds with the spatial boundaries of the national environment.

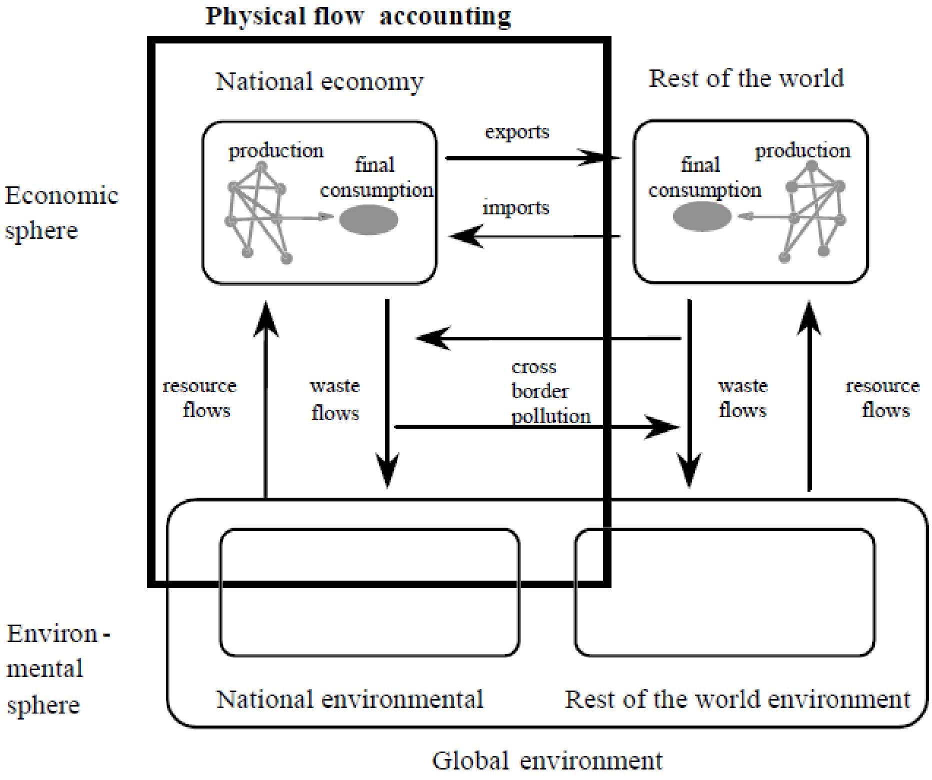

Figure 2. Physical flows and the scope of physical flow accounting

Moving forward with the study, the MFA methodology is founded on a principle emphasizing the necessity of a clearly defined system. This system must adhere to a simple mass balancing[6] concept, ensuring equilibrium for all inputs, outputs, and retained components by the analysis's conclusion. In systems like production or consumption processes, companies, regions, or national economies, the principle of "mass balance" can be articulated using this equation:

Total inputs = Total outputs + Net accumulation

Exactly meaning that everything entering the system either accumulates there or leaves the system as an output. Thus, focusing on each specific physical flow, it can be recognized and identified through the following duality: origin —> destination (or similarly supply —> demand or resources —> uses). Therefore, considering all the origin and destination flows, the sum of the masses by origin must equal to the sum of

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[6] The principle of mass balancing is founded on the first law of thermodynamics, the law of conservation of matter, which states that matter (mass, energy) is neither created nor destroyed by any physical transformation process.

the masses at destination. When this identification is applied to establish economic balances for certain material groups (such as biomass or fossil fuels), the raw materials need to be linked, for instance, to the wastes or emissions generated.

Accordingly, the MFA corresponds to an accurate tracing and quantifying of material flows across the various stages of the process chains encompassing several phases as the extraction of the substances, the chemical transformation, the consumption and the recycling process as well as the final disposal of materials.

Material flow can be analysed at various scale and with different tools depending on the object of interest of the study. The main levels presented and necessary to understand the adaptability and scalability are the following: national macro-economic level (EW-MFA), meso level and micro level.

The first one, known as **Economy Wide-Material Flow Accounting**, provides a systematic and complete overview of the resource taking place within a national environment usually considering direct (directly connected with the economic process through entering or leaving flows), indirect and unused flows (materials flows connected to the upstream exploitation of resources and the processing and use of materials but not directly entering the national economic activity). Decisions related to national waste management and resource conservation policies, the integration of trade, economic, and environmental policies, and the creation of action plans and strategies for sustainable development can all benefit from the use of this macro-level analysis.

On the other hand, applying MFA at the **meso level** allows for more granular tracking and analysis of material flows within the economy, differentiating not only between individual or material categories but also between industries or production branches. This makes it possible to conduct a more targeted problem analysis that is particular to the relevant material, industry, or branch and can be utilised to support management and decision-making that is material, industry, or branch specific. It provides a foundation for determining relevant MF and RP indicators and helps in the identification of material waste, pollution sources, and chances for efficiency gains in particular industries.

Additionally, when MFA is used at the **micro level**, MFA offers in-depth data for particular decision-making processes at the business (company, firm, plant), local (city, municipality, ecosystem, habitat, river basin), or related to particular materials or products level. In addition to supporting firm-, area-, and material-specific decision making and management. Groups of chemicals or specific compounds can be tracked by business and micro level MFA, they can also examine the material flows generated by the production and use of individual product. It also makes it possible to track how well economic and environmental performance are aligned at this level.

As a result, the MFA focus could be lead on a specific chemically defined substances (ex. Cadmium, carbon or carbon dioxide flows), specific materials (ex. Glass flows) or bulk material (ex. Steel and steel scrap flow within an economy). Thus, MFA encompasses all solid, gaseous and liquid materials treated by humans and all related handling and transport systems excluding bulk water, air consumption. These last exceptions are due to the enormous mass flows to be considered that could lead to more complex and time-consuming analyses. Accounts for these flows are more likely to be presented separately through different indicators.

Proceeding with the analysis, towards the conclusion and throughout the intermediate phases of the analysis, quantitative measures play a crucial role in fulfilling diverse objectives such as description, evaluation, and comparison related to treated substances or material flows, encompassing all their aspects. Given this set of purposes, the indicators employed in a Material Flow Analysis (MFA) study become instrumental in unveiling hidden factors of a real phenomenon, providing valuable insights, and fostering policy integration and coherence to facilitate decision-making processes. Therefore, the set of material flow indicators is extensive and their selection is contingent upon factors as the specific material under consideration, the identified needs and the requisite level of detail.

The prevalent indicators categories utilized, aligning with the materials balance scheme, encompass **input, consumption, balance and output indicators**. These indicators offer a comprehensive framework for analysis and can be interlinked or presented in conjunction with additional indicators to provide a well-rounded depiction of the issue under consideration. Furthermore, there is the option to formulate resource productivity indicators, which can parallelly complement those delineating capital or labour productivity.

Correspondingly, throughout the assessment, whether involving indicators sets or internal sub-flows, the predominant unit of measurement employed is (metric) tonnes per year (t/a).

To conclude, one crucial function of Material Flow Analysis's (MFA) is to present its results in a way that is customised to users' individual needs. A certain degree of simplification is often necessary, requiring a careful balancing act between an indicator's statistical precision, analytical robustness, and scientific coherence, as well as its applicability to users and policies. As a result, the indicators, essentially representing the "best knowledge available”, should be seamlessly integrated into comprehensive information systems like databases, accounts, and monitoring systems. This ensures a holistic understanding of the subject matter and enhances the utility of MFA in various contexts.

2.2 Economy–Wide Material Flow Accounting

Moving forward on the study, this paragraph is dedicated to the principle sub-methodology of the MFA employed for the study, the Economy-Wide Material Flow Accounting. The Economy-wide Material Flow Analysis (EW-MFA) stands as a powerful and comprehensive methodology designed to discover the intricate material dynamics that underlie entire economies. The approach often integrates various modelling techniques to handle the complexity inherent in a macroeconomic analysis, ensuring that the results are both accurate and meaningful.

The EW-MFA provides an aggregate overview, in tonnes, of annual material inputs and outputs of an economy including domestic resource extraction, imports and balancing items (inputs) as well as domestic releases to the environment, exports and balancing items (outputs) as showed in **Figure 3** (Eurostat, 2018, p. 12)**.** It’s also possible to account for upstream or downstream flows related to imports and exports (such as resource requirements or emissions).

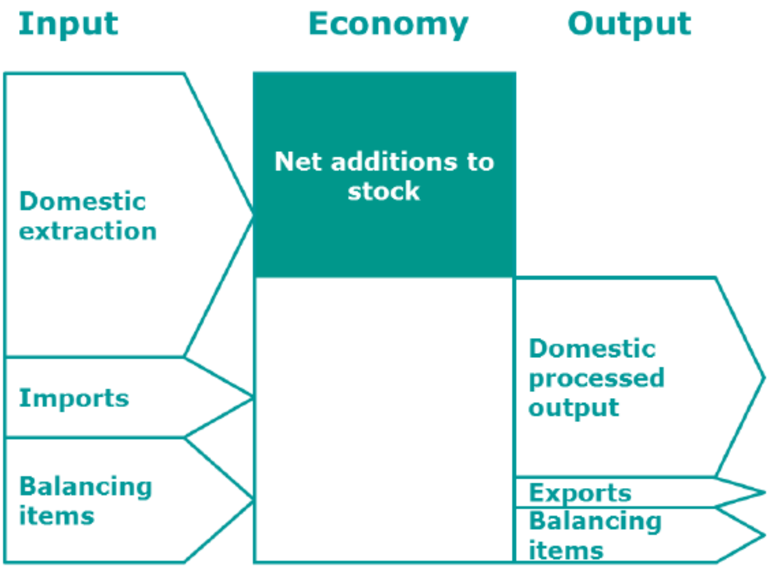


Figure 3. General structure of EW-MFA

Compared with the MFA, that serves as a powerful tool for dissecting material flows within specific systems or sectors offering a detailed examination of inputs, outputs, and stocks, the Economy-wide Material Flow Analysis (EW-MFA), in contrast, broadens the lens to encompass entire economies. EW-MFA extends its reach beyond sector-specific boundaries, capturing the comprehensive material flows associated with national or regional economic activities. The objectives of EW-MFA are adapted towards understanding and evaluating resource use efficiency, environmental impacts, and overall sustainability at a larger scale.

The level of aggregation is a crucial factor distinguishing the two methodologies. MFA allows researchers the flexibility to choose the analysis scale that best suits their research question or system of interest. This flexibility enables more focused and in-depth analyses of material fluxes inside confined boundaries. On the other hand, EW-MFA aggregates material flows at the macroeconomic level, necessitating comprehensive and detailed national or regional economic data. This broader approach allows a holistic assessment of the overall material metabolism within an economy.

Moreover, the data requirements further underline the disparities between MFA and EW-MFA. MFA, depending on its scale, may require detailed data on material inputs, outputs, and stocks within a specific system. In contrast, EW-MFA demands comprehensive economic data, encompassing production, trade, consumption, and waste generation across various sectors of an entire economy. For these reasons, the EW-MFA may require sophisticated modelling technique to handle the major complexity of a comprehensive macroeconomic analysis in which data with higher level of aggregation are requested.

Nevertheless, the detailed purpose is to offer a comprehensive understand of how materials progress through the diverse stages of production, consumption, and waste generation at the macroeconomic level. In doing so, EW-MFA endeavours to educate and assist policymakers, researchers, and stakeholders in formulating decisions that advance sustainable resource utilization and environmental conservation on a broader scale.

EW-MFA generates valuable insights into the environmental implications of a nation's or region's economic activities. It sheds light on resource use efficiency, material productivity, and the interconnectedness between economic growth and environmental impact. The results of EW-MFA are instrumental in guiding policy decisions, fostering sustainability, and encouraging a more conscientious approach to resource management on a national or regional scale.

In the **Figure 4** (Eurostat, 2001, p. 12) below is presented one of the exploded views of the specific general flow headings. In particular, analysing the inputs and outputs showed in Figure 3, the "Material domestically extracted" can be disaggregated into fossil fuels, metal ores, industrial minerals, construction minerals and biomass. Each of these groups can be further broken down into, for instance, fossil fuels into fuel types or biomass into timber, agricultural harvest, fish catch, etc. Moreover, in order to measure material inputs and outputs consistently, is critical to include in the various calculation the **"Indirect flows**" directly related to the physical upstream material flows associated to imports and exports. Another significant feature for the analysis is to consider the **"Domestic Unused extraction"** meaning the movements of the unused materials associated with the extraction of raw materials, domestically and abroad.

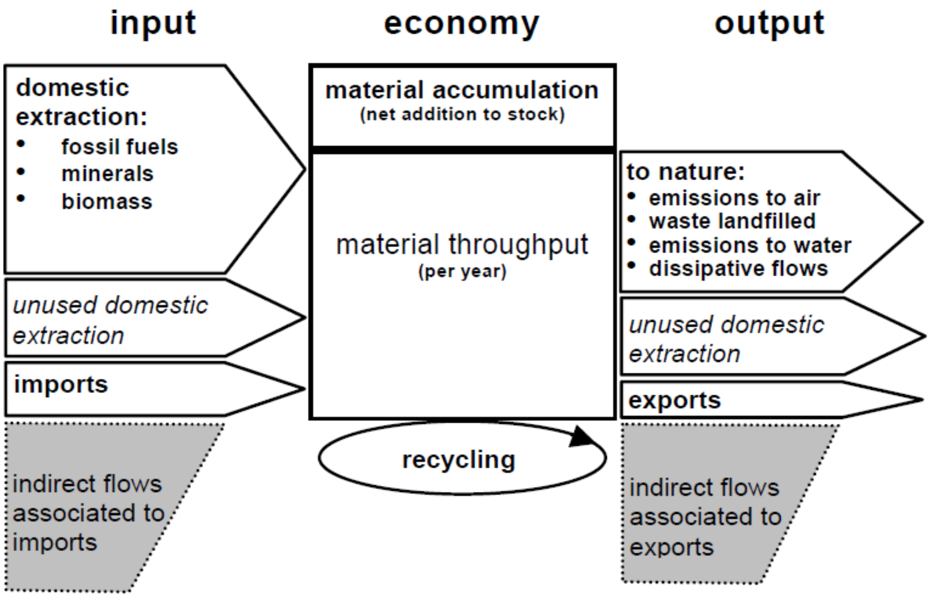


Figure 4. Economy-wide material balance scheme (excluding air and water flows)

In conclusion, Economy-wide Material Flow Analysis (EW-MFA) serves as essential in the study of material dynamics at the macroeconomic level. By offering a comprehensive view of material flows within entire economies, EW-MFA contributes valuable insights that are crucial for guiding sustainable resource management, informing policy decisions, and promoting a holistic approach to environmental conservation.

2.2.2 Main Categories of Flows

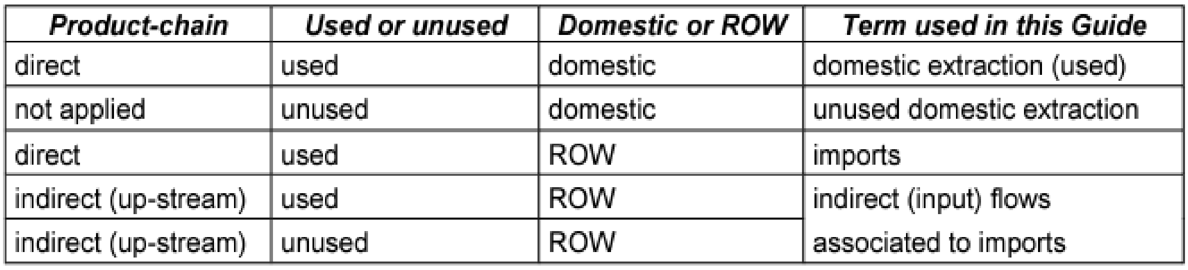
The main categories of flows included in an EW-MFA analysis are defined and described in this chapter. First, some relevant dimension for categorising flows and, related to them, indicators must be introduced:

- The territorial dimension used to indicate the unique pair (Origin-Destination) of a flow, related to the economy, which could be **"Domestic"** or "**Rest Of the World (ROW)";**
- The product chain to indicate whether a flow is directly observed or the result of calculation of up-stream material requirements and it could be evidenced by the terms "**Direct**" or "**Indirect**".

- The product dimension that indicates whether or not the input flows enter or not an economic system, “**Used**” or “**Unused**”. In the case of output flows the two definitions are “**Processed**” or “**Non-processed**”.

Is important to note that the “Domestic” flows represent materials extracted from or released into the national environment, while “Direct” flows represent materials physically entering the national economy as an input. In addition, the term “Used” refers to an input for use in any economy and, as a result, all direct flows have this characteristic, however not all used flows are direct, because some of them are indirect. For instance, the raw materials used in the rest of the world to produce products that are then imported by the economy for which the accounts are made. Furthermore, materials that are taken out of the environment with no plan to use them are known as “Unused” flows. Excavated rock and soil from building projects or leftover material from mining are two examples.

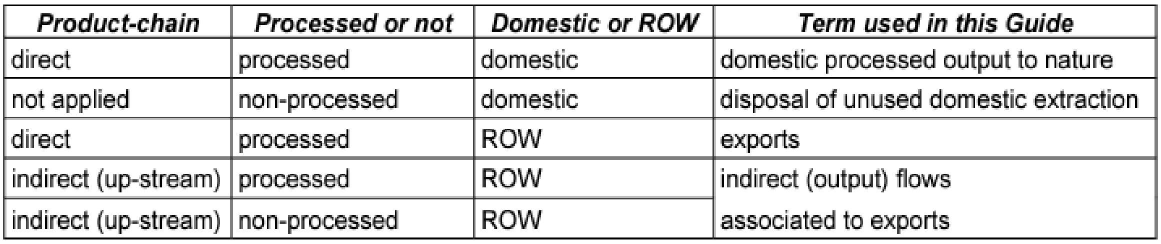
The next to tables, **Figure 6 and 7** (Eurostat, 2001, p. 17,18) contain the summarization of the potential input and output flow combinations that could appear in a EW-MFA analysis with the relatives referring terms.



Product-chain	*Used or unused*	*Domestic or ROW*	*Term used in this Guide*
direct	used	domestic	domestic extraction (used)
not applied	unused	domestic	unused domestic extraction
direct	used	ROW	imports
indirect (up-stream)	used	ROW	indirect (input) flows associated to imports
indirect (up-stream)	unused	ROW	

Figure 6. Summary of terminology for material input categories.

In contrast, for output flows, the distinction between the "Domestic” or” ROW" flows refers to the destination (rather than the origin, as in the input flows) and, as specified before, the terms “Used” and “Unused" are labelled "Processed” or” Non-processed".



Product-chain	***Processed or not***	***Domestic or ROW***	***Term used in this Guide***
direct	processed	domestic	domestic processed output to nature
not applied	non-processed	domestic	disposal of unused domestic extraction
direct	processed	ROW	exports
indirect (up-stream)	processed	ROW	indirect (output) flows associated to exports
indirect (up-stream)	non-processed	ROW	

Figure 7. Summary of terminology for material output categories.

The following part is related to the awareness of the main flows to be considered while approaching an EW-MFA being conscious of the three dimensions mentioned. The first flow refers to any solid, liquid, and gaseous materials (apart from water and air, recommended to be presented in separate flow accounts for their enormous mass flows) that enter the economy for further use in production or consumption, known as "**Direct (used) material inputs".** It encompasses both raw materials domestically extracted and imports.

Secondly, the **"Unused domestic extraction"** refers to materials that are extracted or transported across a country's borders using technology, but which are not suitable or meant for use. Examples are the rock and dirt that are excavated during construction and not used elsewhere.

Equally important are the **"Outputs to the environment"** defined as material flows that enter the national environment during or after production or consumption processes. Emissions into the air and water, waste that is landfilled, and materials that are used dispersively (such as fertiliser or thawing materials) are examples of these outputs. The disposal of domestically extracted material is another aspect of these outputs. Moreover, is important to mention the **imports**, encompassing the materials that are imported into the economy from other regions or countries; the **exports,** materials produced domestically but exported to other nations or regions fall under this category; the **material recycling flows** represent the amount of waste materials that are collected, processed, and reused as raw materials in the economy; the **waste generation,** industrial and household waste generated throughout the manufacturing and consumption processes.

An essential section must be dedicated to the role of **indirect flows,** clearly explained into the following guide (OECD, 2008). Specifically, in EW-MFA only flows that cross the system boundary of the economy are recorded. On the input side, the upstream production of resources that are imported for use in an economy is linked to the generation of residuals (pollution, waste) and unused materials that remain abroad. On the output side, indirect flows are defined as the upstream material input flows associated to exports but are not physically exported. These indirect flows of materials take into account the life-cycle dimension of the production chain but are not physically imported. Their environmental consequences occur in countries from which the imports originate. Moreover, they can only be calculated after the accounts for direct used materials. Specifically, in order to determine their values two main distinguished components are defined, one related to the up-stream indirect flows expressed as the **Raw Material Equivalents (RME)** (1), it represents the used extraction that was needed to provide the products, of the imported or exported products. The other components is related to the up-stream indirect flows of the unused extraction associated to the RME (2). The following chart, shown in **Figure 5** (Eurostat, 2001, p. 20), illustrates how these two components should be taken into account when calculating indirect flows.

