A multi-disciplinary approach to estimate the medium-term impact of COVID-19 on transport and energy: a case study for Italy

*Davide Bazzana [a, c], Jed J. Cohen [f], Nicolò Golinucci [a, b], Manfred Hafner [a, g, h], Michel Noussan [a, g, *], Johannes Reichl [f], Matteo Vincenzo Rocco [b], Alessandro Sciullo [d, e], Sergio Vergalli [a, c]*

[a] Fondazione Eni Enrico Mattei, Milano, Italy
[b] Politecnico di Milano, Milano, Italy
[c] Università degli Studi di Brescia, Brescia, Italy
[d] IRES Piemonte – Istituto di Ricerche Economico Sociali del Piemonte, Torino, Italy
[e] Università degli Studi di Torino, Torino, Italy
[f] Energy Institute at Johannes Kepler University, Linz, Austria
[g] SciencesPo - Paris School of International Affairs (PSIA), Paris, France
[h] Johns Hopkins University - School of Advanced International Studies (SAIS-Europe), Bologna, Italy

* corresponding author: michel.noussan@feem.it, +39 02 520 36814.

Abstract

The aim of this paper is to estimate the potential impacts of different COVID-19 scenarios on the Italian energy sector through 2030, with a specific focus on transport and industry. The analysis takes a multi-disciplinary approach to properly consider the complex interactions of sectors across Italy. This approach includes the assessment of economic conditions using macroeconomic and input-output models, modelling the evolution of the energy system using an energy and transport model, and forecasting the reaction of travel demand and modal choice using econometric models and expert interviews. Results show that the effect of COVID-19 pandemic may lead to mid-term effects on energy consumption. The medium scenario, which assumes a stop of the emergency by the end of 2021, shows that energy-related emissions remain 10% lower than the baseline in the industry sector and 6% lower in the transport sector by 2030, when compared with a pre-COVID trend. Policy recommendations to support a green recovery are discussed in light of the results.

Keywords: COVID-19, energy systems, CO_2 emissions, integrated-models, multi-disciplinary, Italy.

1. Introduction

The effects of the COVID-19 pandemic on the global energy sector in 2020 has caused unprecedented variations in both energy demand and supply. Recent estimates by the International Energy Agency (IEA) quantify this disruption in a 5% reduction in world energy demand from 2019, a decrease of 7% in energy related CO_2 emissions and a 18% drop in investments in energy [1]. The single strongest driver of those figures is the mandatory shut-downs of several activities due to lockdowns and other measures to prevent the virus diffusion, with the most notable effects on energy consumption in transport and in industry. Different research studies have evaluated the impact of the pandemic on energy systems worldwide, considering different phases of the energy supply chain, final sectors and geographical levels.

A direct impact is observed in the transport sector. Daily commuting habits have been strongly affected, with stronger effects observed in international travel, specifically in aviation [2]. Modal shares in urban transportation during the pandemic have been strongly influenced [3,4], with a huge decrease of public transport and a shift towards private cars and active modes, i.e. biking and walking. While the direct effects in 2020 have been widely acknowledged, also thanks to a number of measurements and estimations [5,6], future trends are much less clear. Although transport experts expect an increase in private cars ownership and use, positive behaviours associated with active transport solutions during 2020 could remain after the pandemic.

Local policies will have a strong effect in sustaining the development of active transport, and further research is needed on the citizens' behaviours and choices in this domain. The measures that have been implemented during the pandemic to support a broader use of active mobility may represent a good opportunity to shifts towards a more sustainable mobility planning. Combs and Pardo [7] have collected a database of several actions worldwide, to support the sharing of best practices towards an equitable accommodation of non-car transport modes. The support towards active mobility will be of particular importance in developing countries [8], where the development of proper infrastructure will be the key to ensure an equitable access to mobility solutions.

Considering the buildings sector, the effect on the energy consumption of households is mostly limited to the lockdown phase [9], although some effects may last longer if people opt for remote working. Some studies have evaluated specifically the effect of the COVID-19 on the consumption of hot water [10], finding that the number of active cases during the lockdown has an impact on both the hot water demand and the daily profile. However, those effects, including higher energy consumption for heating and appliances, need to be compared to the corresponding savings in offices for the same activities. While these comparisons may lead to different outcomes depending on the districts that are analysed, the overall effect may be limited when compared with other sectors.

Some research works have also focused on the direct energy and environmental effects of fighting the COVID-19 pandemic [11], highlighting that sustainability is often not treated as a priority. Yet, the authors suggest that alternative solutions exist to decrease the impacts of COVID-19, but additional research is required to ensure that they guarantee the same level of effectiveness, which needs to remain the first priority.

Many studies have highlighted the effect of the COVID-19 pandemic on the electricity consumption, thanks to the wide availability of electricity consumption data, which are generally easier to monitor compared to other energy carriers [12]. Academic studies have been performed for different countries and with different methods, although they were often limited to the effect of lockdowns rather than focused on medium- or long-term effects. Common findings included a generalized reduction of electricity consumption during lockdowns, as well as a higher contribution of renewable power generation compared with a no-COVID scenario. A number of country-level studies have been presented, including an overview of the effects at the European level [13], and specific analyses for Italy [14], the United States [15,16], the United Kingdom [17], Germany [18] and Brazil [19].

Additional energy impacts are related to the ongoing economic crisis due to the effect of the pandemic on the global economic system. A comprehensive study of the environmental and socio-economic impacts of the pandemic response is provided by the work done by Mofijur et al, in which pollution mitigation, increase in oil prices, unemployment and poverty rates are included in the analysis [20]. Other scholars have evaluated the dynamic effect of COVID-19 on oil markets [21], comparing the impact in different countries at different time horizons. Furthermore, economic conditions influence behaviour and future perspectives, also manifesting psychological issues connected with to economic vulnerability induced by the response to COVID-19 spread [22].

Meso-economic modelling frameworks are adopted for determining the short-term impacts on environmental and economic indicators for distinguishing amongst highly disaggregated economic sectors. Lenzen and colleagues [23,24] estimated an annual reduction of gross domestic product (GDP) and greenhouse gases (GHG) on a global basis of about 4.2% and 4.5% respectively through a global input-output model using disaster impact analysis. Pichler et al. analysed the economics and the epidemiology of reopening UK's commercial and educational activities, capturing the complexity of supply and demand shocks on production networks through a purpose-built input-output model, investigating the trade-off between containing the spread of the virus and limiting the economic downturn [25]. Furthermore, Deloitte estimated sectoral output downturns during the early stage of the pandemic describing the relation between expected logistic behaviour of COVID-19 spread and sector-specific response of Italian regulators [26].

Sectoral economic data usually require years of data gathering and analysis, especially in the developing world, therefore past research has developed other methodologies for producing the needed information for impact assessment. Electricity consumption and night-time light intensity can proxy economic activity and can say something about the economic loss faced by countries, and that is how Beyer and colleagues estimated almost real-time gross value added changes in Indian districts during government restriction, showing how relaxing measures without effectively reducing risks of a COVID-19 infection may not guarantee a full economic recovery [27]. Surveys are used for exploring short-term and medium-term perception of citizens, both for developing countries [28] and developed countries [22], highlighting differences in regional, gender and age response to the adopted restrictive measures.

However, the largest part of previous studies has been focussed on the effects during the pandemic or on the short-term consequences related to the recovery. Few studies have tried to evaluate the impacts with a medium- to long-term perspective. Malliet and colleagues investigate the short-term impact of the pandemic crisis in France, also providing a long-term assessment of the impact of carbon pricing on speeding up the economic recovery through a computational general equilibrium (CGE) model [29]. Studies on the long-term environmental and economic impact induced by COVID-19 are lacking in the current literature, and none have been completed for Italy.