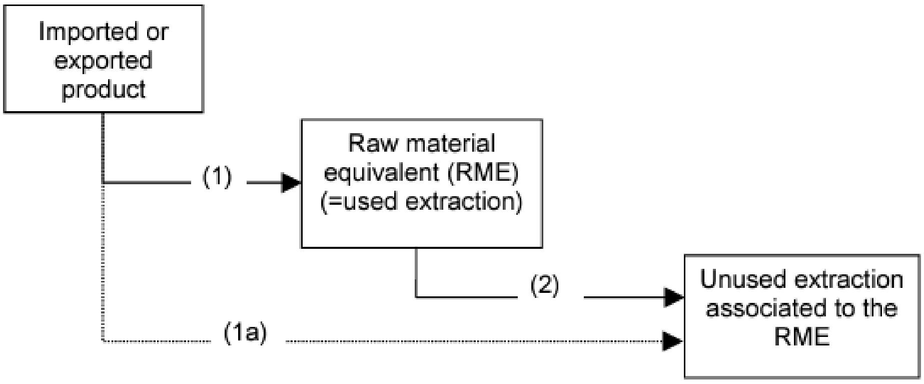


Figure 5. Indirect flows calculation

Given these points, to conclude this paragraph, is essential to talk about a particularity of EW-MFA, **the balancing items (BI)** (Eurostat, 2018, p. 25). Balancing items enable the balancing of material input and output related to a national economy. Two groupings of balancing items are distinguishable: first, BI to be added to material input, such as oxygen for combustion processes and respiration, and nitrogen; secondly, BI to be added to material output, such as water vapour from combustion and gases from respiration.

Finally, the following **Figure 8** (OECD, 2008, p. 15) could serve as a sum up of all the major flows introduced that make up the balanced EW-MFA environment.

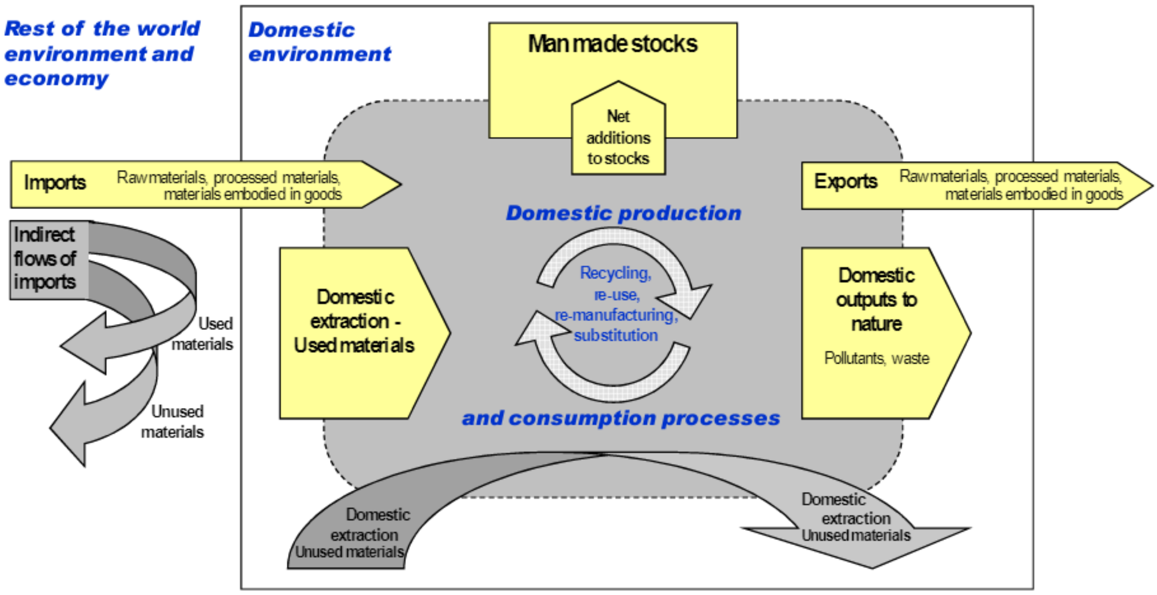


Figure 8. EW-MFA balance flow scheme

2.2.3 Key Indicators

Material flow (MF) indicators are useful tools for explaining how resources are used in the economy, as well as for providing information on how economically and environmentally these resources are used throughout the chain of production, consumption, and disposal. They provide information on:

- The level and characteristics of the physical resource base of an economy or an activity.
- The effects of material resource use on the environment, both domestically and globally.

- The consequences of environment and economic policies on materials use, and the implications of trade and globalisation on national and international material flows.

MF indicators have acquired significance in various countries as material flow and resource productivity challenges have risen up the national and international policy agenda. They are increasingly reported by national and supranational institutions and are often included in environmental or sustainable development indicator sets.

The indicators of Material Flow (MF) usually match the main elements of MF accounts. They show how materials are used in the economy, covering every step from taking resources out of the ground to getting rid of waste at the end. The four primary categories of indicators in accordance with the materials balance scheme are: **input, consumption and balance, and output indicators**. These different indicator categories express complementary data. They can be mixed and matched to provide a more complete picture of the stated problem. They can be used to create efficiency ratios by combining them with economic indicators as "**GDP/DMI" t**o indicate the direct materials productivity.. However, all MF accounting variables can be used as indicators in theory, as long as their significance exceeds beyond of their constituent statistics but in practise, not all of them are useful indicators. Moving forward with the analysis, the following part is devoted to a detailed description of the main categories followed by the most employed indicators for each category (OECD, 2008, p. 78):

- **Input indicators**

Input indicators provide information about the resources mobilised or employed to support economic activity, such as producing of goods and services for export. They are closely related to a country's or region's mode of production. They are sensitive to changes in the volume and patterns of foreign trade, as well as other factors such as a country's natural resource endowment and level of technological development and adoption. The most used input indicators are: Domestic Extraction Used (DEU), Direct Material Input (DMI), Total Material Input (TMI), Total Material Requirement (TMR).

Domestic Extraction Used (DEU)

DEU measures the flows of materials that originate from the environment and that physically enter the economic system for further processing or direct consumption (they are "used" by the economy). They are converted into or incorporated in products in one way or the other and are usually of economic value.

Direct Material Input (DMI)

$$\text{DMI} = \text{DEU} + \text{IMP}$$

equals domestic extraction used (DEU) plus imports (IMP) and measures the input of used materials into the economy, i.e. all materials of economic value that are used in production and consumption activities.

Total Material Requirement (TMR)

TMR includes, in addition to TMI, the upstream indirect material flows associated with imports but taking place in other countries. It measures the total "material base" of an economy. Adding these indirect upstream flows imports are converted into their 'primary resource extraction equivalent. It’s equivalent to the domestic extraction used and unused.

- **Consumption indicators**

Consumption indicators describe the materials consumed by economic activities. They are relatively stable over time and closely correlate with the mode of consumption. The difference between consumption and input indicators is an indication of the degree of integration of an economy with the global economy, that also depends on the size of the economy. The most widely utilized consumption indicators are: Domestic Material Consumption (DMC) and Total Material Consumption (TMC).

Domestic Material Consumption (DMC)

$$\text{DMC} = \text{DMI} - \text{EXP}$$

DMC refers to the subtraction between the domestic used extraction (DEU) plus imports (IMP), that corresponds to the direct material input (DMI) indicator, minus the exports (EXP). It measures the total amount of material directly used in an economy.

Total Material Consumption (TMC)

TMC= TMR – EXP- indirect flows exported

TMC equals to the total material requirement (TMR) minus exports (EXP) and their indirect flows exported. It measures the total primary material requirement associated with domestic consumption activities.

- **Balance indicators**

Balance indicators describe the physical growth of materials within the economy. Either as net flows of materials that are annually added to the economy's stock while accounting for gross additions and removals from the stocks. Or through net flows of products originating from international trade (physical trade flows). Useful additions to consumption indicators are balance indicators. The most often used balance indicators are: Net Additions to Stock (NAS) and Physical Trade Balance (PTB).

Net Additions to Stock (NAS)

NAS= DMI-EXP-DPO

The NAS index measures the physical growth rate of an economy. i.e. the net expansion of the stock of materials in buildings, infrastructures and durable goods. NAS may be calculated indirectly as the balancing item between the annual flow of materials that enter the economy (DMI), minus exports (EXP), minus materials that return to the environment as residuals after use in the economy (domestic processed output: DPO). The NAS could be explained considering that old materials are taken out of stock as buildings are demolished and durable goods are disposed of. At the same time, new materials are added to the economy's stock each year (gross additions) in buildings and other infrastructure as well as materials incorporated into new durable goods like cars, industrial machinery, and household appliances.

Physical Trade Balance (PTB)

$$PTB= IMP-EXP$$

The PTB is a measure of an economy's physical trade surplus or deficit. It is calculated as follows: imports (IMP) less exports (EXP). It is also possible to define physical trade balances that include indirect import and export flows.

- **Output indicators:**

Output indicators describe the material outflows related to production and consumption activities of a given country. They take into account the materials that have been utilised by the economy and are now either exporting or emitting waste and emissions out of it. The most commonly used output indicators are: Domestic Processed Output (DPO), Total Domestic Output (TDO), as well as Exports (EXP).

Domestic Processed Output (DPO)

DPO measures the total weight of materials extracted from the domestic environment or imported, which after use in the economy flow back to the environment. These flows take place along the economic production-consumption chain during the stages of processing, manufacturing, use, and ultimate disposal. Included are emissions to air, industrial and household wastes deposited in landfills, material loads in wastewater and materials dispersed into the environment as a result of product use (dissipative flows). On the other hand, because their wastes are produced in other nations, exported materials are not included as well as Material flows recycled in industry.

Total Domestic Output (TDO)

$$TDO=DPO + UDE$$

TDO equals the domestic processed output (DPO) plus unused domestic extraction (UDE). It represents the total quantity of material outputs to the environment caused by economic activity.

Direct Material Output (DMO)

$$DMO = DPO + EXP$$

The sum of DPO and exports (EXP). This parameter represents the total quantity of direct material outputs leaving the economy after use either towards the environment or towards the rest of the world.

Total Material Output (TMO)

$$TMO = TDO + EXP$$

TMO equals to total domestic output (TDO) plus exports (EXP). Total Material Output (TMO) includes also exports and therefore measures the total of material that leaves the economy.

To provide a clearer understating of enlarged picture, in **Figure 9** (OECD, 2000, p. 18), a comprehensive and integrated assessment is presented, incorporating both material flows introduced in the chapter 2.2.2 and the key indicators newly introduced.

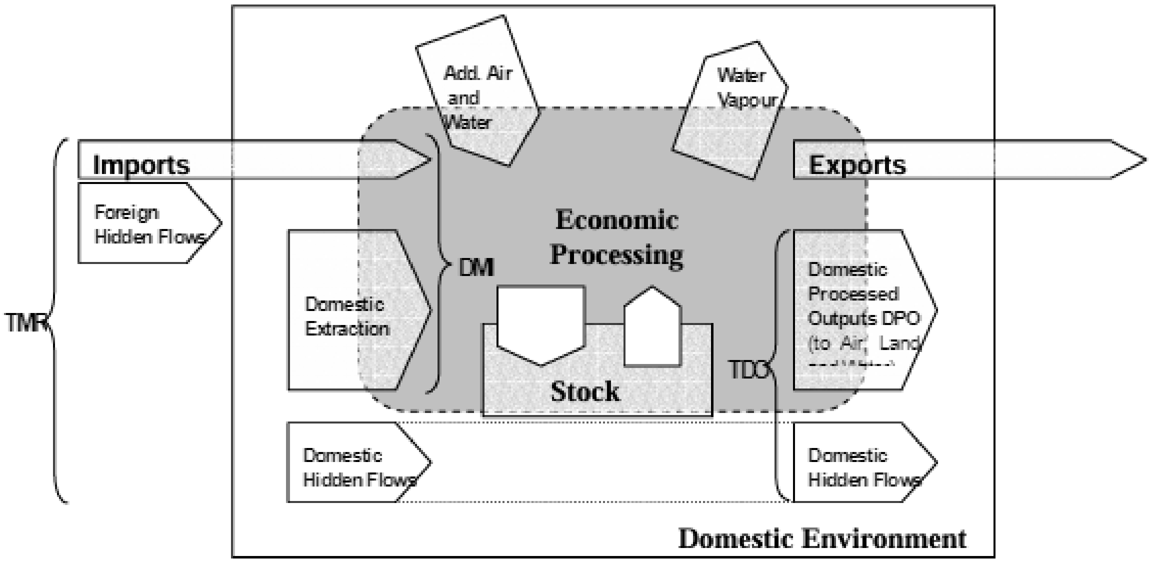


Figure 9. Aggregate material flow balances

In the final analysis, the indicators discussed in the text serve as proxies for the overall environmental impact associated with material use in production and consumption. The main methodology is based on the assumption that sooner or later every material input becomes an output in the form of waste or emissions, and that measuring the inputs therefore gives a rough approximation of the overall environmental burden However, these indicators do not reflect specific environmental impacts. They are valuable for providing an overview of material and energy flows, highlighting key trends, and supporting broader policy goals but their significance is maximized when used alongside indicators of resource productivity, intensity ratios, and trade-related indicators. Moreover, the information value increases when associated with objectives in national sustainable development strategies or circular economy programs, showcasing the materials mix of an economy and the relative weight of different industries in materials use.

2.2.4 The Stepwise Approach

In the pursuit of implementing Economy-Wide Material Flow Accounting (EW-MFA), a systematic and stepwise approach is indispensable. The journey begins with a comprehensive understanding and in-depth study of the EW-MFA methodology, laying the groundwork for subsequent stages.

Following this, a critical decision is made regarding the sector and the specific substance or material in which to apply the methodology, a pivotal choice that guides the entire process. Subsequently, extensive research is conducted into the composition and decomposition of the specific material under consideration, providing insights into its origin and transformation throughout the supply chain.

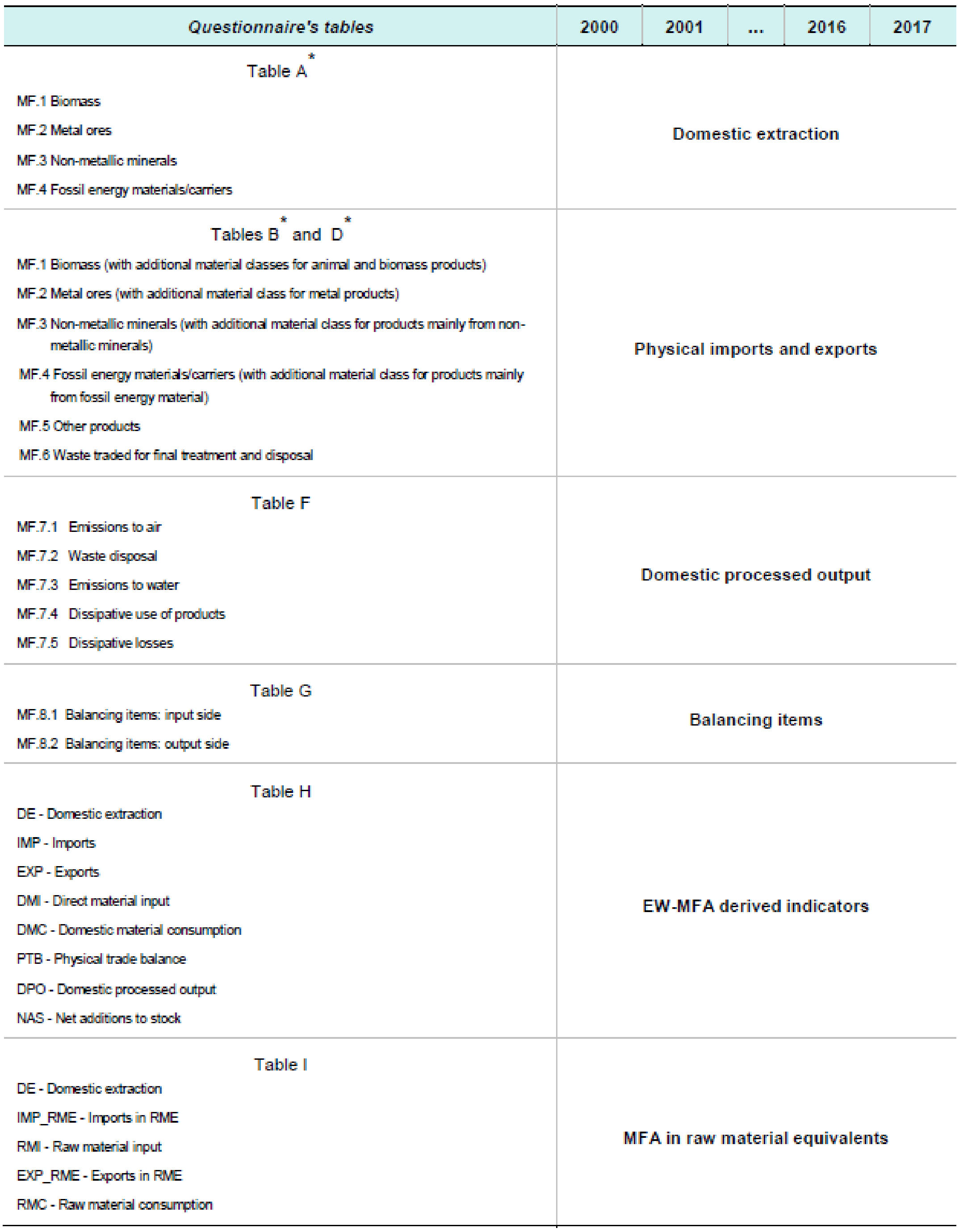
The next crucial steps involve defining the boundaries of the system and identifying the key actors within it. This step is particularly important for the implementation of the simulated model, employing a specialized tool already introduced such as STAN, to represent and visualize the intricate dynamics of material flows and stocks within the chosen sector.

Proceeding to next step, is essential to ensure the accuracy of the model accessing reliable data sources concerning flows and stocks of the material considering also the availability within certain time periods. Finally, the methodology is applied to the selected industry trying to get as more useful insights as possible, with a keen awareness, during the calculations, of data uncertainties and potential errors.

Furthermore, institutions such as the OECD and Eurostat have formulated a series of **modules** designed to ensure consistency in the application of the method. This approach provides invaluable guidance to both national statistical offices and practitioners, aiding in the proper collection and reporting of data. It plays a pivotal role in enhancing the standardization and comparability of material flow information. To attain this comprehensive evaluation and ensure the completion of all technical tables, the series of steps are outlined below ("United Nations Environment Programme", 2021, p. 17):

- **Module 1:** The first module is concerned with Domestic Material Extraction (DE), and Direct Physical Imports (IM) and Exports (EX) of materials.
- **Module 2:** The second module focuses on indirect flows associated with imports and exports, i.e. the Raw Material Equivalents of Imports (RMEIM) and Exports (RMEEX).
- **Module 3:** A third module looks at the output side of the material flow accounts and reports domestic processed output (DPO), i.e. flows of waste and emissions and the gateways through which they leave the economy towards the environment (landfill, soil, water and air).
- **Module 4:** The fourth module measures net additions t4o stocks (NAS) and may contain a stock account of in-use stock (Stock). It allows for closing the material flow balance by linking inputs to outputs and introducing a set of balancing items.
- **Module 5:** The fifth module looks at unused extraction that occurs in the context of domestic material extraction in a target economy or with regard to raw material extraction related to imports and exports abroad.
- **Module 6:** A sixth module would focus on the material flows of different specific industries and would create a true material flow satellite account. It would be related to the full articulation of physical supply and use tables.

In the end, the expected outcome, following the modules, is a set of technical tables as showed in **Figure 12** (Eurostat, 2018, p. 35) presented in a questionnaire form both with annexes, tools and confidential data.



Questionnaire's tables	2000	2001	...	2016	2017
Table A* MF.1 Biomass MF.2 Metal ores MF.3 Non-metallic minerals MF.4 Fossil energy materials/carriers	Domestic extraction				
Tables B* and D* MF.1 Biomass (with additional material classes for animal and biomass products) MF.2 Metal ores (with additional material class for metal products) MF.3 Non-metallic minerals (with additional material class for products mainly from non-metallic minerals) MF.4 Fossil energy materials/carriers (with additional material class for products mainly from fossil energy material) MF.5 Other products MF.6 Waste traded for final treatment and disposal	Physical imports and exports				
Table F MF.7.1 Emissions to air MF.7.2 Waste disposal MF.7.3 Emissions to water MF.7.4 Dissipative use of products MF.7.5 Dissipative losses	Domestic processed output				
Table G MF.8.1 Balancing items: input side MF.8.2 Balancing items: output side	Balancing items				
Table H DE - Domestic extraction IMP - Imports EXP - Exports DMI - Direct material input DMC - Domestic material consumption PTB - Physical trade balance DPO - Domestic processed output NAS - Net additions to stock	EW-MFA derived indicators				
Table I DE - Domestic extraction IMP_RME - Imports in RME RMI - Raw material input EXP_RME - Exports in RME RMC - Raw material consumption	MFA in raw material equivalents				

Figure 10. Outline of the Eurostat EW-MFA questionnaire

2.2.5 Pros, Cons and Limits of the methodology

In this section are illustrated the main advantages, disadvantages and limits of employing the EW-MFA as a tool for assessing material flows. To delve into this topic, it's necessary to outline that the EW-MFA belongs to a family of instruments encompassing a variety of analytical approaches depending on the problem to address and the typology and reliability of the results. Considering these characteristics, we can classify them in two main categories known as "Specification according to economic concepts", which encompass tools focused on general environmental and economic concerns related to the throughput of material, substance or manufactured good at business, economical or national level. On the other hand, the" Specification according to natural science concepts", is primarily associated with specific concerns related to environmental impacts and technology development within certain businesses, economic activities or countries and it's associated with chemical compounds, raw material or manufactured goods. In addition, the family of tools could be further ranked according to two factors, the level of detail of the analysis and the completeness. Taking into account all these aspects, the final classification of all the family of analytical instruments is showed in the following **Figure 10** (OECD, 2008, p. 14) .

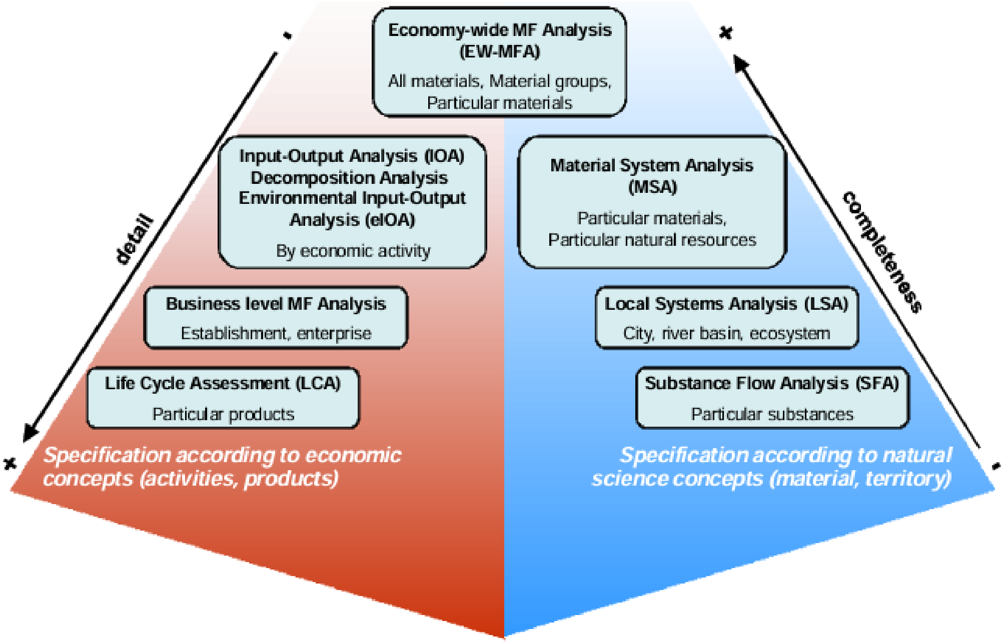


Figure 10. Overall architecture of MFA and related tools

As we can notice the EW-MFA is placed on top of the “pyramid” structure, locating the EW-MFA as a powerful tool being able to assess either raw material, chemical substances, groups of materials throughout their processing chain and including aspects related to their footprint, for these reason through this methodology we can reach out a major completeness level compared to the others. Despite this strength, which can support a broad spectrum of analysis, the method is distinguished by its unique approach that, in contrast to the others, may be limited to and focused on the subject without providing any profound insights, classifying it as one of the instruments with a low level of detail. Therefore, when seeking a broad perspective or overview of a situation, this kind of analysis can be helpful, but it might not be enough for critical choices or actions that call for a more in-depth knowledge of the details arising from similar support instruments.

A brief digression regarding the upstream methodology, the Material Flow Accounting, could be useful to understand the power of a combined approach that could help to overcome this last limitation depending on the specific subject of interest. The following systematic study (Barkhausen, Rosteka, Miao, & Zeller, 2023) is about the literature review of the combination of the Material Flow Accounting (MFA) methodology with another largely used tool, the Lyfe Cycle Assessment (LCA). The results of this publication illustrate the different combination for which the MFA can be employed as a supporting tool. The main methods of combining the two methodologies can be summarized in **Figure 11**, each of them categorized according to their focus and level of integration into the three broad categories: the “Environmentally Extended MFA”, where the MFA results are complemented by a basic environmental assessment and no full LCA is conducted, only environmental inventory data (or emission factors) are used to add an additional environmental dimension to the results; “Systematic Flow Extended LCA”, is similar to the previous category, but focuses on the LCA side. In this case, the stand-alone results of the LCA are the primary goal of the study; Lastly, the “Integrated Modelling”, for which the highest level of integration is achieved, this approach is marked by combined results and/or same system boundaries and/or using the same functional unit or flow object in both MFA and LCA.

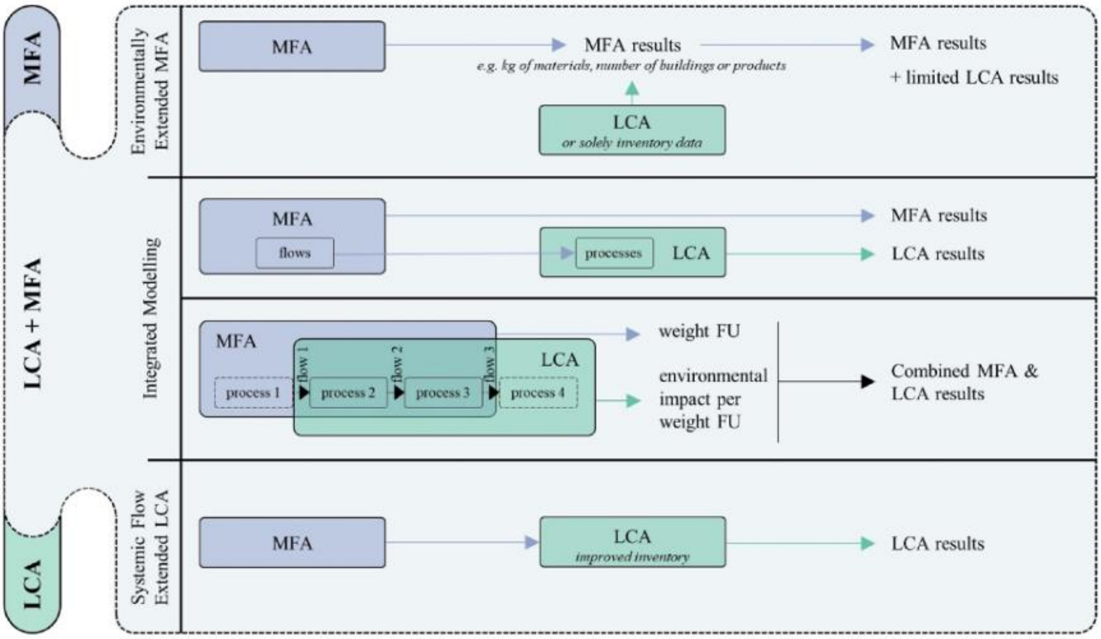


Figure 11. Modelling approaches of prospective studies applying the combination of material flow analysis (MFA) and life cycle assessment (LCA).

Returning to the core examination about the EW-MFA, another consideration should be done about its importance as a valuable tool for policymakers, enabling them to assist decisions regarding resource management and environmental policies. The data derived from this analysis can guide the development of strategies for sustainable development. This is also thanks to the integration of EW-MFA with national accounts ensures consistency and reliability.

One relevant pain point of the EW-MFA is that demands extensive data, including economic, production, trade, and environmental statistics. Obtaining, processing, and maintaining such comprehensive datasets can be resource-intensive and may pose challenges. This point contributes to the overall complexity in addition to the macroeconomic scope of EW-MFA, that encompass the intricate interplay of various economic sectors and need for sophisticated modelling techniques to implement and interpret.

The method can also exhibit temporal and spatial variability, which is a disadvantage. EW-MFA may encounter difficulties in capturing dynamic changes over time and variations across regions, potentially resulting in less accurate assessments.

Regarding the limits is necessary to specify that EW-MFA relies on certain assumptions and simplifications, such as constant process efficiencies and linear material flows. These assumptions may oversimplify real-world complexities, impacting the accuracy of the analysis.

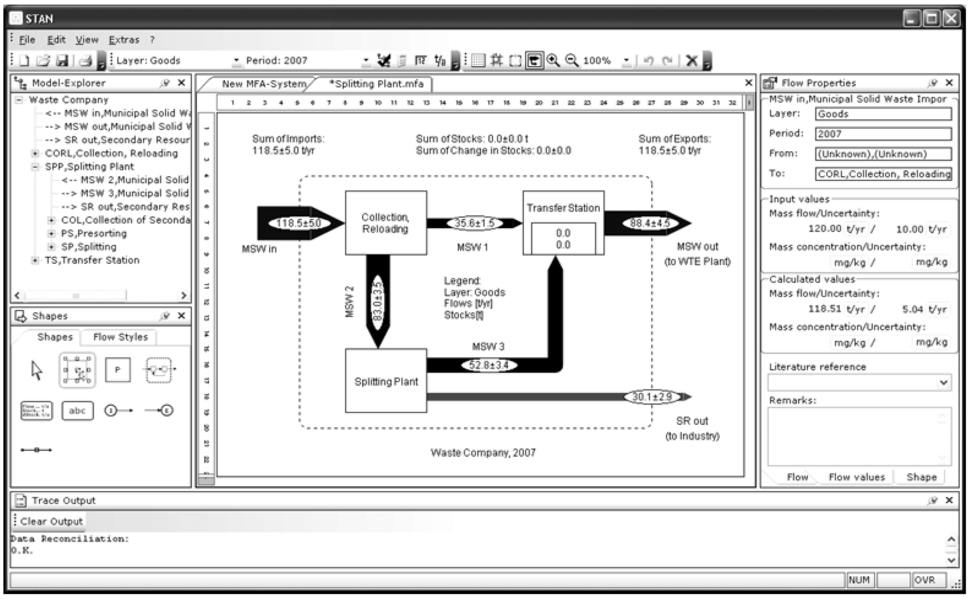
Another limitation arises from the restricted consideration of social and health factors within the scope of EW-MFA. Although the method excels in environmental analysis, its emphasis on material flows may limit its capability to encompass a wider range of social factors. Consequently, the methodology may not fully address the social dimensions of sustainability, including equity and social justice.

In conclusion of this chapter Economy-Wide Material Flow Analysis presents a powerful tool for understanding and managing material flows within economies. Its pros, cons, and limits underscore the need for a nuanced approach. While it provides valuable insights into resource use and environmental impact, the challenges and limitations emphasize the importance of considering contextual factors and using EW-MFA in conjunction with other analytical tools for a comprehensive assessment of sustainability.

2.3 Software STAN and OMAT

The concluding section provides detailed information on the software used for the case study to create the model and maintain system balance with the various material and environmental flows. The first software is named **STAN** (Rechberger & Cencic, 2012), or Substance Flow Analysis Tool, specifically designed to perform material flow analysis by the Research Unit for Waste and Resource Management at Technische of Wien. It was created to address the primary issues that afflict much MFA research, such as how to deal with uncertain or inconsistent data and the fact that numerous software and tools were utilised to carry out a complete analysis.

The principal characteristics of STAN involve building graphical models, through a simple user interface, using several components such as processes, flows, system boundaries and text fields as showed in the **figure 12** (Cencic & Rechberger, 2008, p. 2).



Layer: Goods
Period: 2007

MSW in,Municipal Solid Waste Impor
Layer: Goods
Period: 2007
From: (Unknown),(Unknown)
To: CORL,Collection, Reloading

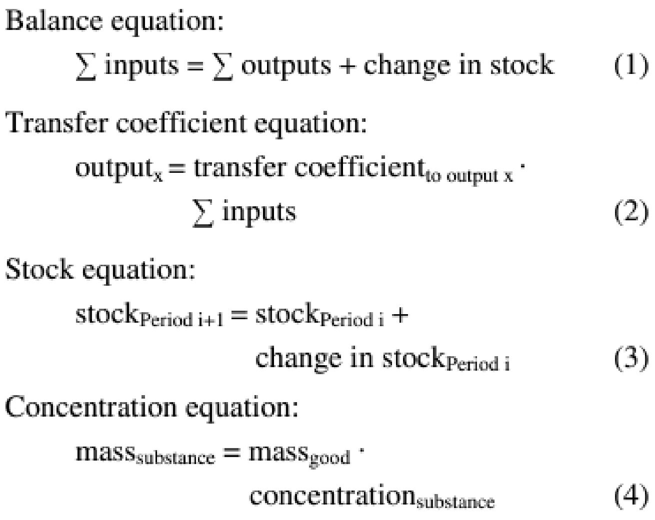
Input values
Mass flow/Uncertainty:
120.00 t/yr / 10.00 t/yr
Mass concentration/Uncertainty:
mg/kg / mg/kg

Calculated values
Mass flow/Uncertainty:
118.51 t/yr / 5.04 t/yr
Mass concentration/Uncertainty:
mg/kg / mg/kg

```
Data Reconciliation:
O.K.
```

Figure 12. STAN graphical user interface (GUI).

The way of working of the STAN algorithm is based on four different types of equations (balance, transfer coefficient, stock and concentration) showed in **figure 14** (Cencic & Rechberger, 2008, p. 4), used during calculation to automatically convert a graphical model made with STAN into a mathematical model. These equations could contain unknown, measured and exactly known (constant) variables.



Balance equation:

$$\sum \text{inputs} = \sum \text{outputs} + \text{change in stock} \qquad (1)$$

Transfer coefficient equation:

$$\text{output}_x = \text{transfer coefficient}_{\text{to output } x} \cdot \sum \text{inputs} \qquad (2)$$

Stock equation:

$$\text{stock}_{\text{Period } i+1} = \text{stock}_{\text{Period } i} + \text{change in stock}_{\text{Period } i} \qquad (3)$$

Concentration equation:

$$\text{mass}_{\text{substance}} = \text{mass}_{\text{good}} \cdot \text{concentration}_{\text{substance}} \qquad (4)$$

Figure 14. STAN calculation algorithm

In order to continue our examination of the tool's features, STAN's primary features let you utilise various input of known data like mass flows, stock, concentrations or transfer coefficients, that may be distributed through different layers (good, substance, energy) and time periods. Through these data the software creates an interconnected database that facilitates the assessment of how substances move through various processes, industries, and environmental compartments and the data may be extracted or exported via the Excel interface. In addition, the software can deal with the challenge of **unknown data** (e.g. internal flows, changes in stocks) or contradictions by utilising and combining the input values, giving an estimation or correction complying with the mass conservation principle. Moreover, it is possible to discover the most reasonable value and acquire information if gross errors are detected using the capacity to estimate a **data uncertainty and STAN's reconciliation capability.** All these features are ensured by a meticulous mathematical framework of intricate equations that underlie both the model and its user-friendly interface. Furthermore, a relevant visualization feature is represented by the capacity to generate a Sankey-style diagram, such as the simple one shown below in **Figure 13** (Lupton & J.M.Allwood, 2017, p. 6), that could be shown, printed, or exported for all the relevant group of data.

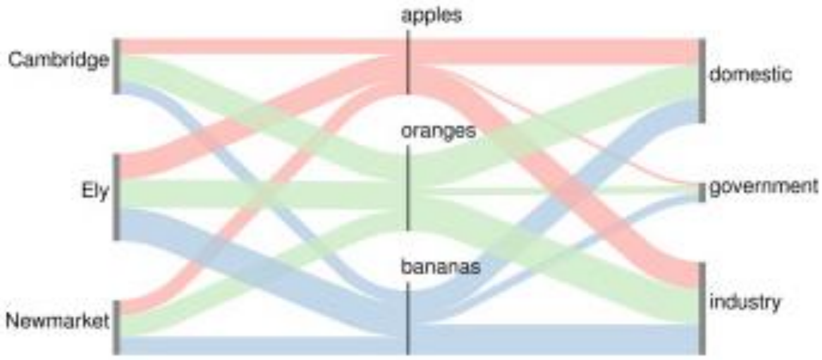
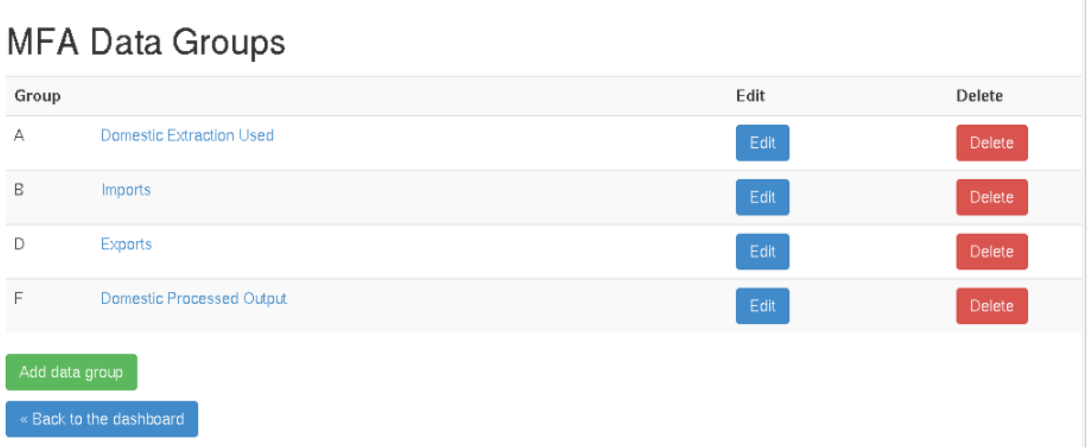


Figure 13. Example of Sankey diagram

Despite all its features, STAN is not without limitations, and a notable constraint lies in its dependence on data availability. The execution of a Substance Flow Analysis necessitates a substantial volume of data, and the precision of outcomes is intricately tied to the quality and comprehensiveness of the input data. In instances where data is not sufficiently comprehensive, the efficacy of the analysis may face challenges. Additionally, due to the intricate nature of Substance Flow Analysis, individuals new to the software might encounter complexities. The learning curve associated with mastering the software could pose difficulties, especially for users lacking a background in environmental accounting or material flow analysis. This limitation underscores the importance of data quality and user expertise in maximizing the utility of STAN for Substance Flow Analysis.

As demonstrated above, the STAN software can rely on several intriguing characteristics, but it requires careful consideration during the data collection, handling of inconsistent data and system modelling phases. Nonetheless, by keeping an eye on these details, STAN undoubtedly makes it possible to identify environmental hotspots and material flow system intervention points. These data are invaluable for policymakers looking to implement targeted interventions to improve resource efficiency and reduce environmental impact.

The alternative software goes by the name **OMAT**, an acronym for Online Material Flow Analysis Tool. It bears notable similarities to STAN, however, being an online platform, OMAT is compatible with any operating system. This feature, combined with the tool's structure and emphasis on collaborative work, enables seamless sharing of datasets among researchers. Consequently, it facilitates concurrent work on the same dataset, fostering efficient collaboration. Another significant feature provided by the software is to make it simple for researchers to store a dataset for an Economy-Wide EUROSTAT-based MFA or for a dataset that has their own data groups defined as showed in **Figure 14**.

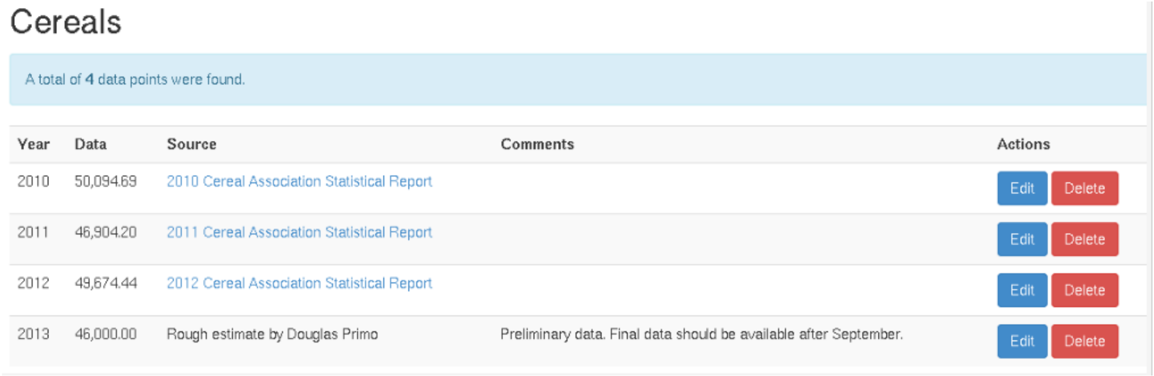


MFA Data Groups

Group		Edit	Delete
A	Domestic Extraction Used	Edit	Delete
B	Imports	Edit	Delete
D	Exports	Edit	Delete
F	Domestic Processed Output	Edit	Delete

Figure 14. Examples of MFA data categories, OMAT software

Furthermore, to possess a practical tool that simplifies the logistics of data collection is crucial for effective material flow accounting. This includes functionalities such as tracking sources, offering a dedicated space for comments, and facilitating discussions around each data point. Such features not only enhance the efficiency of the data collection process but also contribute to the overall transparency and organization of the material flow accounting software. This tool becomes an invaluable resource for users, ensuring meticulous record-keeping, and fostering collaboration by providing a platform for detailed discussions on specific data elements as showed in the **figure 15**.