This work aims at filling this research gap, by generating and comparing alternative future scenarios in the case of Italy, relying on a multi-disciplinary approach that can be replicated for other countries. While existing studies have mostly focused on the direct effects of the COVID-19 during 2020, also for the case of Italy [30], we aim at highlighting the medium- and long-term effects of this pandemic, to draw lessons learnt for potential future events that may cause similar impacts. Our main research question is to assess the specific effect of different pandemic durations in terms of energy consumption and emissions. The choice of combining multiple models allows to adopt a properly-designed methodology for each step of the process of estimating sectoral impact, including economic dimension, energy requirements and consequent environmental impacts. Based on the quantitative scenario results, policy insights and perspectives are then derived and discussed.

2. Methods

The modelling framework of this project is developed in a multi-disciplinary perspective, to account for different drivers related to the COVID-19 pandemic, including the impact and duration of the COVID-19 emergency, the policy framework and the fiscal stimulus, the evolution of the green investments and the user behaviours. Thus, different models have been used to estimate the final effects in terms of energy consumption and CO_2 emissions, as represented in the chart of Figure 1. Please refer to section 2.2 for more information about the integrated modelling framework.

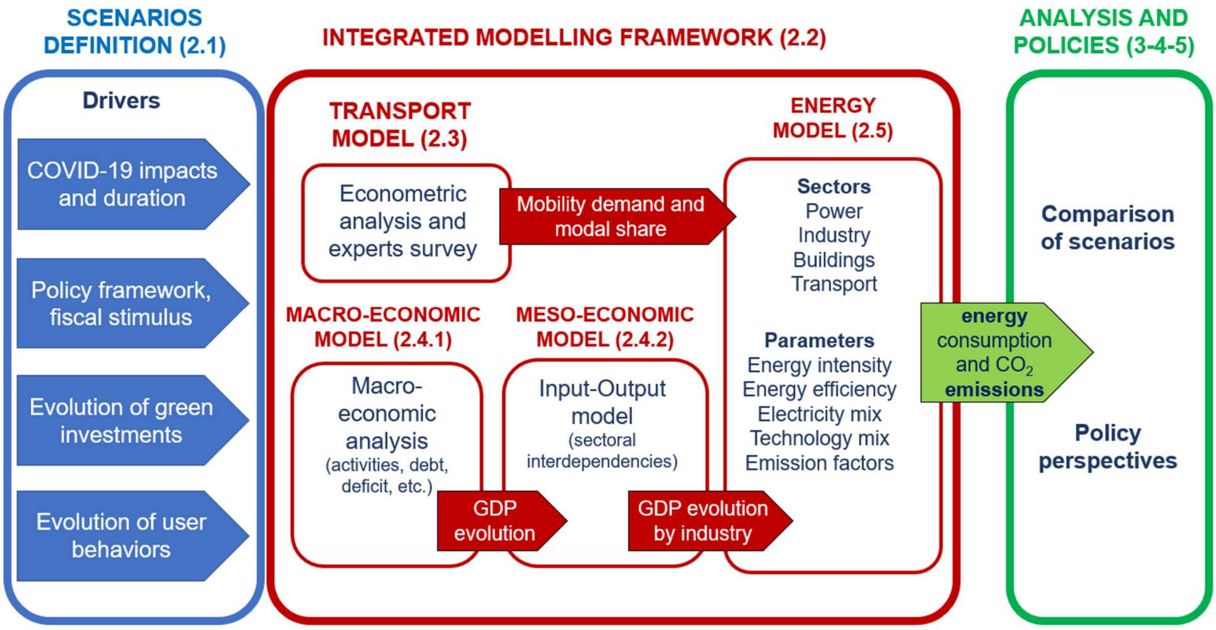

Figure 1 *– Research project workflow and organization of the paper.*

2.1. Scenarios definition

The modelling framework has been applied to three different scenarios, a "best-case", a "medium-case" and a "worst-case". Each scenario assumes a different duration of the "active" phase of the COVID-19 pandemic: we define an end-point of the pandemic when a treatment or a vaccine reduce the stress for the Italian health care system to pre-COVID-19 levels. For all scenarios we assume that before this end-point is met, COVID-19 remains one of the most critical issues for the health care system and significant resources are required to keep the quality of treatment at an acceptable level. After the end-point, the situation in the health care system returns to its pre-COVID-19 situation. All these scenarios have been compared against a pre-pandemic trend, defined as "baseline", that estimated the future energy consumption and emissions if COVID-19 had never happened.

The three end-points that have been considered are January 2021, January 2022 and January 2025. From these end-points onwards, there is no more medical reason for avoiding crowded spots, such as airports, metros/busses, trains or cultural events. The first scenario seems now rather optimistic, also with the rapid development of the vaccines that has been deployed in

European countries. However, these results have been included to evaluate the potential effect of a relatively short shock on the national economy. We believe that these results could be of use for potential future events, to highlight the advantages that can be expected from a quick reaction to a similar shock.

Each of these three COVID scenarios represents a shock (with a different length) to a baseline scenario which refers to the expected pre-COVID economy and energy pathway in Italy to 2030 as it was forecast by the official Italian Energy and Climate Plan of January 2020. In the integrated modelling framework (Sections 2.2. and following) we have tried to simulate short, mid and long term consequences on the economy as a whole and by sector, on the energy system as a whole, by sector and by energy vector, as well as the related greenhouse gas emission changes derived from the pandemic. The main drivers of these impacts for each scenario relate to the intensity of the economic downturn and its recovery (V-, W-, L- shaped), which are a function of many parameters including for instance company bankruptcies representing both a supply but also a demand shock to the economy. It is also driven by the policy framework and in particular the fiscal and macroeconomic stimulus (both national and from the European Recovery Fund), the conditionality of these stimuli on green investments and finally the short term as well as the long term change of behaviour (e.g. increased home office, less business travels, etc). The following sections will present how these drivers have been treated in the different modelling approaches which constitute our integrated modelling framework.

2.2. Integrated modelling framework

As illustrated in Figure 1, the analysis performed in this work is based on an integrated modelling framework that relies on different components which deal with the domains of transport, economy and energy. The framework is based on four modelling tools that are linked together to support an analysis aiming at estimating energy consumption and CO_2 emissions, with additional intermediate results. Those tools, described in the following sections, are a transport model (Section 2.3), a macro-economic model (Section 2.4.1), a meso-economic model (Section 2.4.2) and an energy model (Section 2.5).

The transport model is based on the integration of an econometric assessment and an expert survey, to calculate mobility demand and modal share outputs, to be used to estimate the effect of transport in energy consumption and industrial activities. The macro-economic model has the objective of calculating the future trend of the national GDP by analysing multiple economic indicators, including the debt, deficit and the expected evolution of Italian companies and sectoral activities. The meso-economic model builds on this output to perform a detailed distribution of the GDP in the different industrial activities, by considering the sectoral interdependencies and the users' preferences. Finally, the energy model incorporates the outputs of the previous models to estimate the energy consumption and the direct CO_2 emissions of the different sectors and sub-sectors, by integrating other aspects related to the future National policies. In particular, investments in energy efficiency and renewable generation, as well as the energy intensity of industrial sectors and the evolution of the future vehicles stock, have been considered.

We believe that an integrated modelling framework can provide more accurate and robust results when compared with an analysis performed with a single model, as demonstrated by recent literature on the energy transition [31]. Only multidisciplinary approaches allow to consider the complexity of drivers that lead to energy consumption and emissions. In particular, recent research highlights the importance of an integrated approach when modelling future mobility and energy systems [32–34].

The results of the modelling framework in the different scenarios (Section 3) are then used to support a discussion (Section 4) that aims at evaluating the effect of the pandemic in Italy. Policy recommendations (Section 5) are finally proposed based on the project results and their discussion.

2.3. Transport modelling – users' mobility behaviours

At the height of the 'stay-at-home', or 'social distancing' regulations in May 2020, national GHG emissions decreased by 26%, on average. About half of the GHG reductions are a direct result of changes in surface transportation usage, especially reductions in private car usage and travel intensity, which is in part due to an increasing move to work-from-home (WFH) practices [35]. This paper is a first effort to consider the potential for lasting changes in transportation use, WFH practices, and travel lifestyles even after the pandemic ends.