Cereals

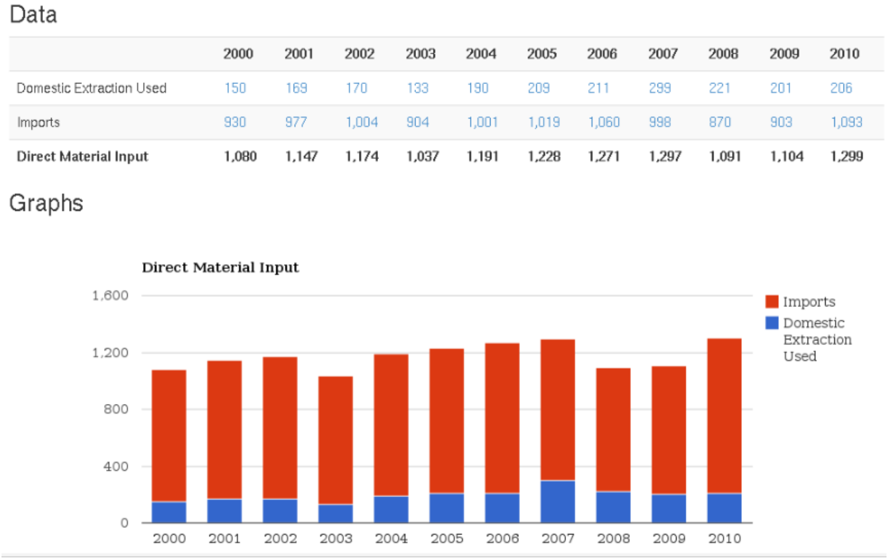
A total of 4 data points were found.

Year	Data	Source	Comments	Actions
2010	50,094.69	2010 Cereal Association Statistical Report		Edit Delete
2011	46,904.20	2011 Cereal Association Statistical Report		Edit Delete
2012	49,674.44	2012 Cereal Association Statistical Report		Edit Delete
2013	46,000.00	Rough estimate by Douglas Primo	Preliminary data. Final data should be available after September.	Edit Delete

Figure 15. Example of specific detailed material source, OMAT software

In conclusion, one noteworthy feature of the OMAT (Online Material Flow Analysis Tool) is its ability to display key indicators as showed below in **figure 16**. This feature gives to the analytical process a further level of clarity, making it easier for users to see and understand the key signs that are crucial for material flow analysis. The tool's main indicator presentation improves user experience overall and makes it easier to comprehend the complex material flow dynamics that are being studied.

While it may not encompass an extensive range of features, this tool proves to be a valuable asset as a supplementary tool by offering support and enhancing specific aspects of a parallel software. This synergy could ensure that users can benefit from a combined approach, capitalizing on the strengths of both the primary and secondary tools for a more effective and versatile user experience.



Data

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Domestic Extraction Used	150	169	170	133	190	209	211	299	221	201	206
Imports	930	977	1,004	904	1,001	1,019	1,060	998	870	903	1,093
Direct Material Input	1,080	1,147	1,174	1,037	1,191	1,228	1,271	1,297	1,091	1,104	1,299

Graphs

Figure 16. Example of relevant indicators, OMAT software

Chapter 3: Glass case study

3.1 Material overview

This section of the thesis conducts a comprehensive exploration of the indispensable component of our industrial landscape, the glass, delving into its composition, manufacturing processes, recycling mechanisms, and ecological implications. Nowadays, the term "glass" is commonly used referring primarily to silicon oxide-based glass, known as silica glass. This type of glass is extensively employed in the production of containers such as bottles, vases, and glasses, serves as a construction material for stained glass and windows, and is utilized in the creation of decorative elements such as giftware and chandeliers.

The diverse applications of glass stem from its transparency, chemical stability, and versatility. Through the incorporation of specific elements, it becomes feasible to produce glass with varying colours and distinctive chemical-physical properties tailored for different applications. Furthermore, glass can be considered a model material for the circular economy, being 100% recycled and endlessly reproduced without losing its properties and without the need to add additives or reagents.

Delving deeper into its composition, the main type of glass , the soda- lime, (Schmitz, Kamiński, Scalet, & Soria, 2011, p. CH. 2) is primarily composed of 70% Silicon dioxide (SiO2) (Silica), derived from **sand**, roughly 15% of Sodium oxide (from **soda ash**) (Na_2O) and 12% of Calcium oxide (CaO), derived from **lime stone**, and 3% of other compounds, it undergoes a transformative journey from raw materials to the finished product. Specifically, Sodium oxide is used to reduce the melting point of Silica, while the Calcium oxide (CaO) is used as a stabilizer, it modifies the viscosity and increases the durability of the glass.

The intricate manufacturing process involves melting, shaping, and annealing, yielding a material celebrated for its transparency, durability, and diverse applications. However, the story extends beyond its creation, encompassing the crucial realm of recycling, where glass demonstrates unparalleled sustainability. The recycling processes associated with glass, often more environmentally advantageous than those of other materials, being one of the contribute significantly to waste reduction and resource conservation. This section aims to unravel the complexities of glass recycling and, subsequently, to add a quantitative dimension to the study of material flows in this sector. By examining factors like recyclability, environmental impact, and product life cycle through the lens of MFA, we seek to underscore the intrinsic value that glass holds in the realm of sustainable materials.

Specifically, as mentioned above, glass mainly consists of silicon dioxide, better known as sand. Merely molten sand is not suitable to produce bottles. It is necessary to use a melting agent, such as **potassium oxide (K_2O)** or **sodium oxide (Na_2O).** One solidifying ingredient needed to produce glass that can be processed is calcium oxide (CaO). It has been widely accepted since 1830 that a mixture of six parts sand, one part soda, and one part calcium works well. Nowadays, barely any glass packaging is produced using only raw materials. Recycled glass (known as **cullet**: pulverized glass dust**)** is increasingly being used in place of raw materials. Suffice to say that **90%** recycled glass cullet can be used to create a new green bottle without sacrificing any aspect of shape, colour, or quality.

However, the quality control standards for recycled glass cullet are stringent, requiring strict adherence to the glass manufacturer's specifications. Ensuring compliance with these standards involves meticulous scrutiny of the cullet's composition to guarantee the absence of undesirable elements such as heat-resistant materials, metals, plastics, porcelain, stones, and biological materials. These elements are subject to rigorous regulations due to their potential to compromise the integrity and performance of the final glass product.

Furthermore, the recycled glass cullet must conform to specific criteria beyond merely excluding contaminants. Factors such as size, composition, colour, and other material characteristics are carefully evaluated. Achieving the proper size ensures optimal integration into the manufacturing process, while the desired composition and colour are essential for maintaining the quality and appearance of the final glass product. A meticulous attention to detail is required in the recycling and manufacturing processes to produce glass products that meet industry standards and consumer expectations.

The purer the cullet, the more of it can be used to make new glass. As a rule, derived from (Testa, Malandrino, Sessa, Supino, & Sica, 2017), a 10% increase of cullet into container glass melting mass decreases the energy consumption by about 2–3% and CO_2 emissions by 5%, as the substitution of raw materials containing carbonate also reduces CO_2 process emissions released by decarbonation. Indeed, melting 1 t of cullet saves not only around 1.2 t of virgin raw materials, but cuts overall CO_2 emissions (direct and indirect) by around 60%. Considering that the production of glass is energy intensive and results in significant global CO2 emissions, contributing around 95 Mt of CO2 worldwide emissions and 22 Mt in Europe [7] in 2022.

Delving deeper into the study of the closed loop lifecycle involved in the glass production and collection, below in **Figure 17** (Westbroek, Bitting, Craglia, JoséM.C.Azevedo, & JonathanM.Cullen, 2021, p. 3) are delineated the main steps that characterize this process.

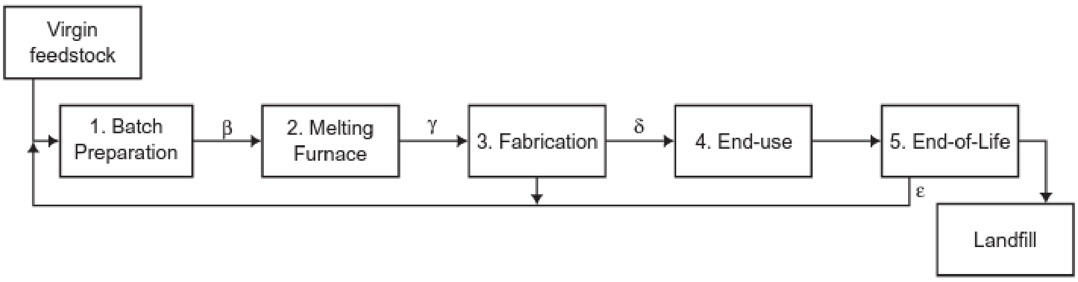


Figure 17. Glass lifecycle

In the first phase, **"Batch preparation",** soda ash, limestone, silica, and cullet are mixed together. The recycling rate (ε), according to a study (Butler & Hooper, 2019 , p. 151-165) about the global container glass is approximately 30-35%: They have assumed that all the container glass at the end of life are used to make new

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[7] Statista, Emissions from glass production worldwide and in Europe in 2022

containers meanwhile they affirm (Butler & Hooper, 2019 , p. 307–322) that end-of-life cullet is not significantly used in flat glass production).

During the **“Melting furnace”** phase the previous prepared batch is heated at high temperature around 1500°C to reach the right melting temperature and reach the final state of glass. The yield of melting (β) was estimated at approximately 85% either flat and container glass melting.

The **“Fabrication”** phase is crucial to transform the unshaped molten glass in the desired flat or container glass through processes such as blowing, pressing, or drawing, followed by annealing to enhance its structural integrity. Globally, 71 Mt of flat glass and 79 Mt of container glass were produced in 2014 with a yield of (γ) around 85% for flat glass and 90% for container glass.

Moving forward, the **"End-use"** phase becomes instrumental as the final products find allocation to specific end-uses within respective industries (δ). To illustrate, flat glass predominantly caters to the construction and automotive sectors, where its unique properties are used for architectural purposes and automotive applications. Conversely, container glass is primarily designated for utilization across various sectors beyond construction and automotive, highlighting its versatile applicability in packaging, food and beverage, and numerous other industries. This phase underscores the tailored distribution of glass products to meet the distinct needs of diverse industries, thereby optimizing the functionality and purpose of the manufactured glass items.

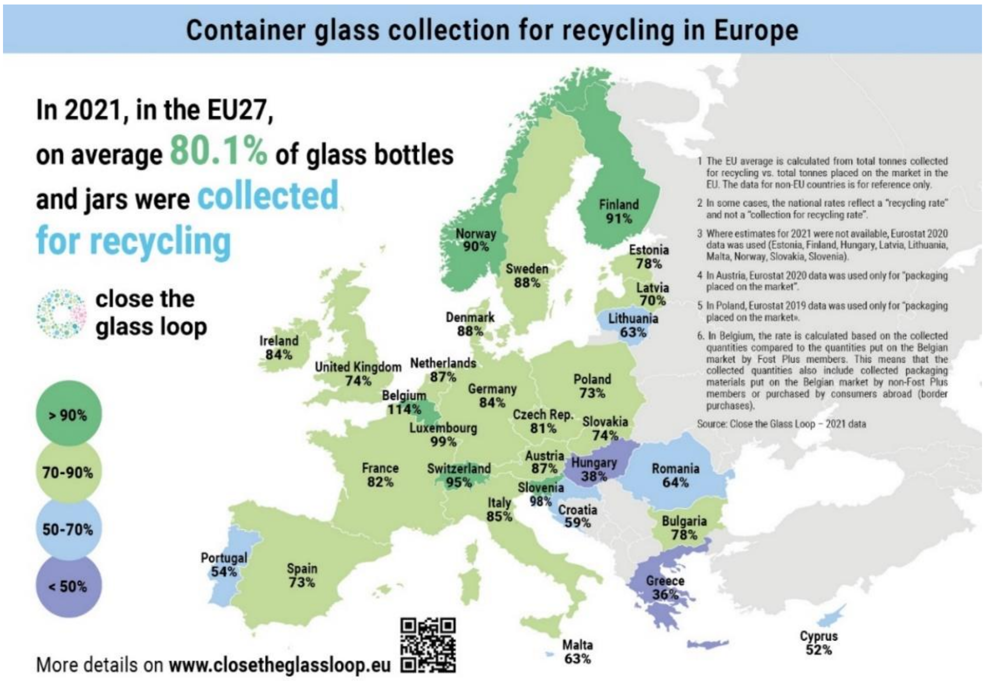
Ultimately, the **"End of Life"** stage assumes a lot of significance in the glass life cycle, serving as a critical juncture to determine the fate of the material. At this stage, careful considerations are made to assess whether the glass is destined for recycling, landfill disposal, or incineration. This decision-making process underscores the importance of responsible waste management practices and aligns with broader environmental objectives. The "End of Life" stage underscores the commitment to sustainability, ensuring that glass products are managed in a manner that minimizes their environmental impact and maximizes resource efficiency.

Giving special attention to the recycling part is crucial to make sure things stay consistent and of high quality, aiming for the best results. It all begins by **collecting** and **sorting** the glass properly. Things like well-organized collection rounds, good maintenance, and making sure suppliers are trained are really important. Also, for things to get started the right way, it's key to store the collected glass properly and in an organized manner. This simple approach highlights how important it is to be careful and efficient when recycling, helping to make sustainable practices work well.

It's crucial to emphasize the significance of the **cleaning** process to get rid of any impurities. This step involves removing external contaminants like labels or caps through manual processing or through specific machinery. After the glass is cleaned and sorted thoroughly, it's crushed into small pieces to be recognized as cullet. Cullet becomes the primary raw material for the new glass manufacturing process bringing all the benefits listed above such as the use of fewer virgin materials, in addition to energy and emission reductions.

Before it's reintroduced into manufacturing, the cullet undergoes meticulous checks to ensure the highest quality trough removing all metals, ferrous as well as non-ferrous materials. Furthermore, a complex phase includes an optical sorter in order to remove ceramics, stone and porcelain from the flow, involving CCD cameras and compressed air valves. Moreover, the cullet is then subject to optical-mechanical colour separation and by means of CCD cameras, the differently coloured cullet is taken from the flow. These careful process guarantees that the recycled material is of the best quality before being used to make new glass products. These represent the fundamental stages that define the manufacturing and recycling processes of glass.

To conclude is necessary to specify that recycling is feasible only for certain types of glass in Europe, including bottles and jars, identified by these following codes as **GL70** clear glass, **GL71** green glass, and **GL72** brown glass. Indeed, materials like crystal glasses, lenses, or glass windowpanes pose challenges for recycling due to the presence of chemical elements, such as lead in crystal glass, rendering them non-recyclable. In **Figure 18** ("Close the Glass Loop", 2022) is showed the average percentage of bottles and jars collected for recycling in 2021 in Europe.



In 2021, in the EU27, on average 80.1% of glass bottles and jars were collected for recycling

1 The EU average is calculated from total tonnes collected for recycling vs. total tonnes placed on the market in the EU. The data for non-EU countries is for reference only.

2 In some cases, the national rates reflect a "recycling rate" and not a "collection for recycling rate".

3 Where estimates for 2021 were not available, Eurostat 2020 data was used (Estonia, Finland, Hungary, Latvia, Lithuania, Malta, Norway, Slovakia, Slovenia).

4 In Austria, Eurostat 2020 data was used only for "packaging placed on the market".

5 In Poland, Eurostat 2019 data was used only for "packaging placed on the market».

6. In Belgium, the rate is calculated based on the collected quantities compared to the quantities put on the Belgian market by Fost Plus members. This means that the collected quantities also include collected packaging materials put on the Belgian market by non-Fost Plus members or purchased by consumers abroad (border purchases).

Source: Close the Glass Loop – 2021 data

More details on **www.closetheglassloop.eu**

Figure 18. Container glass collection for recycling in Europe

The findings indicate that the recycling of this material is notably well-established in most European countries. However, Eastern European nations are trailing behind and must undertake additional efforts to foster a national mindset focused on sustainability and recycling. Nevertheless, it becomes imperative, in the years ahead, for all European countries to intensify their endeavours, aiming to enhance these metrics and achieve the ambitious recycling targets set by the European Union up to 90% by 2030. In the following section, we will explore the specific characteristics and procedures that play a role at the Italian level.

3.2 Italian Glass Industry

In this section, we will focus on the examination of glass under new angles from the Italian point of view, aiming to quantify and provide a clear understanding of its actors and production, energy consumption and emissions generated during its processing.

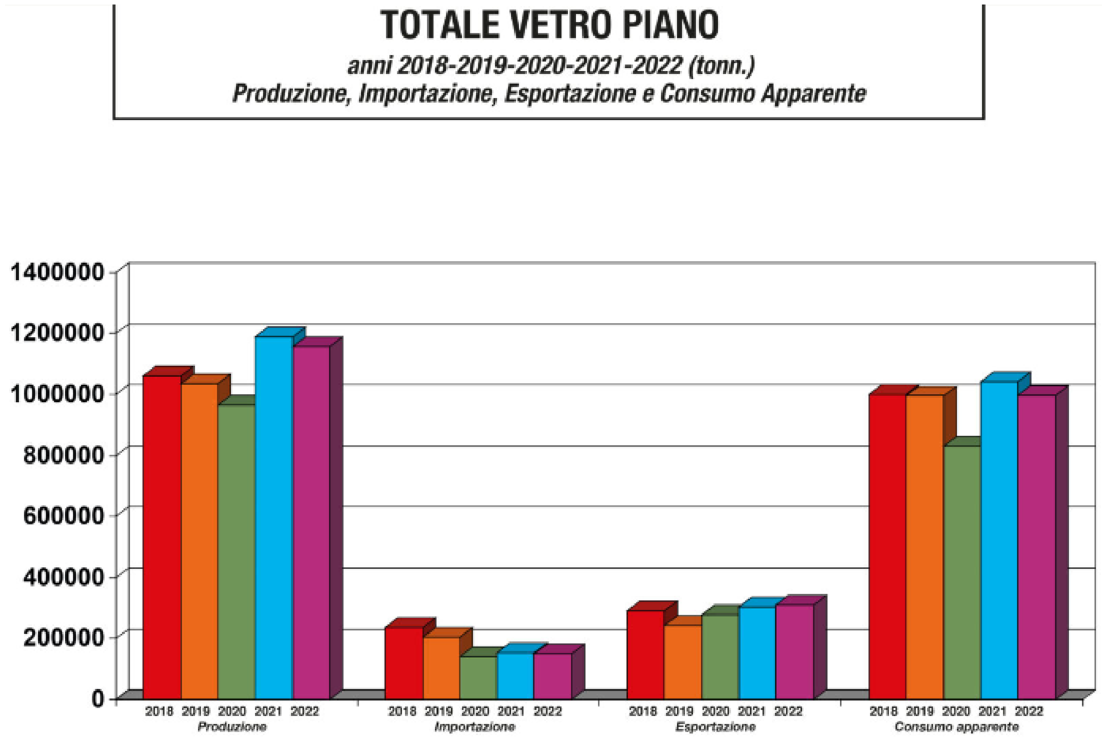
The activities within the Italian glass industry can be straightforwardly classified into two primary categories, as depicted in **Figure 19** (Assovetro, 2021, p. 16): fabrication and processing. Fabrication involves the production of the four main types of glass—**flat, hollow, glass wools and yarns**, and others (e.g., artistic products).

Figure 19. Schematic representation of the Italian Glass Industry

Until 2023, there are a total of 37 Italian companies or groups of companies engaged in the fabrication of flat glass (23.11), hollow glass (23.13), or glass wools and yarns (23.14). The production plants are located 25 in the north, 5 in the centre and 6 in the south. On the other hand, there are a total of 19 processing companies, distributed 11 in the north, 3 in the centre and 5 in the south (CoReVe, 2023, p. 11-12).

Adding further details, the **processing companies** possess authorized facilities capable of converting glass packaging waste into an MPS (Secondary Raw Material), thanks to new sophisticated pollutant sorting machines, suitable for recycling in the production of new glass containers such as bottles and jars. The material exiting the treatment plants, having shed its waste status (End of Waste), is now prepared for the melting furnaces of glassworks that manufacture new bottles and jars for packaging. Thus, the next step involves th**e glassworks companies** mentioned above**,** this is the concept embraced by manufacturers of glass packaging (bottles and jars). Glassworks collaborate with the national consortium CoReVe, and through the principle of shared responsibility, ensure the recycling of glass packaging waste, aligning with a model of a perfect circular economy. The transformed packaging waste, now in the form of MPS, finds a new life in the production of new glass containers, constituting the industrial sector known as 'Hollow Glass.' In this process, waste is indefinitely repurposed without any loss of material.

Continuing the analysis moving on to the products placed in the market, firstly, the **flat glass** sector encompasses pulled sheet glass of raw and float glass. Flat glass finds diverse applications in construction, automotive, furniture, and various other specialized uses. Regarding the flat glass production in Italy and the comparison to 2021, the production in 2022 witnessed a decrease of approximately 3%. Regarding trade, imports experienced a 2.5% decline, while exports saw a 2% increase. The main companies operate distributed throughout the country. The overall statistics for the entire flat glass sector, derived from the cumulative data of the three groups just described, for the 2018-2022 period are as follows in **Figure 20** [8]**:**



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[8] https://www.assovetro.it/dati-di-settore/

Figure 20. Total production, import, export and apparent consumption of flat glass in Italy (2018-2022)

Secondly, **hollow glass** encompasses the manufacturing of glass packaging such as bottles, flasks, and demijohns, as well as bottle ware for pharmaceutical, cosmetics, and perfumery applications. Additionally, it involves the production of food jars and various household articles, including glasses, plates, and table accessories, among others. The main companies operate distributed throughout the country. The last available data about their production during the 2018-2022 period are summed up and presented in the following **Figure 21** [8]**:**

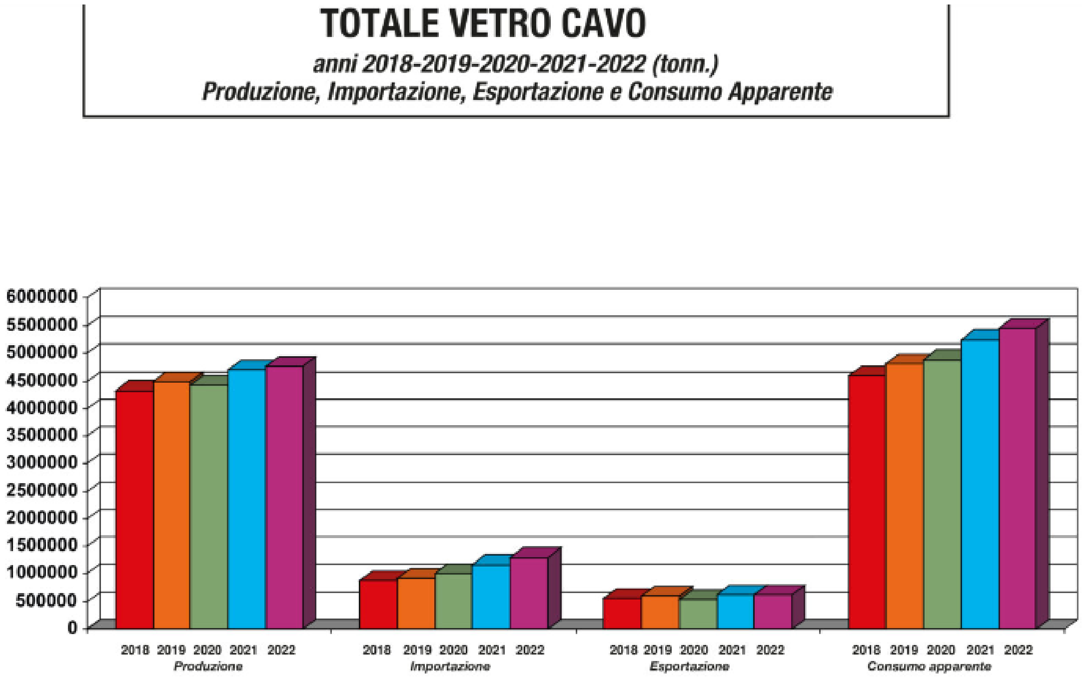


Figure 21. Total production, import, export and apparent consumption of hollow glass in Italy (2018-2022)

Lastly, **glass wools and yarns** are extensively utilized in the construction industry owing to their thermal and acoustic insulation properties. Their application is further attributed to their significant mechanical strength and durability. The main companies are solely located in the north of Italy, and the last available data about their production during the 2018-2022 period are showed in the following **Figure 22** [8]:

LANE E FILATI
anni 2018-2019-2020-2021-2022 (tonn.)
Produzione, Importazione, Esportazione e Consumo Apparente

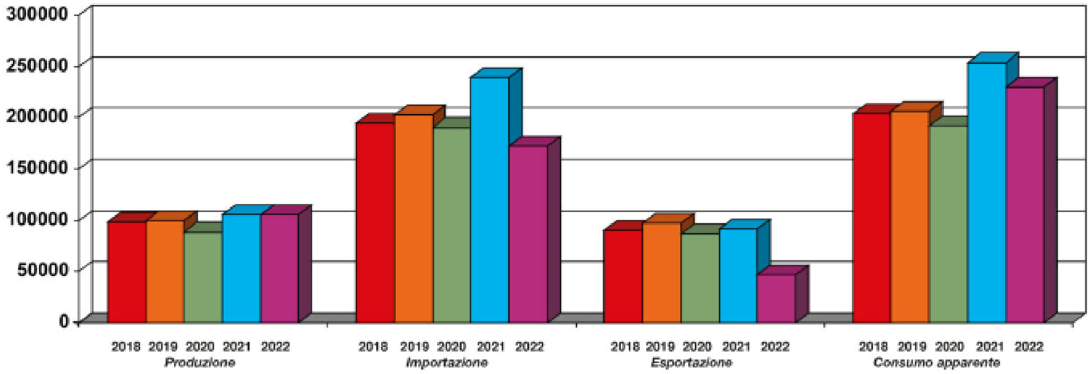
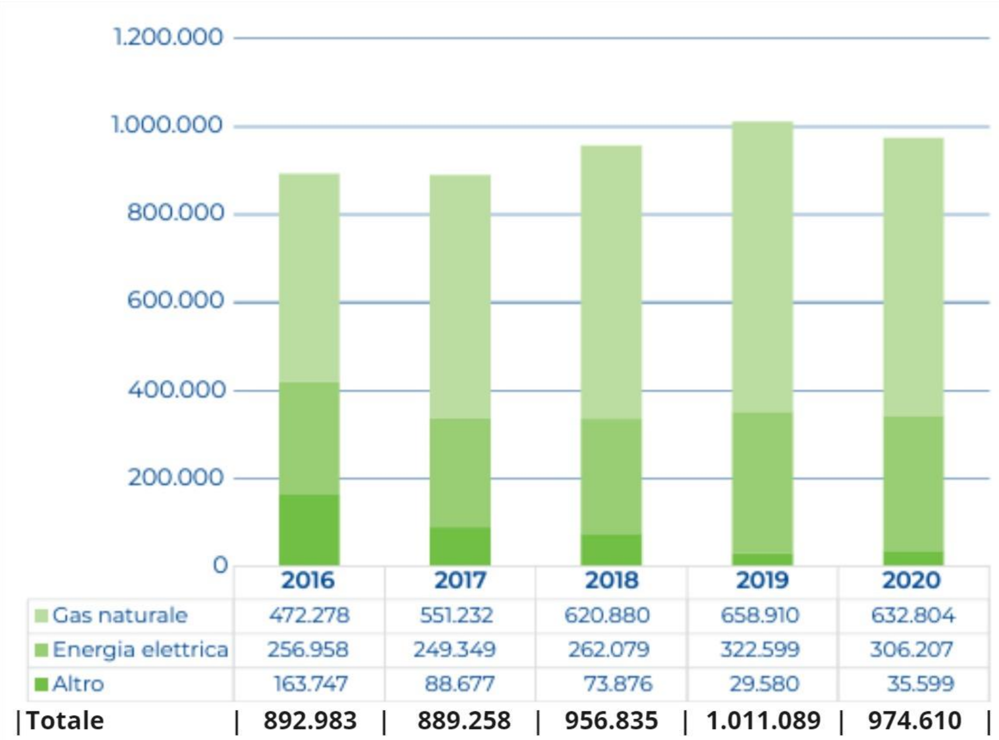


Figure 22. Total production, import, export and apparent consumption of wools and yarns glass in Italy (2018-2022)

Moving forward with the Italian glass analysis, glass production constitutes an **energy-intensive process**, necessitating high temperatures for melting and shaping the material into various desired forms. Unlike some other industries, the consumption of energy in glass production remains consistent and uninterrupted throughout the year, with furnaces rarely experiencing downtime, except for exceptional maintenance or end-of-life situations. The associated energy costs, encompassing both electricity and gas, exert a significant influence on glass production, often exceeding 20% of the total expenses. This has notable implications for the competitiveness of Italian companies relative to their European counterparts.

Despite these challenges, the glass industry has made strides in enhancing its efficiency by continuously decreasing energy consumption per tonne of glass produced. Ongoing investments in projects and research aim to further curtail energy consumption. However, substantial milestones lie ahead to meet the new European decarbonization targets for 2030 and 2050 (Climate Law). Hence, energy consumption serves as a pivotal indicator for the sector, carrying significance in both economic and environmental dimensions. This encompasses considerations of both absolute consumption levels and energy efficiency.

In light of these considerations, showed in **Figure 23-24** (Assovetro, 2021, p. 66-67) the cumulative energy consumption, , expressed in TEP (tonne of oil equivalent), documented for the 90% of Italian companies based on the energy source employed and, in the following bar chart the overall energy performance indicator. Regarding the energy consumptions, energy saving remains the primary goal for this industry, which consumes more than 1 billion cubic metres of gas annually (1.5 per cent of national consumption).



	2016	2017	2018	2019	2020
🟩 Gas naturale	472.278	551.232	620.880	658.910	632.804
🟩 Energia elettrica	256.958	249.349	262.079	322.599	306.207
🟩 Altro	163.747	88.677	73.876	29.580	35.599
Totale	**892.983**	**889.258**	**956.835**	**1.011.089**	**974.610**

Figure 23. Energy consumption by source (TOE), (Assovetro, 2021, p. 66-67)

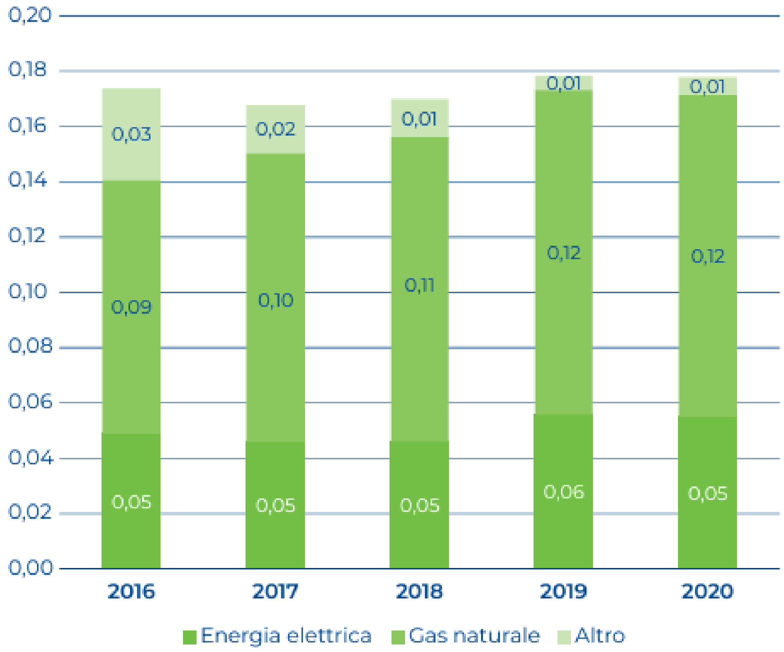
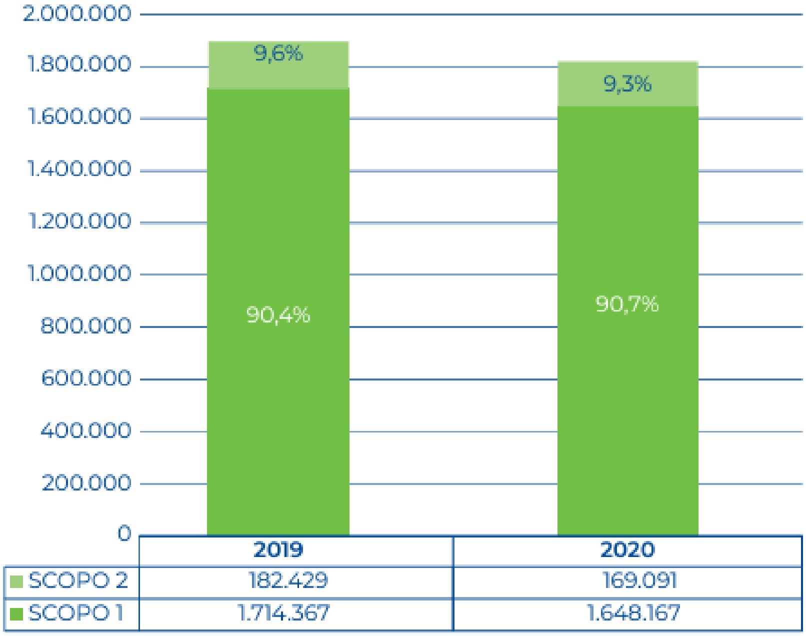


Figure 24. Overall energy performance indicator (TEP / TON molten glass), (Assovetro, 2021, p. 66-67)

The upward trend in total energy consumption is primarily attributed to increased production and the enlargement of the sample size over the last two years. The relevant performance indicator to consider, represented by the overall energy performance illustrated in **Figure 24**, remains notably stable throughout the five-year period, consistently standing at 0.17 TEP per ton of molten glass.

Concluding, the last environmental considerations within the glass industry pertains to **atmospheric emissions,** primarily resulting from the high temperature melting process. The extent of these emissions is contingent on various factors such as the type of glass, raw materials, melting furnace type, and fuel selection. Nitrogen oxides, sulphur oxides, carbon dioxide, and dust emerge as the primary pollutants. European regulations enforce emission controls through primary and secondary measures, with continuous monitoring being a common practice.

The accompanying **Figures 25-26** (Assovetro, 2021, p. 75-76) illustrate absolute values of CO2 emissions from furnaces in the 2019-2020 period and emissions per tonne of melted glass, both showing a slight decrease in the last year. These figures signify a notable improvement in the glass industry's environmental performance over recent decades, marked by a consistent reduction in emissions. Nevertheless, persistent challenges must be addressed to sustain progress towards achieving climate neutrality.



	2019	2020
🟩 SCOPO 2	182.429	169.091
🟩 SCOPO 1	1.714.367	1.648.167

Figure 25. CO2 emissions from furnace (TON), (Assovetro, 2021, p. 75-76)

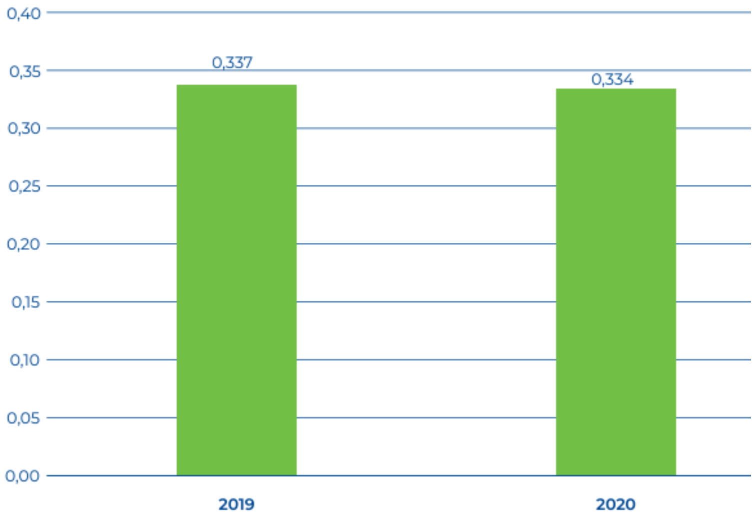


Figure 26. CO2 emissions from furnace per tonne of molten glass (TON/TON), (Assovetro, 2021, p. 75-76)

3.2.1 Recycling System

Glass undergoes a complete revival as material, adopting forms and uses identical to those of its previous lives. With no loss of material or reduction in quality, glass can be recycled indefinitely. Therefore, glass can be unequivocally regarded as a 'permanent material,' embodying the concept of a circular economy with utmost efficiency. However, for the successful execution of the recycling process, additional prerequisites are essential: an effective system for the separation and collection of municipal solid waste, enough plants distributed across the territory, equipped with cutting-edge treatment technologies, and the active involvement of citizens who understand the significance of proper waste separation.

It’s relevant to recall that, as detailed in Chapter 3.1, only specific types of glass, can be collected and recycled, identified by the following codes: **GL70** for clear glass, **GL71** for green glass, and **GL72** for brown glass.

When focusing on the recycling system, it's crucial to highlight that the approach to recycling varies across EU countries, with two main types prevailing. Some countries, such as Sweden, France, Spain, Italy, Germany, and Norway, primarily rely on **national municipal waste collection**. On the other hand, countries like Serbia, Belgium, Poland, Romania, the UK, and Denmark opt for municipal waste collection supplemented by additional sources. The Italian case study, a recycling system operating almost exclusively with national municipal waste collectors, complemented for a small fraction by material from pre-sorting plants, is clearly represented in **Figure 27** ("Close the glass loop", 2023, p. 10).

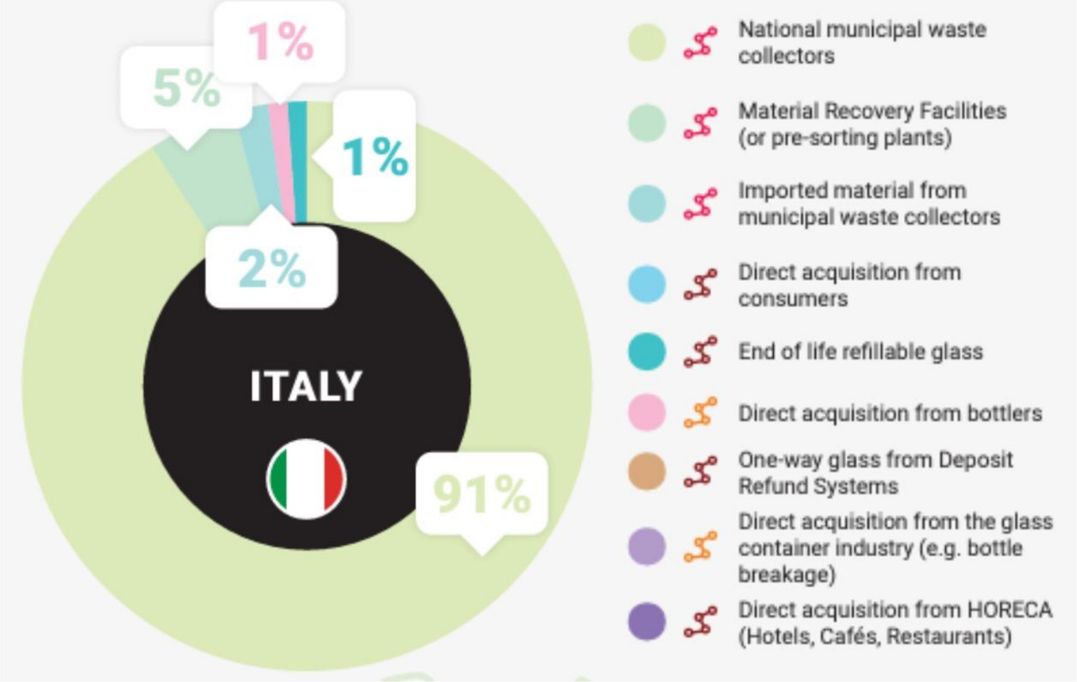


Figure 27. Italian recycling system – national municipal waste

Taking a closer look at the national system, with the crucial support of the studies conducted by the Italian Glass consortium CoReVe (Glass Recycling Consortium) established in 1997, we can present an illustrative model of the recycling system outlined in the **Figure 28** (CoReVe, 2023, p. 7) below. It encompasses the previously mentioned processing and fabrication companies, which become involved after the commercialization and collection stages in this industry.

Figure 28. Glass recycling system

Furthermore, examining the collecting system involved in recycling, there are two central methods in glass collection, **street bins** collection or **"door-to-door"** collection, showed in **Figure 29** [9], and two models, the **mono-material** system or the **multi-material** system, employed for selective glass collection. The preferred collection model is the mono-material system, focusing solely on glass and can be executed through both street bins or "door-to-door" collection. Nevertheless, when the treatment company and the collection area are far apart, it might be necessary to establish a middle storage station that follows specific guidelines.

The first collection method is the most know, convenient and efficient with a capacity of 2-3 m^3/container and located every 250/350 residents. Moreover, it's crucial to ensure sufficient service standards and maintain appropriate emptying frequencies, triggered when the bins reach 70% capacity to prevent the abandonment of waste in the vicinity of the bins.

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[9] https://coreve.it/sistemi-di-raccolta/

On the other hand, the “door-to-door” collection employs smaller bins from 20 to 260 litres/bin based on the specific situation. In addition, in this scenario, it is imperative that sufficient checks and controls are implemented on the quality of the collection, leveraging the intimate interaction between operator and user, in addition to setting frequencies suitable for the collection demands.

However, achieving excellent quantitative and qualitative results requires meticulous and punctual management of the service in every circumstances.