To accomplish this, the analysis described in this section contributes updated projections of passenger kilometres (PKM) travelled annually by specific modes of transport for use in the energy system model described in Section 2.5. The analysis has three distinct parts:

1) Econometric assessment linking COVID-19 severity, measured by number of patients in the ICU, with the mobility behaviours of Italian citizens as measured through Google Mobility Data.
2) An expert survey as a foresight exercise to predict the long-term impacts of the pandemic on transport demand and mode choice.
3) The merging of steps 1 and 2 to produce predictions of PKM values for the 6 categories of passenger transport, as shown in **Table 1**.

***Table 1**: Original "reference" PKM input data for the energy-transport system model showing 6 categories of passenger transport (source: NECP Italy, https://www.mise.gov.it/images/stories/documenti/it_final_necp_main_en.pdf)*

		2015	2020	2025	2030	2035
Population	Millions	60.8	61.2	62.2	63.3	64.4
Public road transport	Mil. PKM	102,605	105,080	107,022	108,901	112,051
Cars	Mil. PKM	676,350	717,501	714,012	724,982	730,551
Motorcycles	Mil. PKM	41,300	40,966	41,442	42,321	44,314
Rail transport	Mil. PKM	58,900	64,919	73,433	87,268	91,549
Aircraft	Mil. PKM	55,919	63,446	70,138	75,439	82,748
Domestic navigation	Mil. PKM	4,861	5,001	5,127	5,234	5,373
Total passenger transport	Mil. pkm	939,935	996,913	1,011,175	1,044,145	1,066,586

2.3.1. Econometric analysis

The econometric analysis correlates the severity of the Italian COVID-19 pandemic with the mobility patterns of Italian citizens. Mobility patterns are measured by the Google Mobility data

[36]. Mobility is grouped by type of location: retail and recreation, grocery and pharmacy, parks and outdoor recreation, public transit, workplaces, and residential. For all categories besides 'residential', the data show the number of visits to these location types. The data are expressed as percent change from the Pre-COVID baseline for that day of the week, which is calculated based on the mobility patterns in January 2020. The data show that overall mobility in Italy declined during March and April bottoming out at the end of May. Mobility slowly returns toward the baseline with the exception of time spent at parks and outdoor recreation that Italians enjoyed in the summer, possibly due to the lower risk of infection when outdoors. By early August, weekend work, grocery and public transit mobility is back to baseline values, while weekday mobility remains about 5% and 25% below the baseline for public transit and work, respectively.

To correlate mobility patterns to the COVID-19 severity we use the number of patients in the intensive care unit (ICU) on a given day [37]. Measuring COVID-19 intensity via ICU patients avoids the issue of testing that would be incumbent in other measures such as active cases. Figure 3 gives a first look at the development of the COVID-19 pandemic in Italy as measured by ICU patients versus the Google mobility data for the public transit category. A clear negative relationship between COVID-19 prevalence and public transit use emerges.

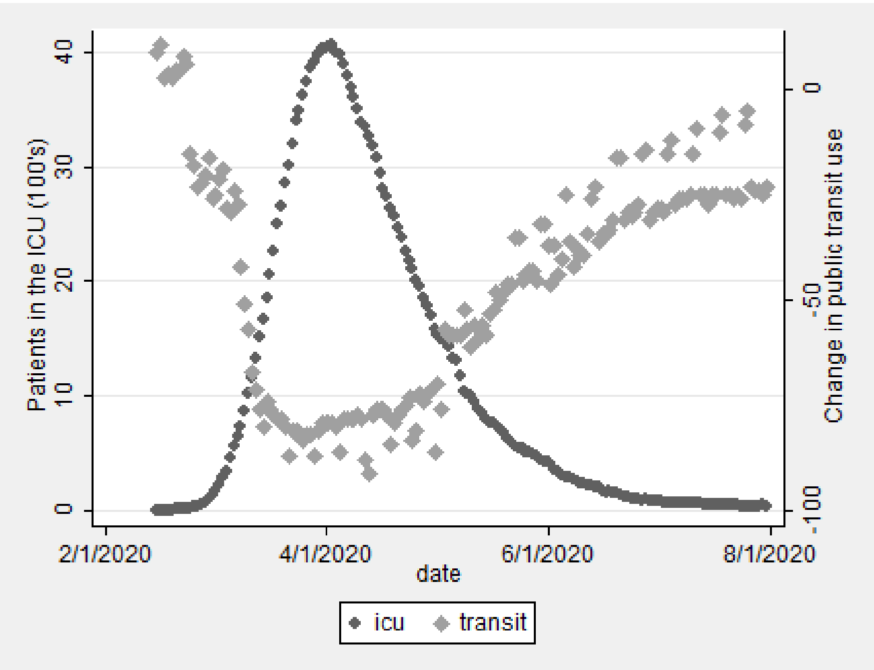

Figure 2 *– Daily COVID-19 ICU patients vs. public transit usage in Italy*

To quantify the correlation between COVID-19 patients in the ICU and Google mobility trends we implement a Seemingly Unrelated Regression (SUR) model with the following form:

$$Mobility_i = \alpha_i + \beta_i ICU_i + \gamma_i ICU^2{}_i + \epsilon_i \quad (1)$$

Where $Mobility_i$ is an *n* by 1 vector of daily deviations in mobility from the baseline for mobility category *i*. This is related to the vectors of ICU patients and their squared values by the slope coefficients β_i and γ_i. The full model is a system of equations where the single equation for each category *i* are estimated simultaneously via FGLS. The ϵ_i terms are normal i.i.d within each equation, but allow for cross-equation contemporaneous correlation. The estimation data are summarized in Table 2.

Table 2*: Summary statistics for data used in econometric estimation– 168 observations from Feb. 15th – July 31st. Variables retail, grocery, parks, transit, workplaces and residences are daily Google mobility data given as pct. change from pre-COVID baseline for location categories, as explained above.*

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max**
retail	-41.23	32.77	-96	3
grocery	-22.85	22.86	-94	23
parks	-5.70	60.36	-91	119
transit	-45.03	26.89	-91	11
workplaces	-35.30	23.26	-90	12
residences	13.43	12.30	-7	41
ICU (100s of people)	11.11	13.04	0	40.68
ICU-squared	292.54	485.49	0	1654.86

The results of the SUR model system of equations are given in the supplementary materials (Table 2). They show a statistically significant negative correlation between ICU patients and the frequency of visits to retail, grocery, parks, public transit, and workplace locations. The significant γ_i coefficient on these 5 equations suggests a diminishing marginal negative relationship of ICU patients on mobility. Note, the high R-squared values for most equations and the low RMSE relative to the variable means suggest that ICU patients are a good indicator of mobility patterns during the pandemic period in Italy, and that predictive errors will be reasonable. The variable 'constant' in the supplementary materials (Table 2) gives the estimates of α_i.