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Figure 29. Types of glass collection in Italy

Moving forward, when quantitatively analysing the recycling system in Italy, the latest available data are from 2022, thanks to the contribution of CoReVe. Specifically, the subsequent figures, starting with **Figure 30** (CoReVe, 2023, p. 16-17), depict the tons collected in Italy in 2022 both with data concerning the average glass quantity collected per person (expressed in kg) divided by region. In 2021, the collected tons amounted to approximately 2,417,000, signifying a 3.8% increase in 2022. Moreover, 91.4% of the total has been successfully recycled, while the remaining portion, around **216,000 tons**, has been disposed of in landfills.

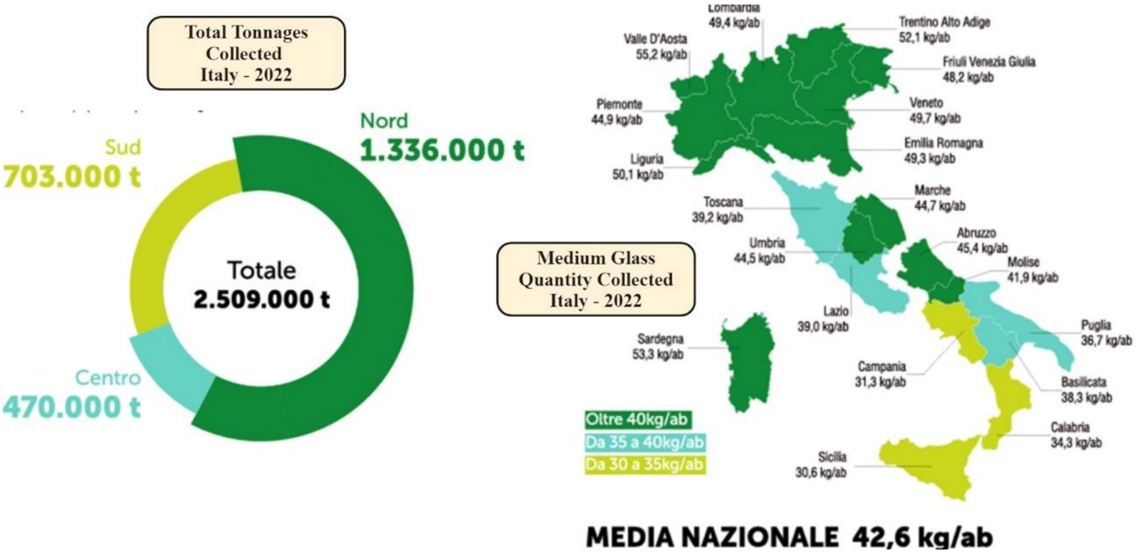

Figure 30. Data on total tonnages collected and medium glass quantity collected per person in Italy (2022)

Finally, to emphasize the previously mentioned insights about the Italian national system, as depicted in **Figure 31** (CoReVe, 2023, p. 17-18) the data present details regarding recycling systems categorized by types of management in 2022, underscoring the significance of the consortium management model. Furthermore, on the right side of the same figure, there is information about the recycling rate in 2022, reaching a consistent value of **80.8%.** This value aligns optimally with the EU goal of 75%, which had already been surpassed in 2021, achieving a rate of 76.6%. These data present a promising outlook for the present and future of the recycling system in Italy. Indeed, these values are anticipated to exhibit growth over the next three years, with a projected increase to reach values of 86%.

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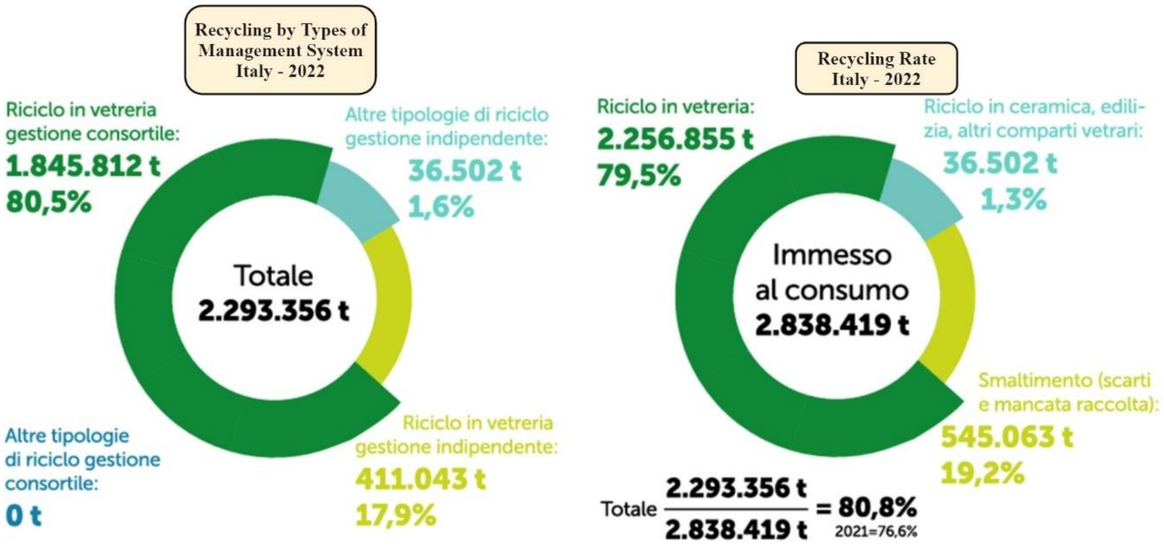

Figure 31. Recycling by Types of Management System and Recycling rate in Italy (2022)

3.4 Data and Source analysis

The foundation of any rigorous scientific examination lies in the robustness of its data sources and the precision of its analytical methods. This chapter outlines the comprehensive approach adopted in sourcing and analysing data for the study of material flow accounting in Italy's glass sector. My research navigated through a multitude of sources to gather the most reliable and up-to-date information, ensuring that every data point contributes effectively to our understanding of the sector. The selected year for analysis, chosen for its comprehensive data availability, is 2021. However, some data might pertain to 2020 and will be marked with an asterisk "*". This data can be updated when more recent information becomes available.

The analytical process involved in this study was both rigorous and iterative. It began with the extraction of relevant data, followed by a thorough verification process to ensure consistency and accuracy. Subsequent steps included normalization and reconciliation of data where necessary, particularly fostered by the rigorous mathematical model of the software STAN.

The previous chapter 2.2.4, "The Stepwise Approach," featured several summary tables that summarized the results of our comprehensive data gathering and analysis.

To extract valuable insights, the current chapter goes into greater detail about the data sources and the techniques used, immediately below are presented the main database employed:

- **Eurostat, material flows and resource productivity database [10] :** As the fundamental pillar of our data gathering initiative, Eurostat, the statistical office of the European Union, provided invaluable data specific to Material Flow Accounting (MFA). This database was pivotal for obtaining accurate Domestic Extraction, Import, and Export values. Eurostat's reputation for reliability and its focus on harmonized statistical methods across EU member states made it an ideal primary source.
- **Material Flows.net [11] :** In collaboration with the United Nations International Resource Panel (UN IRP), MaterialFlows.net offers an extensive database that complements the data obtained from Eurostat. It provides insightful data on raw materials and country profiles, allowing for a broader understanding of the material flows in the context of both Italy and the European market. This database was instrumental in offering a comparative prospect, particularly in the context of raw material utilization.
- **UN IRP Global Material Flows Database [12] :** This database provided an additional layer of global context to our study. Offering updated values and comprehensive global material flow data, it allowed for a deeper understanding of Italy's glass sector in the larger global framework. The data from the UN IRP was particularly useful in validating and cross-referencing the figures obtained from Eurostat.
- **UN Comtrade Database [13] :** The United Nations Commodity Trade Statistics Database (UN Comtrade) was a supplementary source, especially useful in instances where specific sub-materials of glass required detailed import and export trade analysis. Although not the primary source, the UN Comtrade database provided essential estimations that filled gaps in other databases.

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[10] https://ec.europa.eu/eurostat/databrowser/view/env_ac_mfa__custom_10057694/default/table?lang=en

[11] https://www.materialflows.net/visualisation-centre/

[12] https://www.resourcepanel.org/global-material-flows-database

[13] https://comtradeplus.un.org/

In addition to the databases previously mentioned, our research also greatly benefited from the official papers and publications, listed below, provided by several key national institutions in Italy, each offering unique insights into various aspects of the glass industry:

- **Assovetro**: As a national institution dedicated to the glass industry in Italy, Assovetro has been a crucial source of industry-specific data. Their publications provided in-depth information on production and emission trends, technological advancements, and market dynamics within the Italian glass sector. This information were key to interpret the specific characteristics of the industry within Italy, enhancing the wider European context provided by Eurostat.
- **COREVE**: The National Consortium for Glass Recycling, COREVE, played a significant role in our study, especially in terms of data related to recycling and collection processes. Their detailed reports and statistics on recycling rates, collection methods, and the overall efficiency of recycling systems in Italy enriched our understanding of the lifecycle of glass products. These kinds of information were pivotal in assessing the sustainability practices within the Italian glass sector.
- **ISPRA**: The Italian Institute for Environmental Protection and Research (ISPRA) offered invaluable data through reports on environmental impact, waste generation, and emission levels. They provided a critical perspective on the ecological footprint of the glass sector essential for a complete material flow analysis, allowing us to evaluate the environmental implications of glass production, recycling and waste management.

Despite the comprehensive nature of the national publications and databases, there were instances where specific data points were missing or incomplete. In such situations, our research turned to industry papers, authored by experts and practitioners, as a supplemental source of information not available through the standard channels.

Our methodical comparison of comparable values between these databases, papers and industry reports helped us find the most reliable information attainable. This cross-validation approach not only enhanced the reliability of our data but also helped identify and fix any discrepancies.

In summary, this chapter underscores the complexity of the data sourcing and analysis processes underpinning this study according to the material flow accounting tables. The meticulous approach to data validation and analysis ensures that the conclusions drawn are reasonably both reliable and valuable, providing a substantial contribution to the field of material flow accounting in the glass sector.

3.4.1 Domestic Extraction and Imports

First, is necessary to note that statistical information regarding domestic extraction, illustrated by the arrow connecting the left box (natural environment) and the middle box (extraction activity) in **Figure 32** (Eurostat, 2018, p. 22), is notably scarce. Consequently, those compiling Environmentally Weighted Material Flow Accounts (EW-MFA) often resort to using data on outputs from extraction processes to estimate the flows associated with domestic extraction.

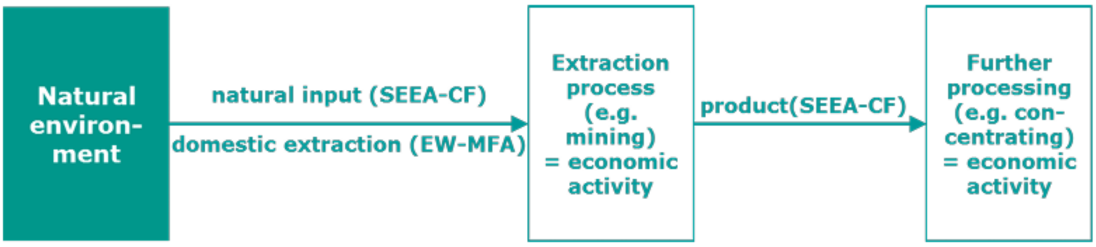
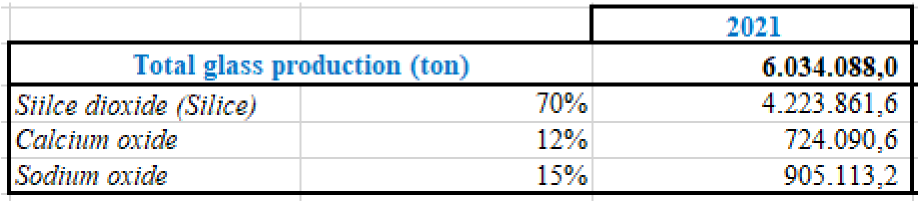


Figure 32. Physical inputs and outputs of the material extraction process

After this clarification, we will begin our examination with the two Tables A and B of **Figure10**, which respectively represent the **Domestic Extraction** and the **Imports** of materials for glass production in Italy during 2021. It is important to note that our analysis of Domestic Extraction will concentrate specifically on "Used Domestic Extraction," omitting any "Unused Domestic Extraction" data due to its lack of relevance in my case study. The key categories we will focus on within these tables are "**MF.3 Non-metallic Minerals**" and **"MF.4 Fossil Energy Materials/Carriers."**

We begin our analysis with the primary category **MF.3, focusing on the non-metallic minerals**, considering the two official categories *"Sand and gravel (3.08)"* and *"Limestone and gypsum (3.06)"*, that are either extracted or imported, which are vital for glass production. These minerals account for all the materials required by the industry, a fact attributable to the composition of glass as detailed in Chapter 3.1, that primarily consists of silica dioxide (70%), calcium oxide (12%), and sodium oxide (15%). In exploring the sources of these elements, we find that silica dioxide is derived from sand extraction, while calcium oxide and sodium oxide originate from limestone extraction, each undergoing distinct processing stages. Furthermore, considering that the value produced in Italy in 2021 is **6.034.088 tons** [14], these percentages can be allocated across the individual constituents as depicted in **Table 1** below.



		2021
Total glass production (ton)		**6.034.088,0**
Siilce dioxide (Silice)	70%	4.223.861,6
Calcium oxide	12%	724.090,6
Sodium oxide	15%	905.113,2

Table 1. Total glass production and percentages of glass constituents, 2021

To determine the annual upstream extraction and import volume of sand and limestone, measured in tons, a sequence of necessary steps and consideration must be undertaken starting from these values.

When examining the primary constituent, **silica dioxide (SiO_2),** and its main source, sand, it's crucial to note that most of the sand in Italy is classified as "Silica Sand," containing over **90% of SiO_2** [15]. Given the correspondent value of Silica dioxide from the production value for the year 2021, along with the yield from extraction and, in the end, the ratio of 95,68% Domestic Extraction (DE) and 4,32% Imports (IM) - as derived from the division of "Industrial Sand and Gravel" imported and extracted found in the Material Flow.net database - the final value of sand extracted and

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[14] https://assovetro.it/dati-di-settore/

[15] https://www.sinopiarestauro.it/db_update/allegati/schede_sicurezza_t/3915010.pdf , pg 2

imported to guarantee the production value is respectively **4.490.254,9** and **202 924 tons** , presented in the sum-up **Table 2** below.

Proceeding further, we now focus on the other constituent of glass, the **calcium oxide (CaO).** To derive it the process begins with the extraction of limestone, that typically contains between 80-95% of calcium carbonate (CaCO3) [16]. Next, to obtain the calcium oxide from the calcium carbonate, the process involves heating the calcium carbonate through the calcination process. This results in the production of calcium oxide and carbon dioxide (CO2) as a by-product, as detailed in the relevant study (Stanmore & Gilot, 2005).

To determine the yield of the calcination process and accurately calculate the required amount of limestone for a specific quantity of Calcium oxide, certain considerations about the molecular weight are needed. Specifically, the molecular weight of CaCO3 is about 100.09 g/mol, while that of CaO is about 56.08 g/mol. To calculate the exact yield, we use the ratio of molecular weights dividing 56.08 g/mol / 100.09 g/mol. The conversion process from calcium carbonate (CaCO3) to calcium oxide (CaO) has a yield of approximately **56.03%.** Therefore, from each gram of CaCO3, roughly 0.560 grams of CaO are produced. Considering the dual yields from limestone extraction through to the final production of calcium oxide (CaO) and focusing on the calcium oxide required for the 2021 production, while considering the imported quantity of limestone irrelevant, according to Eurostat databases, the solely value of limestone extracted for Calcium oxide production is **1.448.181,1 tons**, presented in the summarized **Table 2.**

To complete the analysis of the key components, **Sodium oxide (Na2O)** stands as the final essential ingredient in glass production. The process to derive it, in Italy, begins with the extraction of limestone and the subsequent combination with salt brine (unquantifiable) and water and, as a result, a specific compound, **Soda Ash (NACO3),** is created. This specific procedure is known as the "Solvay process" [17], characterized by efficiency **yields** around **75-85%.** This process is predominantly

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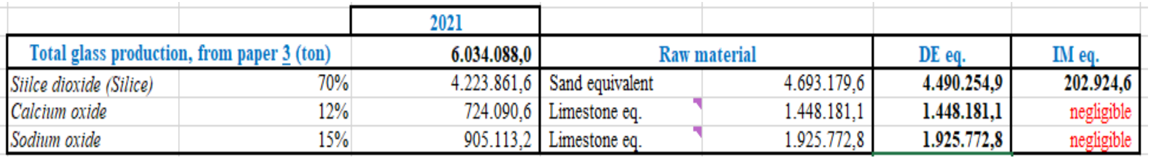
[16] https://www.chem21labs.com/labfiles/UKY_111_Exp4.pdf, pg. 2

[17] https://www.solvay.com/sites/g/files/srpend616/files/2022-01/Solvay%20Rosignano%20-%20Factsheet.pdf

carried out by the Solvay company in Rosignano, Italy which fulfils about 90% of the country's demand for this compound since decades [18].

Following the production of soda ash (Na2CO3), it undergoes the calcination process as already descripted, where it is transformed into sodium oxide (Na2O). To verify the yield of this process, it is essential to consider the molecular weights of both compounds. This consideration is crucial for determining how much sodium oxide is produced from a given amount of soda ash. Specifically, the molecular weight of Na2CO3 (soda ash) is approximately 106 g/mol, while that of Na2O (sodium oxide) is about 62 g/mol. To calculate the exact yield, we use the ratio of these molecular weights by dividing 62 g/mol by 106 g/mol. The conversion process from sodium carbonate (Na2CO3) to sodium oxide (Na2O) has a yield of approximately **58.49%.** Therefore, from each gram of Na2CO3, roughly 0.585 grams of Na2O are produced. Thereby, considering the dual yields from Solvay process through to the final production of sodium oxide (CaO), and focusing on the sodium oxide required for the 2021 production, while considering the imported quantity of limestone irrelevant as above, the solely value of limestone extracted for Sodium oxide production is **1.925.772,8 tons**, presented in the summarized **Table 2 below.**



		2021				
Total glass production, from paper 3 (ton)		**6.034.088,0**	Raw material		DE eq.	IM eq.
Siilce dioxide (Silice)	70%	4.223.861,6	Sand equivalent	4.693.179,6	**4.490.254,9**	**202.924,6**
Calcium oxide	12%	724.090,6	Limestone eq.	1.448.181,1	**1.448.181,1**	negligible
Sodium oxide	15%	905.113,2	Limestone eq.	1.925.772,8	**1.925.772,8**	negligible

Table 2. Tons of non-metallic minerals (MF.3) required for glass production in 2021, Italy.

Continuing with the evaluation of **Domestic Extraction and Imports** in the category **MF.4, titled Fossil Energy Materials/Carriers**, the primary subcategories focused on in this instance are *Coal and Other Solids (4.1), Liquid Energy Carriers (4.2), and Natural Gas (4.2.2).* The evaluation starts with the last available data from 2020, starting from Tonnes of Oil Equivalent (TOE) as the unit of measurement. This data,

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[18] https://www.agcm.it/dotcmsCustom/getDominoAttach?urlStr=192.168.14.10:8080/41256297003874BD/0/8828DCEDA46F904FC12564660040D8AA/$File/p4742.pdf

published in (Assovetro, 2021, p. 66), details the total energy consumption by source in the glass sector of Italy for the year 2020. It reveals that approximately 632,804 TOE of natural gas, 306,207 TOE of electricity, and 35,599 TOE from other sources were consumed in that year.

Concentrating exclusively on the consumption of **natural gas** measured in Tonnes of Oil Equivalent (TOE), as outlined in the Assovetro report, and subsequently converting this data into cubic meters[19] and then into tons[20], considering the average density of the natural gas 0.8 kg/m^3 as suggested in the Eurostat Guide, the relevant amount in my primary assessment for that year is approximately **607,000 tons** of Natural Gas. This value of 607,000 tons should be broken down into the respective shares of domestic extraction and imports of natural gas. According to the data from the Ministry of the Environment and Energy Security - Energy Department – DGIS showed below in **Figure 33**, in the year 2021 just the 4.5% of the total natural gas is domestically produced, while the remaining 94.5% is imported. From these two percentages, for my MFA accounting turns out that only **27.3 tons of natural gas are produced domestically**, in contrast to the significantly higher amount of **579.6 tons that are imported**.

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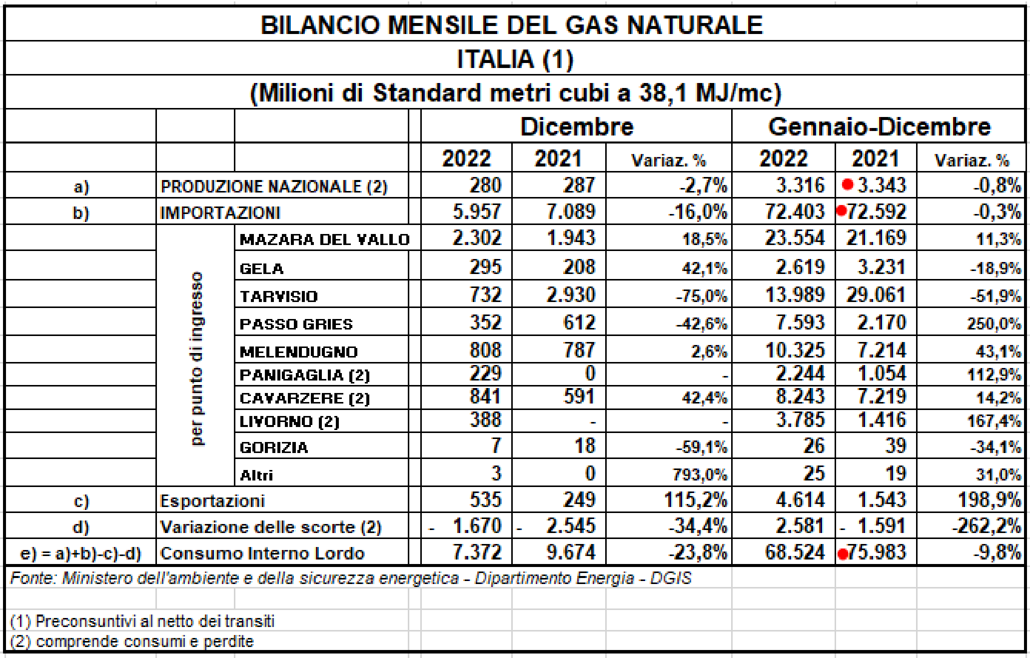
[19] https://www.argoit.com/it/sezione_id,3/faqsez_id,57/che-cos-e-un-tep-e-a-quanto-equivale-un-tep-in-termini-di-energia-elettrica/faq.html#:~:text=In%20termini%20di%20equivalenze%20un,1.200%20m3%20di%20gas%20naturale

[20] https://vodoprovod.blogspot.com/2021/01/converti-tonnellate-in-m3.html



BILANCIO MENSILE DEL GAS NATURALE

ITALIA (1)

(Milioni di Standard metri cubi a 38,1 MJ/mc)

			Dicembre			Gennaio-Dicembre		
			2022	2021	Variaz. %	2022	2021	Variaz. %
a)	PRODUZIONE NAZIONALE (2)		280	287	-2,7%	3.316	● 3.343	-0,8%
b)	IMPORTAZIONI		5.957	7.089	-16,0%	72.403	●72.592	-0,3%
	per punto di ingresso	MAZARA DEL VALLO	2.302	1.943	18,5%	23.554	21.169	11,3%
		GELA	295	208	42,1%	2.619	3.231	-18,9%
		TARVISIO	732	2.930	-75,0%	13.989	29.061	-51,9%
		PASSO GRIES	352	612	-42,6%	7.593	2.170	250,0%
		MELENDUGNO	808	787	2,6%	10.325	7.214	43,1%
		PANIGAGLIA (2)	229	0	-	2.244	1.054	112,9%
		CAVARZERE (2)	841	591	42,4%	8.243	7.219	14,2%
		LIVORNO (2)	388	-	-	3.785	1.416	167,4%
		GORIZIA	7	18	-59,1%	26	39	-34,1%
		Altri	3	0	793,0%	25	19	31,0%
c)	Esportazioni		535	249	115,2%	4.614	1.543	198,9%
d)	Variazione delle scorte (2)		- 1.670	- 2.545	-34,4%	2.581	- 1.591	-262,2%
e) = a)+b)-c)-d)	Consumo Interno Lordo		7.372	9.674	-23,8%	68.524	●75.983	-9,8%

Fonte: Ministero dell'ambiente e della sicurezza energetica - Dipartimento Energia - DGIS

(1) Preconsuntivi al netto dei transiti
(2) comprende consumi e perdite

Figure 33. Mix of Italian Natural gas production and imports, 2021

Although these figures provide valuable insight, the value attributed to **natural gas** consumption is only **a partial representation**, as the production of electricity also relies on it. Therefore, the following and final part of this paragraph will be dedicated to deeply analysing the electricity sources to ensure a comprehensive consideration of each fossil energy source.

Beginning with the value of **306,207 TOE** for electricity consumption as reported from Assovetro, it's important to exclude the portion attributed to renewable energy such as hydro, wind, solar and geothermal, considered as immaterial into a Material Flow Accounting analysis. According to (Assovetro, 2021, p. 72), **10.9%** of this electricity comes from renewable sources, both external and self-made. As a result, the value to start considering is **272.830 TOE** of electricity. To refine the analysis, it's crucial to account for the national production, which comprises a significant 86.4% of the total, alongside the imports, which contribute 13.6% [21]. Additionally, the composition of Italy's energy mix, predominantly thermal electricity at 57.5% [21] in 2021, plays a key role. Factoring in these considerations, the calculated values of

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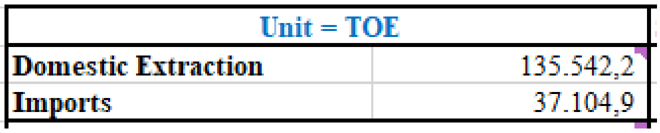
[21] https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche

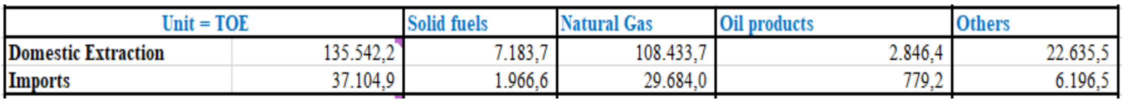
energy produced domestically and imported are comprehensively presented in the subsequent **Table 3**.



Unit = TOE	
Domestic Extraction	135.542,2
Imports	37.104,9

Table 3. DE and IM of electricity (TOE) in Italy, 2021*

The values of the general electricity expressed in TOE alone are not adequate for my model to align with the specific categories already introduced of *Coal and Other Solids (4.1), Liquid Energy Carriers (4.2), and Natural Gas (4.2.2)* under analysis. From Terna's data for 2021, we can obtain the percentages for the specific energy sources in Italy, which are 5.3% for solid fuels, 86.9% for natural gas **(to be added to the previous values of 27.3 tons of natural gas produced domestically, and 579.6 tons imported),** 2.1% for oil products, and 16.7% for other fuels. With these percentages in mind, the subsequent breakdown of the energy produced and, by extension, assumed to be similarly imported, is displayed in the **Table 4** below.



Unit = TOE		Solid fuels	Natural Gas	Oil products	Others
Domestic Extraction	135.542,2	7.183,7	108.433,7	2.846,4	22.635,5
Imports	37.104,9	1.966,6	29.684,0	779,2	6.196,5

Table 4. DE and IM of each source of electricity in Italy in 2021*

After establishing the specific sources of electricity in Italy for the relevant period, incorporating a variety of factors, it becomes necessary for my analysis to convert these values, currently expressed in Tonnes of Oil Equivalent (TOE), into tons. This conversion involves a three-step process: firstly, the TOE values are transformed into kilowatt-hours (kWh) by using a conversion factor of 5,347 kWh for 1 TOE [22]. Secondly, these kWh values are then converted into Megajoules (MJ) by multiplying them by 3.6. Thirdly, these MJ values must be converted into the correspondent tons according to different factors for each energy source to accurately reflect their

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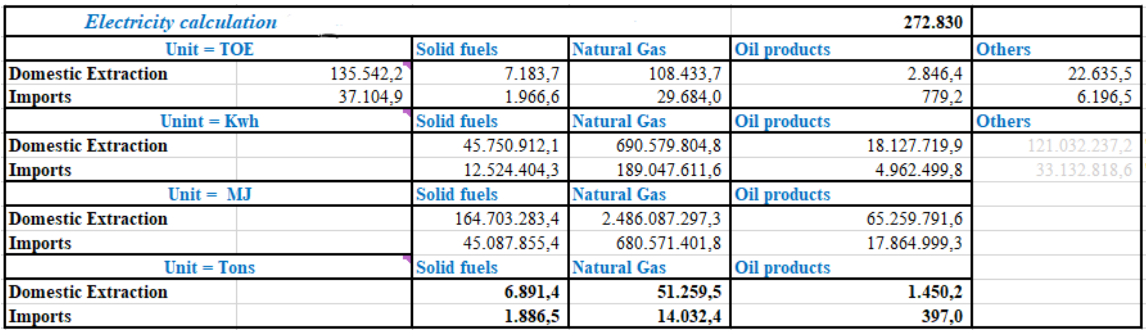
[22] https://www.ri-esco.it/tep-unita-misura-energia/

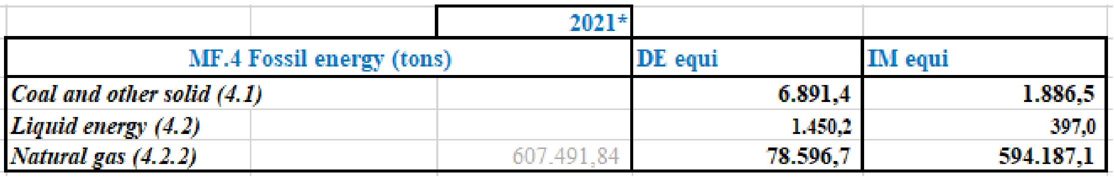
specific energy contents [23]. All these steps and the final **relevant values** are showed at the bottom of the **Table 5**.



Electricity calculation				272.830	
Unit = TOE		Solid fuels	Natural Gas	Oil products	Others
Domestic Extraction	135.542,2	7.183,7	108.433,7	2.846,4	22.635,5
Imports	37.104,9	1.966,6	29.684,0	779,2	6.196,5
Unint = Kwh		Solid fuels	Natural Gas	Oil products	Others
Domestic Extraction		45.750.912,1	690.579.804,8	18.127.719,9	121.032.237,2
Imports		12.524.404,3	189.047.611,6	4.962.499,8	33.132.818,6
Unit = MJ		Solid fuels	Natural Gas	Oil products	
Domestic Extraction		164.703.283,4	2.486.087.297,3	65.259.791,6	
Imports		45.087.855,4	680.571.401,8	17.864.999,3	
Unit = Tons		Solid fuels	Natural Gas	Oil products	
Domestic Extraction		**6.891,4**	**51.259,5**	**1.450,2**	
Imports		**1.886,5**	**14.032,4**	**397,0**	

Table 5. Sum-up table of the conversion from TOE to Tons of the electricity in 2021*

Concluding this calculation process, the **Table 6** below presents the summarized values for the macro category "**MF.4, Fossil Energy Materials/Carriers**" according to Domestic extraction and imports values.



		2021*		
MF.4 Fossil energy (tons)			DE equi	IM equi
Coal and other solid (4.1)			**6.891,4**	**1.886,5**
Liquid energy (4.2)			**1.450,2**	**397,0**
Natural gas (4.2.2)		607.491,84	**78.596,7**	**594.187,1**

Table 6. Tons of fossil energy materials/carriers (MF.4) required for glass production in 2021, Italy.

To reach the conclusion and ascertain the total Domestic Extraction (DE) and Imports (IM) stemming from both the macro categories "**MF.3 Non-metallic Minerals**" and **"MF.4 Fossil Energy Materials/Carriers",** the final step involves aggregating all the data from **Table 2** and **Table 6**, along with data on mere glass imported into Italy in 2021, equal to **1.760.000 tons** [14]. This comprehensive summation will yield the final values of DE and IM crucial for my final model and showed below in **Table 7.**

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[23] https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

Total DE (tons)	7.951.147,05
Total IM (tons)	2.559.395,25

Table 7. Total values of DE and IM (tons) in Italy, 2021

3.4.2 Exports

Regarding Table D of the pre-mentioned official questionnaire's tables showed in **Figure 10**, which addresses Exports, the data originates from Assovetro [14], which also provides information on production and imports. Therefore, in 2021, the data about **total volume of glass exported** from Italy is documented at **1,000,000 tons.**

3.4.3 Domestic Processed Outputs

A crucial component in this analysis is Table F of the **Figure 10**, which represents the Domestic Processed Output arising from different processes within my core system. The primary categories under consideration are **"MF 7.1, Emissions to Air"**, **"MF 7.2, Waste Disposal",** and **"MF 7.3, Emissions to Water".**

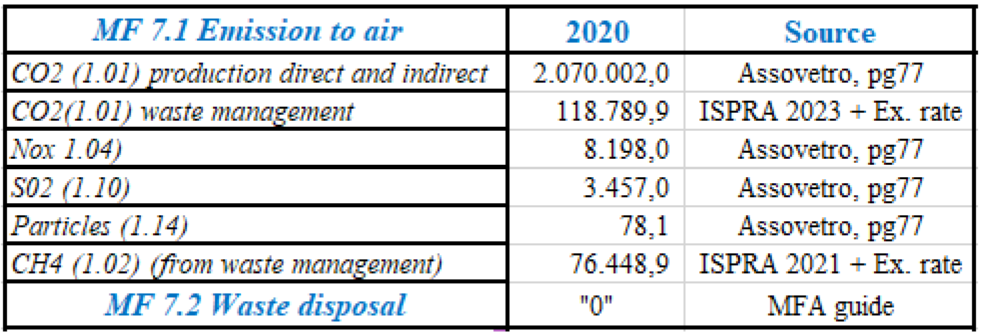
Concerning **"MF 7.2, Waste Disposal,"** as delineated in the official Eurostat guidelines, this category encompasses solely the quantities of solid waste disposed of in the natural environment, specifically uncontrolled landfills. Given that uncontrolled landfills are prohibited in Europe, it can be reasonably assumed that this figure is negligible or zero as showed in **Table 8**. Consequently, the focus is directed on the remaining two categories.

In relation to the **"MF 7.1, Emissions to Air"** category, the most recent and comprehensive data on emissions from the glass industry and their environmental impact pertains to the year 2020 but will be considered as similar for our year under investigation. The primary emissions identified within this sector include *Carbon Dioxide (CO2, labelled as 1.01 in the guide), Nitrogen Oxides (NOx, 1.04), and Sulphur Dioxide (SO2, 1.14)*. These emissions data have been documented and published by Assovetro (Assovetro, 2021, p. 77) in their report, with specific figures presented in the **Table 8** below.

Furthermore, the same Table 8 also includes estimated emissions of **118.789,9 tons** of Carbon Dioxide *(CO2, 1.01)* and **76.448,9 tons** of Methane *(CH4,1.02)* from glass waste management and controlled landfills. These estimates derive from different paths.

The estimation of **Carbon Dioxide emissions** related to waste management in Italy was significantly reported by (ISPRA, Le emissioni di gas serra in Italia: obiettivi di riduzione e scenari emissivi, 2023, p. 45) for the year 2020, similar to the year 2021, and estimated around 20,5 million tons at a national level. To ascertain the specific contribution of the glass sector into the total CO2 emissions from waste management, this report’s data was combined with the ratio of CO2 emissions from the general glass sector (**2.070.002,0 tons**, provided by Assovetro) to the national CO2 emissions (**352.425 million tons**) (ISPRA, Le emissioni di gas serra in Italia: obiettivi di riduzione e scenari emissivi, 2023, p. 22). This method yielded a precise figure, indicating that the glass sector accounted for **0.006%** of Italy's total CO2 emissions from waste management in 2020. By applying this rate to the emissions originating from waste management, and assuming a similar contribution pattern, it's possible to deduce the specific contribution of the CO2 emissions from the waste management of glass sector in Italy. This calculation leads to an estimated total of **118,789 tons** attributed to the glass sector's carbon dioxide emissions.

Likewise, by applying the same rate and considering the total national methane (CH4) emissions from of **13,000,000 tons** (ISPRA, 2021, p. 68), it can be inferred that the amount of methane emissions attributable to glass waste disposal is approximately **76,448 tons.** Immediately below in **Table 8** showed the summary of the emissions to air and waste disposal considered.



MF 7.1 Emission to air	2020	Source
CO2 (1.01) production direct and indirect	2.070.002,0	Assovetro, pg77
CO2(1.01) waste management	118.789,9	ISPRA 2023 + Ex. rate
Nox 1.04)	8.198,0	Assovetro, pg77
S02 (1.10)	3.457,0	Assovetro, pg77
Particles (1.14)	78,1	Assovetro, pg77
CH4 (1.02) (from waste management)	76.448,9	ISPRA 2021 + Ex. rate
MF 7.2 Waste disposal	"0"	MFA guide

Table 8. Emission to air and Waste disposal amounts for the glass sector in Italy

In wrapping up the analysis on Domestic Processed Output, the final macro category to address is **"MF 7.3, Emissions to Water".** Acquiring accurate data for this category presents a significant challenge due to the absence of official data. Nevertheless, I have endeavoured to make an estimate by referencing the total amount of harmful substances discharged into water across Italy reported by the EEA (European Environmental Agency). Employing the same proportional rate used for CO2 and methane emissions, it appears that the glass sector's contribution to these water emissions is noteworthy. Based on a national total of 108.376.915,2 tons[24] of harmful substances discharged for the year 2021, the share attributable to the glass industry is estimated to be approximately **637.330,8 tons**.

To summarize the analysis that encompasses contributions from **"MF 7.1, Emissions to Air," "MF 7.2, Waste Disposal,"** and **"MF 7.3, Emissions to Water,"** the overall total for the domestic processed output is comprehensively presented in **Table 9.**

DPO from production*	2.719.006
DPO from Waste Manag.	195.238,83
Total DPO* (tons)	**2.914.304,70**

Table 9. Total DPO from glass sector and its waste management in Italy, 2021*

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[24] https://sdi.eea.europa.eu/data/0e2e16ac-06e9-40b8-9aef-b3d228100564?path=%2FEXCEL , Table F2_1

3.4.4 Balancing Items

In the process of evaluating the final **Table G o**f the official questionnaire's table in **Figure 10,** my approach involved calculating the balancing items for the input side of the equation. This task was guided by the established principles outlined in the (Eurostat, Economy-wide material flow accounts - handbook, 2018, p. 91) following three main steps. I've adopted the assumption suggested in the guide about the balancing items on the output side analogous to those on the input side. This approach ensures that the representation of data remains balanced and reflective of the underlying dynamics.

The three-step process begins with **Step 1**, focusing on calculating the oxygen needed for combustion processes. This calculation is based on stoichiometric principles, using data for emissions of CO2, CO, SO2, N2O, and NO2 from combustion sources. The guide provides specific factors for these calculations: 0.727 tonnes of oxygen are needed for the combustion of one tonne of CO2, 0.364 tonnes of oxygen are required for one tonne of N2O, and 0.5 tonnes of oxygen are necessary for one tonne of SO2. The resulting values derived from applying these factors are systematically presented in **Table 10.**

Continuing the process**, Step 2** involves calculating the oxygen demand in tonnes per tonne of energy carrier. This step takes into account different types of energy sources, each with its specific oxygen demand factor: the oxygen demand for one tonne of **coal** is **0.215** (average), the oxygen demand for one tonne **oil** is **1.41**, and, in the end, the oxygen demand for one tonne of **natural gas** is **1.83**. These calculations are pivotal in determining the oxygen requirements for each energy carrier type, reflecting their respective combustion characteristics. The resulting values, similar to the step 1, are presented in **Table 10.**

The process culminates with **Step 3**, which is based on the understanding that most combustible materials inherently contain oxygen. This existing oxygen content is utilized during the combustion process. Therefore, it's necessary to deduct this intrinsic oxygen content from the oxygen demand computed in the earlier steps. This adjustment is essential to accurately determine the actual requirement for external (exogenous) oxygen. In this step, specific coefficients are applied, denoted as **3,32 %**

(average) oxygen content of weight of coal and **0.19 %** oxygen content of weight of natural gas, for the oil products the percentage was not specified and consequently not computed. However, all the exact values are showed in the **Table 10** below.

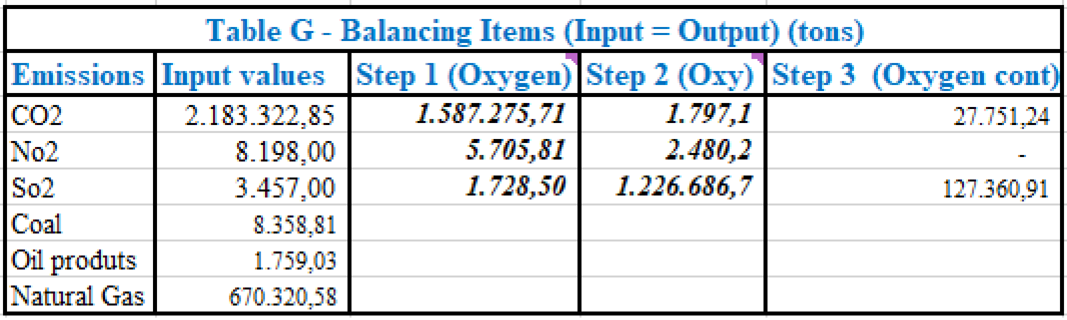


Table G - Balancing Items (Input = Output) (tons)				
Emissions	**Input values**	**Step 1 (Oxygen)**	**Step 2 (Oxy)**	**Step 3 (Oxygen cont)**
CO2	2.183.322,85	*1.587.275,71*	*1.797,1*	27.751,24
No2	8.198,00	*5.705,81*	*2.480,2*	-
So2	3.457,00	*1.728,50*	*1.226.686,7*	127.360,91
Coal	8.358,81			
Oil produts	1.759,03			
Natural Gas	670.320,58			

Table 10. Steps to calculate the Balancing items of the glass system.