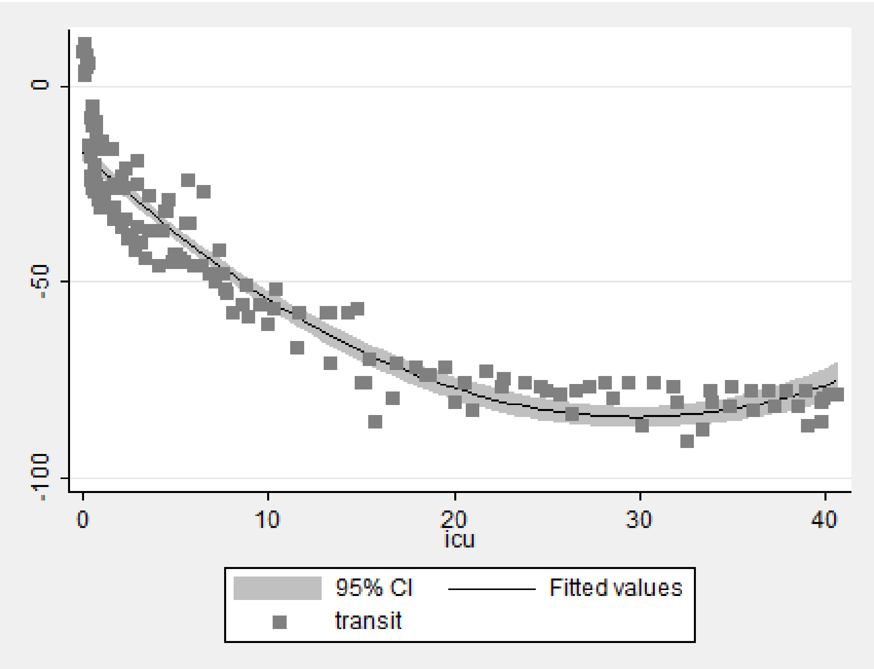

Figure 3 *– Fitted regression line for transit category and public transit Google mobility observed data.*

Testing the equality of β_i coefficients across each equation *i* via Wald test with Bonferroni-adjusted p-values confirms differential effects of additional ICU patients on each mobility category, with the exception of grocery and workplaces. Figure 3 shows the fitted regression line versus the public transit mobility data. This confirms the very strong fit of the model using only ICU patients as explanatory variables. Note that the fit of the model is poorer when the number of ICU patients is low.

2.3.2. Expert survey

An expert survey was conducted using a panel of Italian professionals in the mobility field representing academics, practitioners and public administrators. The experts were asked to provide their estimate about the variation in mobility choices and demand, in total and broken down by the modal split shown in **Table 1**. Experts provided their predictions for each of the three COVID-19 scenarios adopted in this study and two time horizons, by 2025 and by 2030. The predictions were submitted in terms of the percentage change in PKM from the status quo values in 2019.

Through a snowball sampling procedure, a group of 34 experts was surveyed in July 2020. The majority (73%) hail from research institutes followed by public administrators (15%). The most represented area of expertise was 'transport and mobility' (62%), followed by 'planning' (15%), and 'environmental and sustainability' (14%). The responses may reflect sampling bias; however, as the survey specifically targeted experts in the mobility field such sampling techniques are needed to recruit expert participants within a short timeframe. Further details on the surveying procedure, sample statistics, full results and discussion are provided in the Supplementary Materials.

Table 3 gives a summary result of the expert survey. The expert-predicted percentage change is calculated as the weighted mean of the midpoint (or endpoint) of the range over all 34 responses. The weights are the proportion of experts that chose a given range as the mobility change for the referenced year.

***Table 3**: Expert survey summary responses (mean change from baseline in % change of PKM category for 3 COVID-19 scenarios; N=34)*

	Scenario (end of pandemic)	*% change by 2025*	*% change by 2030*
Public Transit	Jan. 2021	-16.1%	-14.7%
	Jan. 2022	-20.9%	-19.1%
	Jan. 2025	-29.2%	-25.4%
Car	Jan. 2021	-2.6%	-2.0%
	Jan. 2022	1.2%	0.1%
	Jan. 2025	6.4%	2.6%
Motorbike	Jan. 2021	2.7%	2.4%
	Jan. 2022	5.1%	6.4%
	Jan. 2025	10.3%	8.6%
Train	Jan. 2021	-11.2%	-10.3%
	Jan. 2022	-13.3%	-13.1%
	Jan. 2025	-20.0%	-14.6%

2.3.3. Combining econometric estimates and expert survey results

The econometric analysis reveals the effects of active COVID-19 outbreak on Italian mobility patterns, while the expert surveys give foresight as to the lingering impacts of the pandemic on mobility after the virus itself is eliminated. There are three distinct time frames in relation to the length of the pandemic scenario for current and future PKM estimation. Each time frame uses a distinct method to produce the final prediction as explained below.

In-sample predictions of PKM under COVID-19 (Jan. 1st – June 30th, 2020). The public transit Google category maps 1:1 with rail and bus usage PKMs. The other four relevant Google mobility categories (parks, workplaces, retail, and grocery stores) are combined in a weighted average to give the predicted change in PKM for motorbike and car usage under COVID-19. We use the rule of thumb that 1/3 of personal travel in Italy is related to each of work commuting, necessary errands (i.e. grocery and pharmacy), and recreation travel [38]. Therefore, the weighted average PKM gives weights of 1/3 to the Google grocery and workplace categories and weights of 1/6 to the parks (outdoor recreation) and retail (indoor recreation) categories. The calculation of predicted PKM under COVID-19 is carried out by applying these weights to the mobility changes. We obtain the predicted relative change in the mobility mode types as from **Table 1**. These predicted changes (e.g. $Change_{cars}$) are then applied to the reference data of the respective period for obtaining the absolute expected PKM in the respective category as the equation below

$$\widehat{PKM}_{cars,period} = Change_{cars} \, x \, PKM_{cars,period} \qquad 2$$

with

$$Change_{cars} = Mobility_{retail} \, x \, 0.165 + Mobility_{parks} \, x \, 0.165 + Mobility_{groceries} \, x \, 0.33 + Mobility_{workplace} \, x \, 0.33$$

where $PKM_{cars,period}$ is the PKM for the mobility mode "cars" during the period of interest in the reference data and $\widehat{PKM}_{cars,period}$ is the estimator of the same quantity under COVID-19. $Mobility_i$ holds the mean daily change of Google mobility category *i* and $Change_{cars}$ then refers to predicted relative change of the transport mode "cars".

Out-of-sample predictions after June 30th, 2020 where COVID-19 is assumed to still be circulating in the Italian population. For each period after June 30th, the number of patients in the ICU and the Google mobility data are not available. The analytical strategy thus estimates these two quantities first, and once these estimates are available, $\widehat{PKM}_{m,period}$ is predicted in the same way as in equation 2, where subscript *m* refers to any of the analysed mobility mode types from **Table 1**. We use the SUR statistical model results shown in in the supplementary materials (Table 2) to compute expected values for each Google mobility category under COVID-19. For the number of ICU patients in this imputation we use the mean observed ICU patients for May – July (=383) to represent a situation where COVID-19 spread is still underway within the population. This avoids the large early spike in Italian cases (on April 3rd 2020 4,068 patients were in the ICU), which arose when the nation was not fully prepared for the pandemic and social distancing practices were not in use.

Out-of-sample predictions after COVID-19 is assumed to be neutralized in Italy. For the post COVID-19 period in each scenario, we rely on the expert interviews, which give an estimate of mobility usage by mode for 2025 and 2030. The predicted PKM for each mode goes immediately to the expert-predicted value when the scenario assumes COVID-19 is neutralized.

The expert predicted values expressed as changes from the baseline are shown in Table 3. The 2020 reference value (pre-COVID, **Table 1**) is then multiplied by this weighted average predicted change in mobility to give the predicted level of PKM in each modal category.

2.4. Economic modelling

In this section, we present the models adopted for evaluating the economic impact of COVID-19 in Italy. First, we describe the macro-economic model adopted for projecting Italian GDP up to 2023, then we outline the meso-economic model used for determining sectoral GDP distribution.

2.4.1. Macro-economic model

The future evolution of the Italian GDP has been forecasted considering the projections from the main international institutions (e.g. International Monetary Fund, European Commission, OECD, Bank of Italy) aiming to reduce the level of uncertainty in the analysis. The time series of the developed economic scenarios cover the period 2016-2030 and can be divided in two subsamples: the period 2016-2019 which accounts for historical data, and the GDP forecast for the period 2020-2030.

Apart from the three COVID-19 scenarios, the evolution of the GDP has been projected for a fourth counterfactual scenario. This baseline scenario has been developed using the long-term growth projections available until November 2019, pre-COVID-19 forecast. We used data of the real GDP long-term forecast from the OECD [39].