After applying the three-step methodology recommended by Eurostat to my specific case, the final computation of the Balancing Items in Input (BII) is achieved through a precise process. This involves initially summing up the values derived from step 1, then adding the total from step 2, and subsequently subtracting the values obtained in step 3. The culmination of this detailed calculation process yields a resultant total value of the Balancing Items in Input, equal to the output one, is **2,670,561 tons.**

3.5 Application of MFA

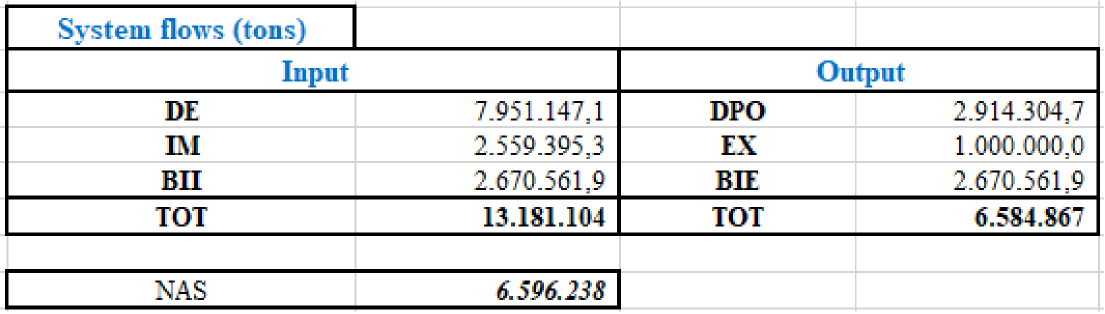
Embarking on the implementation of Economy-Wide Material Flow Accounting (EW-MFA) necessitates in the early stages a meticulous consideration of boundaries and assumptions. The delineated boundaries of my system encompass the entirety of the Italian national system and all actors intricately involved in the glass industry.

Simultaneously, some data assumptions come into play, particularly in the realm of statistical values within the STAN software. Here, the assumption of data distributed following a normal distribution is pre-defined and fundamental to the modelling process.

Additionally, it is crucial to recall and acknowledge certain exclusions inherent in the methodology, such as the omission of flows related to water, air, or direct energy.

These exclusions, while substantial, align with the methodology's focus and are presumed to be adequately covered in other specialized reports due to their scale and complexity.

However, regarding the practical application, taking into account the mentioned assumptions and simplifications involved, we can begin to illustrate the model by focusing on the resultant input and output flows, along with the net additions to the stock calculated and explained in the Chapter 3.4. The summary and final elements to be considered are detailed in the **Table 11** provided below.



System flows (tons)			
Input		Output	
DE	7.951.147,1	**DPO**	2.914.304,7
IM	2.559.395,3	**EX**	1.000.000,0
BII	2.670.561,9	**BIE**	2.670.561,9
TOT	**13.181.104**	**TOT**	**6.584.867**
NAS	***6.596.238***		

Table 11. Main total glass system flows in Italy, 2021

This table serves as an optimal and essential foundation for developing the model through the software STAN. To elucidate the visual representation crafted in STAN, along with the primary processes and flows, the total model showed below in **Figure 33** will be dissected into three key components: The Input, The Core, and The Output of the system.

To facilitate the recognition of the different flows I've coloured them according to three main colours: Green flows to represent the Inputs, Dark Blue flows for the Outputs, Red flows for the emissions generated inside the system and Black flows to represent the inside flows.

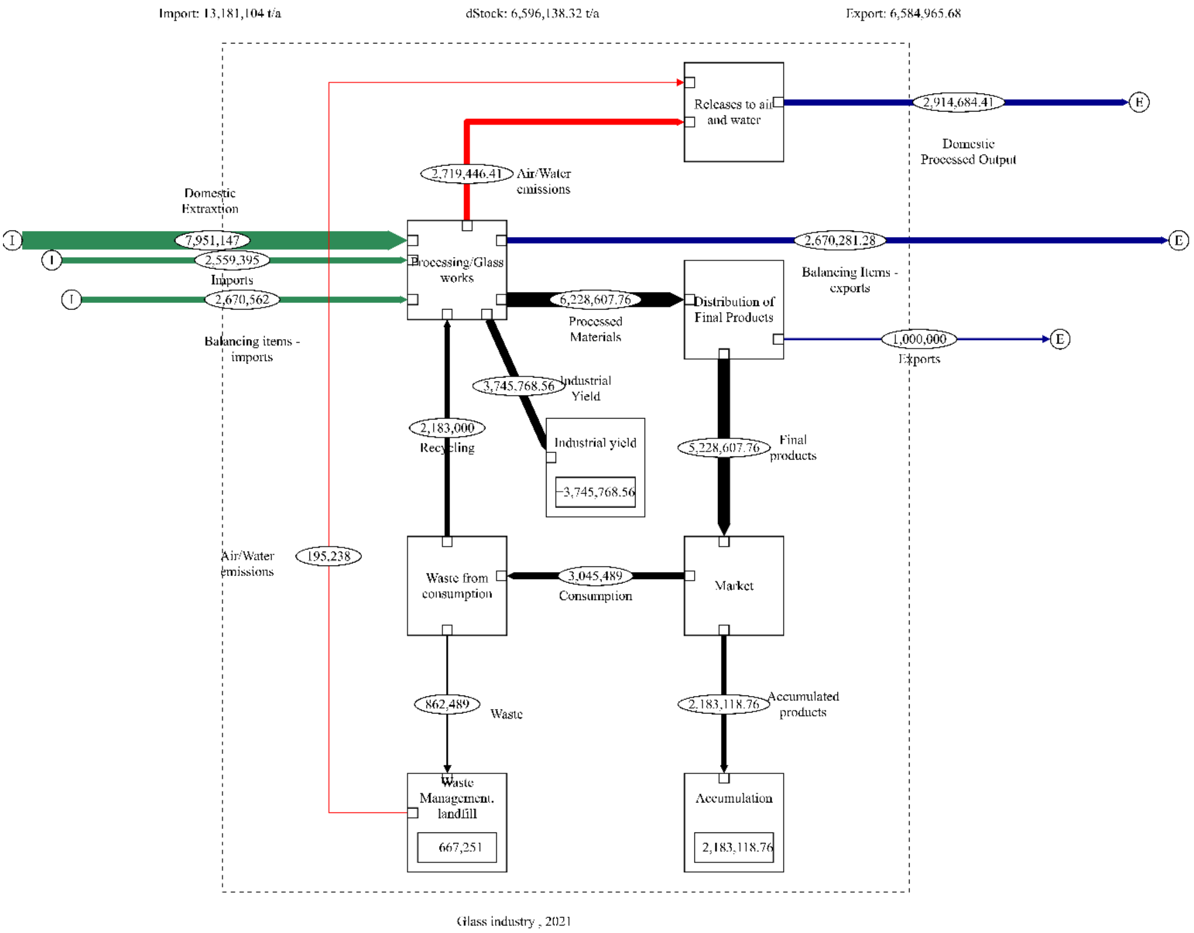


Figure 33. Complete visual representation in STAN of the Italian glass sector in Italy, 2021

The examination of the entire flows and stocks of my system begin with the input aspect of my model, distinguished by three principal flows: *Domestic Extraction, Imports, and Balancing Items (Imports).* I have extensively detailed and described each of these flows and, to consider their figures in the software, I've simply uploaded the gathered data (tons), showed in **Table 11**, into my model. In addition, all these three streams originate from our natural environment and feed into the system, primarily into the key manufacturing activities, specifically marked as the **"Manufacturing/Glassworks"** process as shown in the following **Figure 34**. The core process will be detailed in the following page.

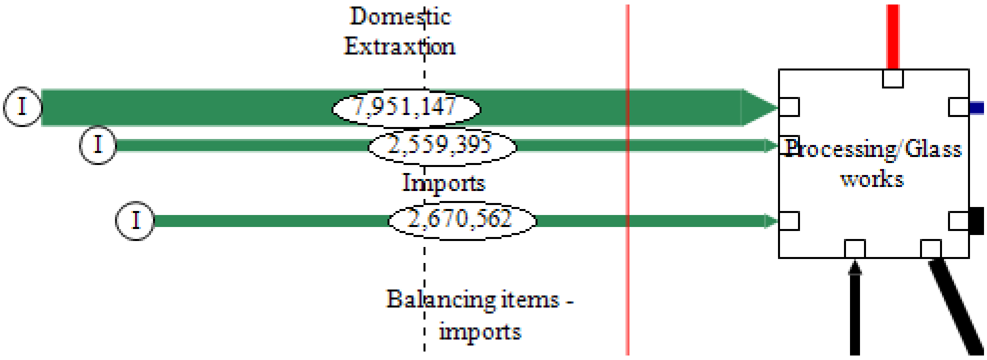


Figure 34. Representation of the Inputs of the Italian glass sector in Italy, 2021

Continuing the analysis with a focus on the system's core, the main processes developed to closely mirror reality are represented by eight distinct processes, each elaborated in the following sections:

- **Processing/Glassworks:** This is the initial stage of the glass production system where raw materials are processed. It represents all the manufacturing processes addressed and the transformation of domestic extraction and imports into processed glass materials and into the related emissions. This process is central and acts as the primary source for subsequent stages.
- **Industrial Yield**: This process stock encapsulates key aspects, notably the productive output as the quantity of glass products that meet the quality standards required for distribution, the transformation of energy and the yields from the raw materials extraction (sand, limestone), that directly enter the process from the Domestic Extraction flows to the final constituents of glass *(Silicon dioxide ($SiO2$), Sodium oxide (Na_2O) and Calcium oxide (CaO)).* The result estimated value, after the mass balancing calculation, of this stock for the period 2021 is roughly **3.745.768 tons.**
- **Distribution of Final Products**: From the flows of the processed material that comes out the main process, this flow represents the transition from

manufacturing to making these products available for consumers, markets and exports.

- **Market:** The market is where the final products are sold or exchanged. This process captures the economic transaction and movement of glass products from distribution to the hands of consumers.
- **Accumulation:** It’s a process stock that receive the main flows of final products from the market, it represents the storage or holding of glass products that can’t be processes within the year under investigation. It can be seen as the products in use, indicating the total amount of glass that remains within the economic system over that time. The estimated quantity, after the mass balancing calculation, for this stock in the year 2021 in Italy is approximately **2,183,118 tons.**
- **Waste from Consumption:** As glass products are used and eventually discarded, they become waste from their consumption. This process indicates the end-of-life phase of glass products waiting to be distributed according to the national regulations. Particularly focusing on the output flows from this process that are channelled back into the main system to complete the glass recycling loop, it was recorded that in 2021 in Italy, an amount of **2.183 million tons** (CoReVe, 2023, p. 19) were successfully processed for recycling.
- **Waste Management, Landfill:** A portion of the waste generated ends up in waste management, specifically in controlled landfills. This is represented by a stock within the period that accumulates the material destined for controlled disposal. Furthermore, this process generates emissions that are channelled into the corresponding emission process. An estimate of **667,000 tons** (CoReVe, 2023, p. 19) is the amount of this stock in 2021 in Italy.
- **Release into Air and Water:** Throughout these processes, there are inevitable and hazardous releases into air and water. This process represents the emissions and effluents that arise from glass processing and waste management activities. For the disaggregated values for pertaining to processing and waste management refer to **Table 9.**

Each of these processes and stocks are interconnected, representing the lifecycle of glass products from raw material processing through to their eventual disposal or recycling as showed in the summary **Figure 35**.

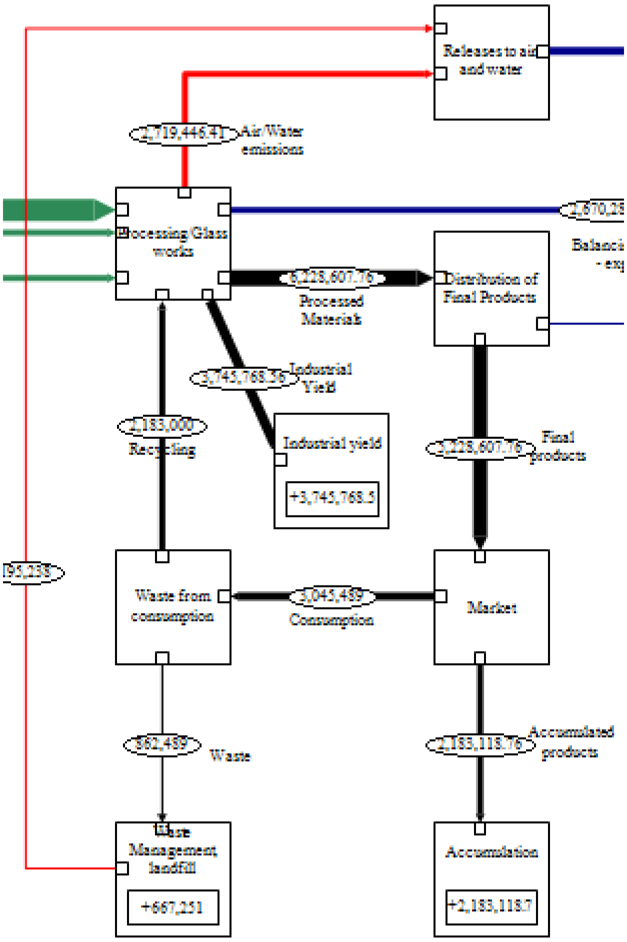


Figure 35. Representation of the Core of the Italian glass sector in Italy, 2021

To round out the description of the system's flows, **Figure 36** graphically represents the key streams considered into the output part towards the environment: *Domestic Processed Outputs, Exports, and Balancing Items (exports).* The values for these flows are displayed on the right side of the summary **Table 11** and have been widely explained in the previous part of the thesis.

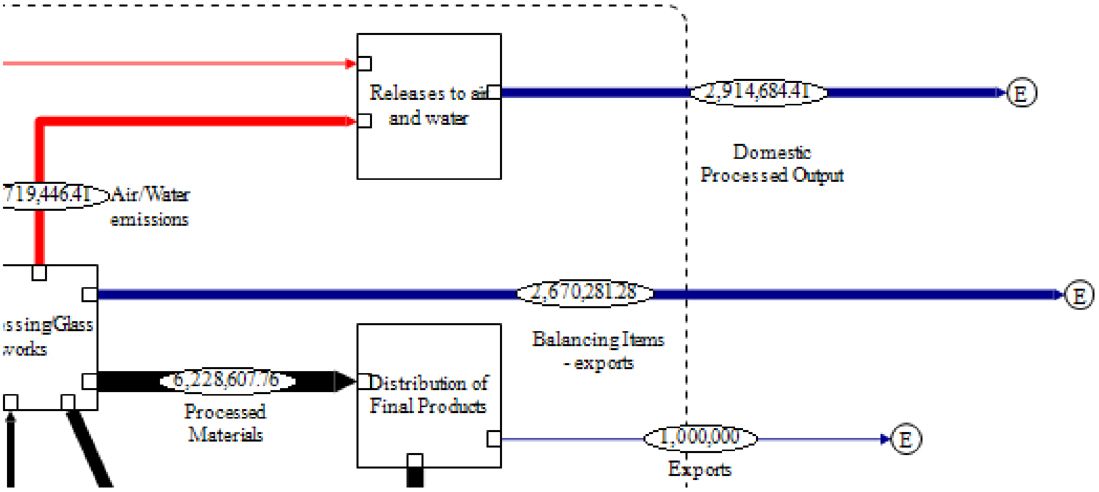
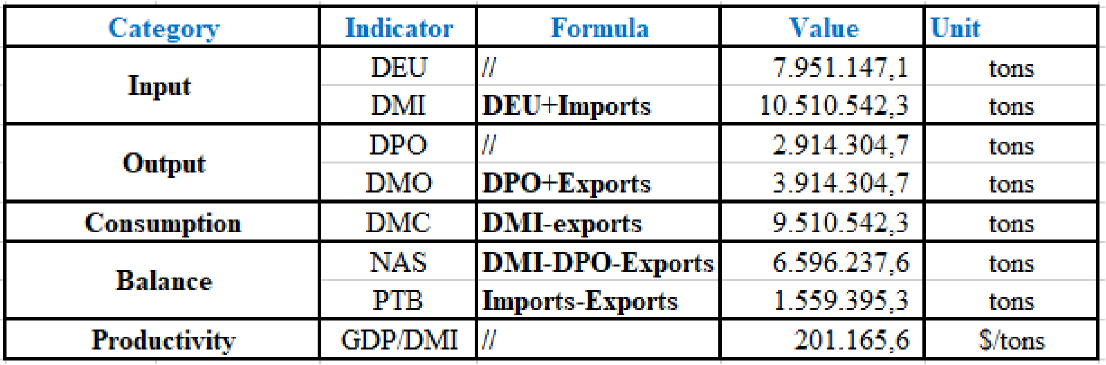


Figure 36. Partial representation of the Outputs of the Italian glass sector in Italy, 2021

3.5.1 Model Indicators

To enhance our understanding of the system and to draw meaningful conclusions from the assembled data, the indicators outlined in **section 2.2.3** have been computed. It is important to clarify that, unlike the comprehensive detailing of indicators in the chapter, certain metrics, especially the input indicator **Total Material Requirement (TMR),** could not be quantified due to negligible values in my model for Unused Domestic Extraction (UDE) and the complexity involved in estimating the indirect resource extraction associated with imports. Similarly, for outputs, the **Total Domestic Output (TDO)** is infeasible to calculate due to the UDE component, and the **Total Material Output (TMO),** which is contingent on the TDO, also remains uncomputed. Additionally, on the consumption side, **the Total Material Consumption (TMC)** could not be determined due to the indirect flows linked with exports.

Nevertheless, all other indicators have been meticulously calculated. The results of these computations and their formulas are presented in the summary **Table 12**, providing a comprehensive overview of the system's material flows and stocks.



Category	Indicator	Formula	Value	Unit
Input	DEU	//	7.951.147,1	tons
	DMI	**DEU+Imports**	10.510.542,3	tons
Output	DPO	//	2.914.304,7	tons
	DMO	**DPO+Exports**	3.914.304,7	tons
Consumption	DMC	**DMI-exports**	9.510.542,3	tons
Balance	NAS	**DMI-DPO-Exports**	6.596.237,6	tons
	PTB	**Imports-Exports**	1.559.395,3	tons
Productivity	GDP/DMI	//	201.165,6	$/tons

Table 12. Summary of the indicators for the glass sector in Italy, 2021

The metrics presented are quantified in tons, except for the final indicator, which is expressed in dollars per ton. This distinction arises because the last indicator is an economic efficiency measure calculated by dividing the Italian Gross Domestic Product (GDP), for the year 202 amounting to **2114,36 billion dollars** [25], by the Domestic Material Input (DMI) calculated for my case study the same year.

These figures offer deeper understanding of the developed model and the data I've gathered despite the consideration of certain assumption and estimation. In the final analysis, their significance could be further amplified and valued when used for comparative analysis. Through comparative analysis we can discern patterns, trends, and deviations, providing critical insights into glass sector performance over time or compared to other materials.

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[25] https://www.macrotrends.net/countries/ITA/italy/gdp-gross-domestic-product

Conclusion

In concluding this thesis on the application of Economy-Wide Material Flow Analysis (EW-MFA) to the glass sector in Italy, we reflect on the journey undertaken, the milestones achieved, and the insights gained. The development of the EW-MFA model for this sector represents a significant step towards understanding the environmental impacts and resource flows within this industry.

One of the key achievements of this thesis has been the creation of a consistent and coherent EW-MFA model. This accomplishment was paralleled by the intensive and often challenging phase of data collection and analysis. The process of navigating through diverse data sources and integrating them into a cohesive model has been both enlightening and demanding.

The model crafted closely mirrors the realities of the glass sector according to the level of disaggregated data we have gathered. This alignment with real-world data underscores the model's validity and relevance. Nevertheless, it is important to acknowledge that there are areas where data accuracy and availability can be improved. Specifically, more precise information pertaining to emissions, mining activities, and energy use could be further refined. In their current state, these data points, while useful, offer an opportunity for enhancement to achieve a more comprehensive and precise understanding.

Despite these limitations, the model stands as a reliable foundation for analysing the glass sector in Italy. It offers a robust starting point for both industry professionals and researchers to delve into the intricate dynamics of this sector, particularly from an environmental perspective.

Through this research, I have gained a profound understanding of the MFA methodology, an experience that will undoubtedly be valuable in my future endeavours. As the world increasingly turns its focus towards sustainability, the skills and insights acquired through this work will be crucial.

In conclusion, this thesis marks a meaningful contribution to the field of EW-MFA and provides a solid foundation for future research and application in the glass industry and beyond. It emphasizes the need for continuous improvement in data collection and model refinement, ensuring that our tools for understanding and managing environmental impacts keep pace with the evolving industrial landscape.

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