For the sake of simplicity, we model the economy according to the standard Keynesian approach with an exogenous public expenditure equal to a certain level (G_t). Hence, the equilibrium in the market occurs when:

$$Y_t=C_t+I_t+G_t-T_t+\epsilon_t,$$

where *Y* is the production (GDP), *C* and *I* represent consumption and investment respectively (i.e. the private expenditure), *T* represents the tax revenues, whereas ϵ_t is the aggregate shock. The pandemic shock evolves according to an auto-regressive process:

$$\epsilon_t=a_t*\epsilon_{t-1}+\xi_t$$

with ξ_t representing a random shock and where the duration changes according to the COVID-19 fade assumption, i.e. the weight of a_t is positive when the pandemic effects are still in the economy and it is fixed to zero otherwise A number of assumptions have been used: to reduce the level of uncertainty due to possible nominal variations (i.e. exchange rates or inflation dynamics), all the scenarios are expressed in terms of real GDP at constant local currency unit (euro) fixing 2016 as base year. All three COVID-19 scenarios contain three common elements: I) the convergence to the benchmark growth path (i.e. baseline) when the effect of the health crisis fades; ii) a set of direct expansionary measures from the European Union (i.e. grants) during the COVID-19 pandemic aiming to boost the recovery; iii) the assumption that the growth rate is negatively affected by the interest payment on public debt which depends on the debt evolution over time [40–42]. According to the literature, increase in the government-debt-to-GDP ratio leads to higher government bond yields affecting the economic growth rate. This allows to take into account in the GDP forecasts not only the COVID-19 crisis effect but also its impact on the soundness of the Italian public finance introducing an amplification mechanism.

Analysing the three scenarios separately, the downturn of the best-case has been computed using the average consensus of the forecasts of the main financial institutions which, when the analysis was made in Summer 2021, assumed that the negative impacts of COVID-19 would fade by January 2021 [43–46].

We adopt the same approach to forecast the 2020 GDP disruption for the medium and worst cases. Then, fixing the pandemic length, according to the scenario definitions, we forecast the GDP growth rates, using historical crises with comparable duration with the two scenarios. For the medium scenario, which lasts until January 2022, we assume that it will be comparable with the evolution of the European debt crisis and which will last two years, with a convergence process to the pre-COVID-19 growth rate when the crisis will fade. The economic dynamics of the worst-case has been calibrated estimating the growth rate in the period 2008-2016 which recorded two turmoils, subprime and European debt crises, rebalancing it to match the long-term growth projection, produced before the pandemic crisis. Finally, the growth rates have been adjusted introducing the European aids which are proportional to the duration of the COVID-19 in line with the European principle of subsidiarity and proportionality. According to the Recovery Plan proposal of the European Commission, the magnitude of the EU aids for Italy should be 209 billion euros (€82 billion of which in grants, the balance in loans) to be mainly spent between 2021 and 2023 (Piano Nazionale di Ripresa e Resilienza, approved by the Council of Ministers of January 12, 2021).

2.4.2. Meso-economic model

The role of the meso-economic model is to provide a sectoral disaggregation of the GDP pathways derived by the economic model: this constitutes an essential step and an input to the Energy model which requires sector-specific activity levels for every scenario. The Input-Output model adopted for this purpose can be defined as a single-region, multi-sectoral, linear optimal resource allocation model grounded on empirical data in the form of Input-Output tables (Eurostat national accounts). The model represents the transactions of goods and services across all national industries and final consumers in one given time frame (1 year). In particular, the model assumes the structure of all industries in the economy as fixed and not influenced by the level of production of each sector (this is usually mentioned as the *Leontief technology assumption*), while the production must serve an exogenously fixed product distribution of final demand (sometimes referred to as the *Kantorovich assumption*) [47]. Final demand yield is bound by the availability of factors of production at aggregated national level, which is determined by the macro-economic model (section 2.4.1). Notably, the industrial structure of production and the composition of the consumers' consumption basket are determined exogenously in order to be coherent with the assumed scenario narrative. This approach has been recently adopted for assessing future development scenarios in [48,49]. The so-called Leontief-Kantorovich model is formalized by the linear optimization problem 3, working for each of the *j* cases resulting from the combination of years and scenarios.

$$
\begin{aligned}
&max \quad Y_j = \mathbf{y}_j{}^T \cdot \mathbf{i} \\
&s.t. \\
&\qquad (\mathbf{I} - \mathbf{A}_j) \cdot \mathbf{x}_{\boldsymbol{j}} \geq \mathbf{s}_{\boldsymbol{j}} \cdot Y_j \\
&\qquad (\mathbf{B}_j \cdot \mathbf{x}_j)^T \cdot \mathbf{i} \leq GDP_{\boldsymbol{j}} \\
&\qquad \mathbf{x}_{\boldsymbol{j}} \geq \mathbf{0}
\end{aligned} \tag{3}
$$

In particular, the model determines the vectors of output ($\mathbf{x}$) and absolute demand ($\mathbf{y}$) of both products and economic activities, as well as the resulting maximized scalar value of aggregated final consumption (Y). This is done while:

- guaranteeing the satisfaction of both final demand, which is distributed as described by the consumer preferences ($\mathbf{s}$), and intermediate demand, determined by the supply and use representation of the technological structure of the economy ($\mathbf{A}$);
- respecting the exogenous constraint of not exceeding the overall scalar level of gross domestic product (*GDP*), represented by sum (being $\mathbf{i}$ a sum vector) on each activity product between the representation of the input factor (labour and capital) structure of each economy activity ($\mathbf{B}$) and its output;
- providing positive values of product and activity output.

In order to perform this analysis, a dataset of supply and use input-output tables (SUT), economic-wide databases able to capture the flows of monetary value between different sector, was used. Eurostat's data explorer tool allows for the extraction of Italian supply and use tables from 2010 to 2016 [50]. The dataset, which presents a high level of detail resulting in 65 products, 65 activities and 5 factors of production, serves two purposes:

- offering the Italian supply and use structure of products, activities, imports and factors of production for years 2014, 2015 and 2016 which is adopted also for representing years from 2017 to 2030, being the must updated input-output database available;
- projecting linearly future preferences of product consumption on the basis of past values (from 2010 to 2016) of vector $\mathbf{s}_j = \mathbf{y}_j \cdot (\mathbf{y}_j{}^T \cdot \mathbf{i})^{-1}$.

The approach assumes that past trends properly fit changes in consumer preferences: some products are becoming less relevant in final demand share (e.g. printing and recording services) while some others weight more and more (e.g. electricity, gas, steam and air conditioning services). It should be mentioned, that even if a final product would be no longer demanded, its production is not necessary going to 0 since indirect demand of intermediate industries may be necessary.

For the sake of simplicity of case definition as well as result analysis and comparison, the same annual share of final demand is adopted in every scenario. This approach may seem simplistic but we think that more complex yet speculative approaches, still to be supported by the literature, are not necessary superior in modelling future changes in consumer preferences. The level of sectoral GDP is therefore solely determined by the optimal solution of production for maximizing final demand while respecting the shares of the basket of products consumed and constraining economic activities' overall output to the level of national GDP provided by the economic model. This assumption implies the continuation of relative trends in production by activity and, consequently, sectorial energy demand, in each scenario.

The resulting sectoral GDP is delivered to the energy model for every combination of year and scenario.

2.5. Energy model

Our analysis focuses on transport and industry, which are the sectors that are most strongly affected by the effects of the pandemic. A precise estimation of the effects of COVID-19 on buildings is beyond the scope of this work, since there are no evident drivers to analyze clear phenomena in buildings. The potential increase of households' energy consumption due to teleworking, as suggested by some research studies, may be offset by a comparable decrease in the energy consumption in offices, with little effect on the total buildings' consumption. Thus, an historical trend has been considered to incorporate this sector in the final results, which reflects the continuous increase in both energy efficiency and electricity penetration in the sector. Other sectors, including agriculture, forestry and fishing have not been considered due to their very low impact on final energy consumption (they represent together 2.5% of the total consumption).

The energy consumption of the industrial sector has been calculated by considering the historical trend of the energy intensity, measured as energy consumed per unit of GDP. This trend has been calculated for the main energy carriers used in the industrial sector, by considering seven industry sub-sectors that represent more than 90% of the energy consumption in the Italian industry (cement, chemicals, food manufacturing, machinery, metals, paper and printing, textiles). Electricity and natural gas are the main energy carriers across all the activities, while specific industries use also heat (produced by external plants), coke oven coke and petroleum coke, in addition to a marginal share of other fuels.

The input data used in this estimation are: (1) the historical energy consumption of different industrial sub-sectors, (2) their historical GDP and (3) their expected future GDP in the different scenarios. These data have been used to calculate a trend of energy intensity per each sub-sector and per each energy vector (expressed in Mtoe/M€) in the years 2014-2018. This historical trend has been used to estimate the future evolution of the energy intensity for each subsector by a linear extrapolation. Those coefficients are used to estimate the future energy demand of industry, divided by sub-sector and fuel. This choice relies on the assumption that past energy efficiency trends will continue in the future, for all the COVID-19 scenarios presented above. On the one hand, lower GPD may lead industries to decrease investments in energy efficiency, but on the other hand, since energy costs may represent a significant share of total costs, lower margins may also lead to increased effort in cutting energy costs. In addition, economic resources included in the Recovery Fund are dedicated to improving the energy efficiency in different sectors. Thus, we believe that this assumption is on average a reasonable approximation.

To model the energy consumption of the transport sector, we used a model that estimates the performance of the future vehicle fleet considering the technological evolution, both in terms of efficiency and share of vehicle types. Such an evolution is not an endogenous result of a least-cost optimization, but it is based on the expected penetration of different technologies based on the national targets presented in official sources. In particular, the evolution of the stock of private cars has been considered in accordance with the goals of the National Energy and Climate Plan [51]. The energy consumption is estimated by considering the evolution of the mobility demand, with the support of average consumption coefficients per each mode, technology and fuel, based on different literature sources. Reference values have been assumed to consider vehicle occupancy, based on historical values for Italy and the expected trend in the future. The model is also accounting for the evolution of the carbon intensity of the electricity, which will be a key aspect in a sector that aims at increasing the electricity penetration. The same model has been applied to both passenger and freight transport, although with different methodologies to estimate transport demand, as better described below. Further information on the model, which has also been presented in other publications [52], is available in the Supplementary materials of this article.

Passenger transport demand has been obtained by defining future trajectories of passenger demand (expressed in passenger-km, PKM) on selected land transport modes (cars, motorcycles, public road transport, rail), as described in Section 2.3. Other passenger transport modes, such as domestic aviation and domestic navigation (international travels are not considered in national statistics), have been estimated by a common trend throughout the scenarios, due to a lack of reliable data to perform separate estimates. This approximation is acceptable since they represent a marginal contribution to the energy consumption of the transport sector (around 4% of the final transport energy consumption in 2018). Conversely, the freight transport has been built on the very same model used for passenger transport, considering as input data the expected evolution of freight demand (expressed in tons-km – tkm), adjusted by the overall industry GDP trajectories estimated in the different scenarios (the freight transport demand is available in the supplementary materials).

3. Results

In this section, a selected set of results are provided, with special focuses on mobility demand, national and sectoral economic performance, and energy uses (sub-sections 3.1, 3.2, 3.3 respectively).

3.1. Future mobility demand

Estimated future mobility demand in Italy under COVID-19 is expressed as PKMs (person kilometres) travelled annually for each transit mode represented in Table 1. The complete set of estimated values is given in the Supplementary Materials, Table 3. Summary results for public and private transport modes are shown graphically in Figures 3 and 4, respectively.

Public modes of transport include buses and trains, while private modes include cars and motorbikes. Consistent with the observed data, the estimates reflect a decrease in public transport use by 44% in 2020 under all COVID-19 scenarios *vis a vis* the baseline. By 2030 public transit use rebounds somewhat to 24-31% below the baseline, reflecting the experts' views that the public transit sector faces a long-term decrease in demand due to the pandemic.

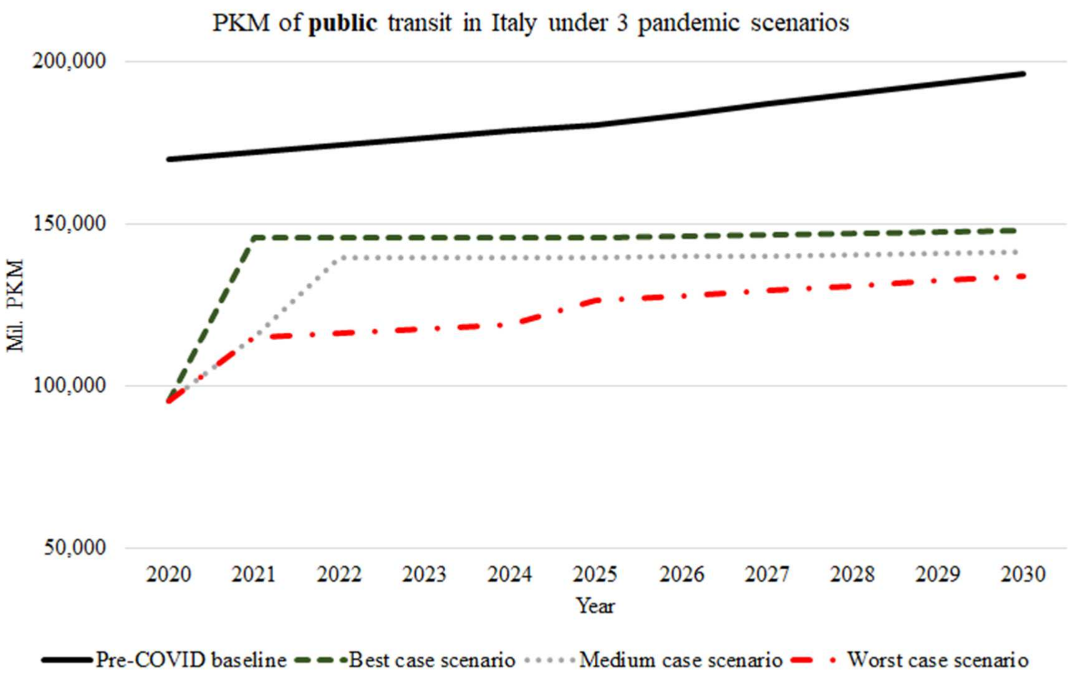

Figure 4 *– Annual PKM of public passenger transport modes in Italy under 3 pandemic scenarios through 2030.*

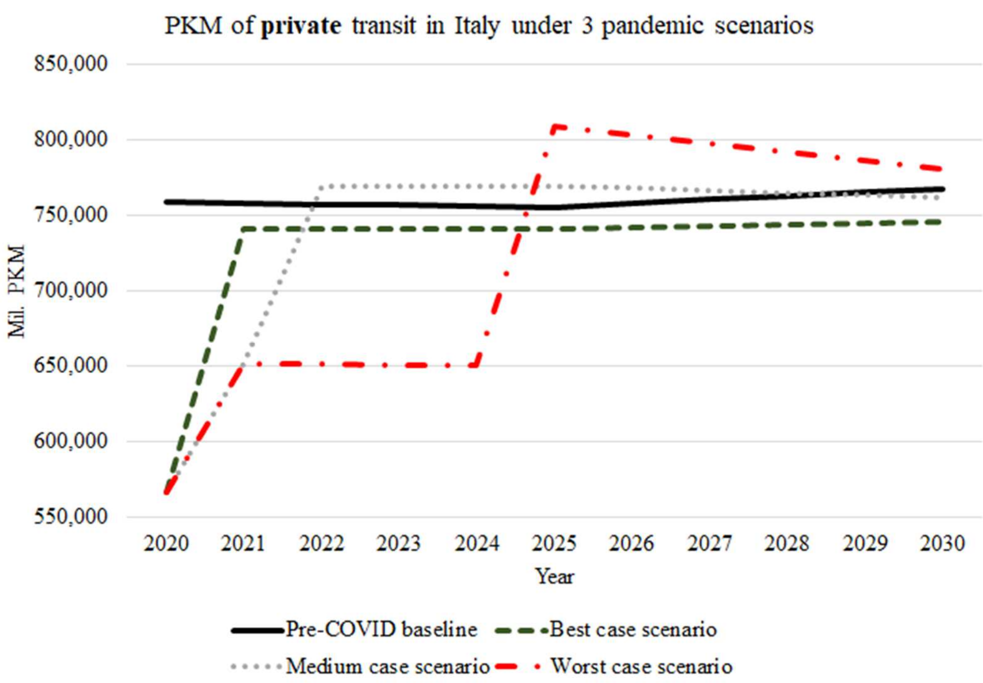

Figure 5 *– Annual PKM of private passenger transport modes in Italy under 3 pandemic scenarios through 2030.*

In contrast, demand for private modes of motorized transit is not estimated to deviate substantially from the baseline trend due to the pandemic. In 2030, private PKMs are expected to deviate by between 2.9% and -1.7% from the baseline prediction. The expert opinions suggest that the longer COVID-19 remains in society, the higher future demand for private transit will be. In 2020, demand for private transport is estimated to be 25% below the baseline, showing lower impacts from the pandemic in the private transit sector also for 2021. Overall, the results suggest a shift away from public motorized transport, little to no long-term effects on private motorized transport and a resulting small decrease in overall motorized transport demand until 2030. The overall decrease in transport demand likely reflects a decrease in motorized mobility, for example as work-from-home practices become more common, and perhaps an increase in active modes of transport such as biking and walking.

3.2. Economic conditions

The first part of the economic analysis relates to the evolution of the aggregate GDP growth rate, which is represented in **Figure 6**. For each COVID-19 scenario, we have investigated two different possible frameworks: one in which the European grants are supplied without any conditionality (solid lines), and one in which the recovery funds from the European Union must be followed by restrictive measures aiming to restore a fiscal consolidation (dotted lines); i.e. by increasing the taxation to converge to the pre-pandemic public deficit level. We introduce these twin scenarios, accounting for the possibility that after the first months of pandemic, in which there has been a call for solidarity in the European institutions, the compliance to the Treaty on Stability, Coordination and Governance in the Economic and Monetary Union (i.e. fiscal compact) returns to be required. In the simulations, this implies a fiscal restriction from 2022 till 2025, aiming to partly stabilize the public deficit.

Under our assumptions, the three COVID-19 scenarios projection points to contracting by 8% in 2020. After this sharp fall, in the best-case scenario, the GDP growth rate exhibits a rebound, thanks to the expansionary measures, converging to the long-term rate of growth by 2025. Considering the medium-case scenario, the reduction becomes significant both in the medium and long-term. Even if the economy will register positive growth rate (+3% in 2023) when the COVID-19 could fade, this growth will be weaker than in the best scenario because the extended pandemic will have depleted the economic system for more periods. The worst scenario exhibits the same evolution of the variables but with a higher magnitude. In all the three COVID-19 cases, the implementation of restrictive fiscal policies (I.e. new or higher taxes) reduces the restoring capability of the Italian economy reducing the growth rate. Compared to the twin alternative, this decrease in the GDP level is equal to 0.75%, 0.83% and 0.94% for the best, medium and worst scenario, respectively. Hence, a trade-off between economic growth and public finance sustainability arises.

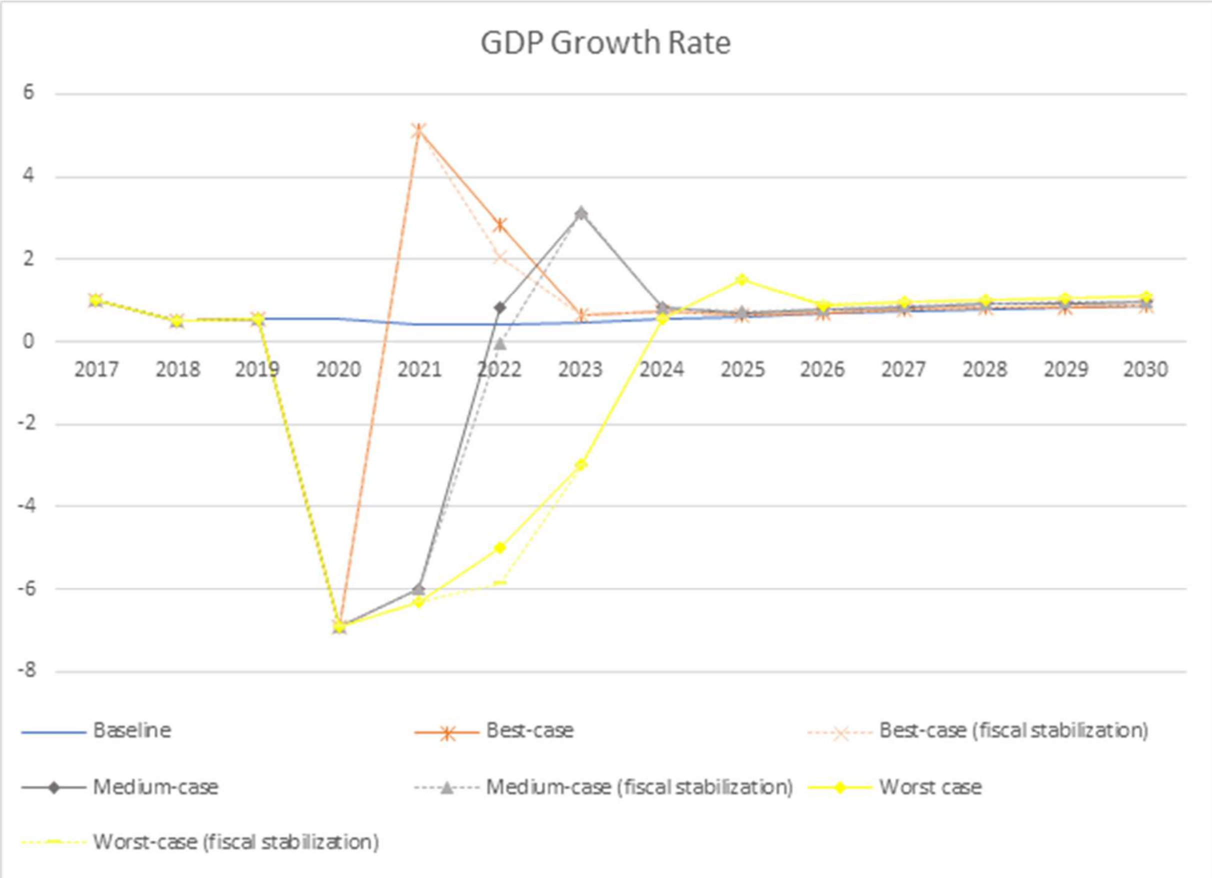

Figure 6 *– Evolution of the GDP growth rate in the four scenarios, percentage.*

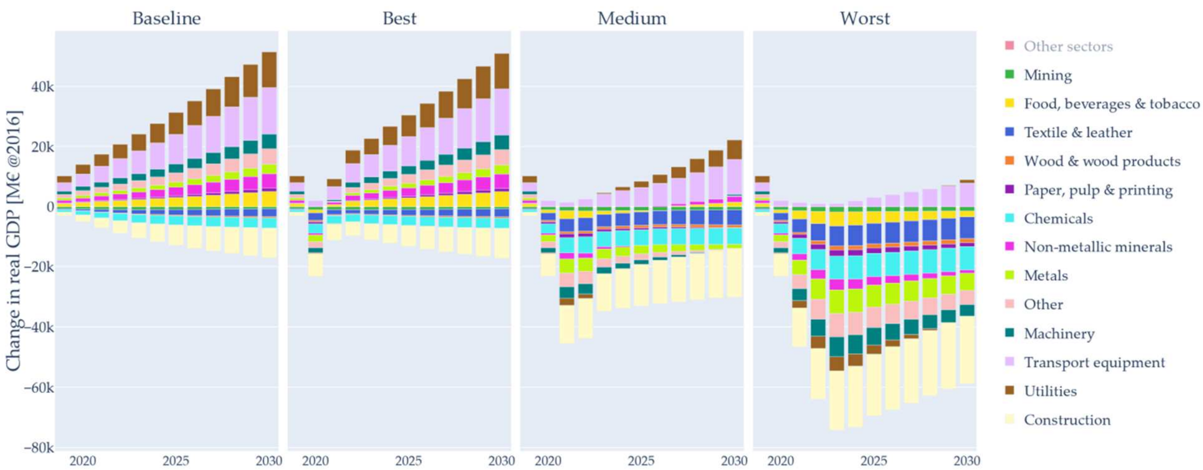

Figure 7 *– Change in real GDP by industrial sectors from 2019 to 2030 in different scenarios with respect to 2016 baseline in million euros at 2016 prices.*

The presented evolution of GDP by year and scenarios is then distributed among industrial sectors based on the input-output model described in section 2.4.

Figure 7 provides the change in GDP by industrial sector, expressed as the difference with respect to the values observed for the reference year 2016, for all the analysed scenarios.

In the "Baseline" scenario, the national GDP was expected to grow as the sum of different opposing contributions, obtained by projecting the historical national consumption trends of recent years (2010-2016). Among others, Utilities, Transport equipment, Machinery and Food industries were expected to steadily increase their contribution to national GDP growth, increasing by about 37 B€ between 2016 and 2030 (representing an increase of 2% compared to the 2016 GDP). Some other industries on the other hand, in particular Construction and Chemicals, were expected to see in the baseline scenario a continuation of their downward trends.

The "Best" scenario differs only slightly from the "Baseline": after the 2020 shock, which causes a short term sharp GDP reduction across all national industries, the overall and sectoral GDP values are expected to recover quickly (already by 2022) coming almost back in line with the projections of the "Baseline" scenario.

In the "Medium" and the "Worst" scenarios on the other hand, almost all the industries are experiencing a much more sustained and stronger downturn in the short term (in the “Medium” scenario up to 2022, in the “Worst” scenario an even more brutal downturn lasting until 2023) before a slight recovery starts but which will never allow overall and sectoral GDP levels to reach pre-COVID levels within the analysed time horizon. In these scenarios, only the Utilities and Transport equipment industries show positive contributions to GDP, overall contributing by +1% ("Medium" scenario) and +0.5% ("Worst" scenario) by 2030 with respect to total 2016 GDP. All the other industries are expected to reduce their GDPs. More specifically, in the "Medium" and “Worst” scenario, the downturn of Textile & leather, Chemicals and Construction industries are expected to experience a reduction in sectoral GDP ranging from -21% up to -30% in 2030.

3.3. Energy consumption and emissions

The medium-term effects of the COVID-19 in terms of energy consumption have been estimated for each scenario. In comparison with the baseline (i.e. a world without the COVID pandemic), the “Best” scenario shows a 1% reduction, and the “Worst” scenario a 9% reduction in 2030. Considering the sectorial energy consumption, the negative effect on industry appears stronger, with a 23% reduction of energy consumption by 2030 in the “Worst” scenario in comparison to the baseline. Conversely, the influence on the energy consumption in the transport sector in the “Worst” case is limited to 10%. A comparison across the sectors is reported in Figure 8.

Yet, the largest contributor to Italian final energy consumption remains the buildings sector (45% in 2018), which was not included in this analysis due to the little consequences expected on buildings consumption in different pandemic scenarios. A potential effect could be related to the operation of some commercial buildings (e.g. hotels, cinemas, closed commercial activities, etc.), and additional research may be needed to assess if such an effect would have a significant impact on the total energy consumption on the medium and long term.

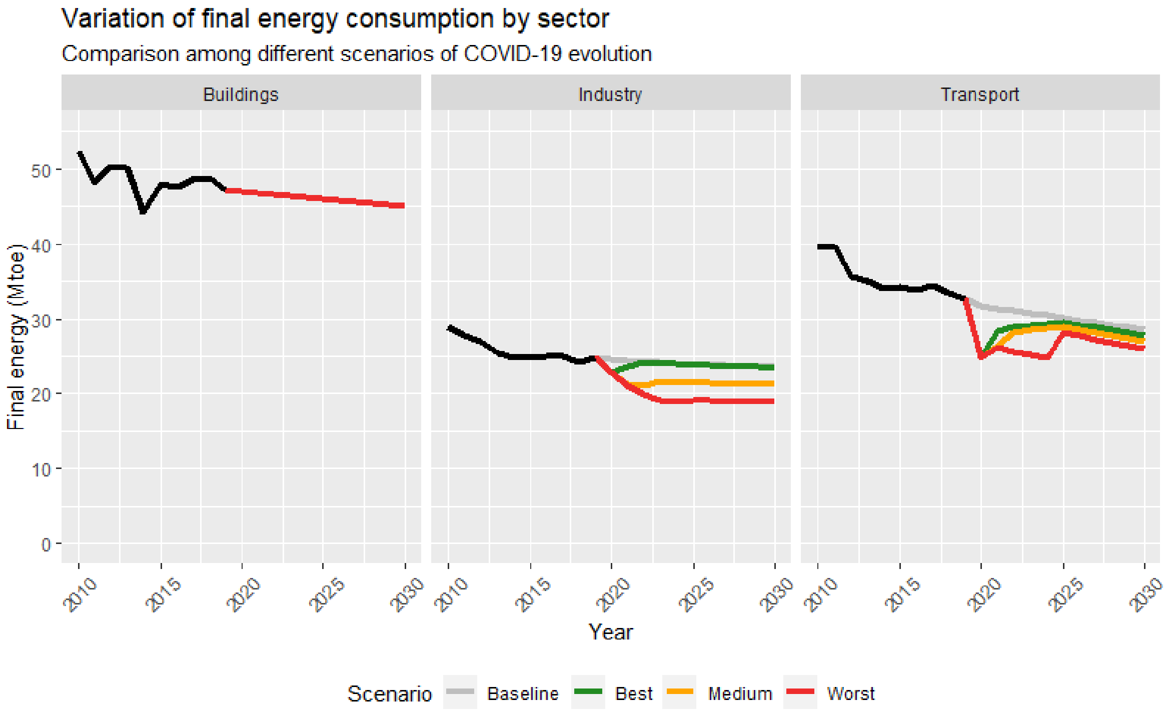

Figure 8 – Future final energy consumption in Italy by scenario and by sector.

The results presented above have been used to calculate the related CO_2 emissions, by considering specific emission factors for each energy carrier. The emission factors account for the direct emissions generated during the combustion phase, including the production of electricity and district heat that are consumed by final users.

The future trends of direct CO_2 emissions are reported in Figure 9, divided by energy carrier. Their evolution across scenarios follows the one represented above for the final energy consumption, but there is a strong decrease of the electricity-related emissions, thanks to a rise of the share of renewable sources in power generation, in accordance with national targets. In the Medium scenario, CO_2 emissions in 2030 sum up to 210 Mt, representing 5% less than the baseline and a 33% decrease against 2015 emissions. In the Best scenario 2030 emissions reach 218 Mt, 1% lower than the baseline, while in the Worst scenario they sum up to 202 Mt (8% less than the baseline).

In the medium scenario, and considering the sectors addressed in this study, industry shows a 10% decrease with respect to the baseline, while transport reaches a 6% decrease (emissions totalling 46 Mt and 80 Mt respectively). When compared with 2015 values, sectoral emissions show a 42% decrease for industry and a 27% decrease for transport.

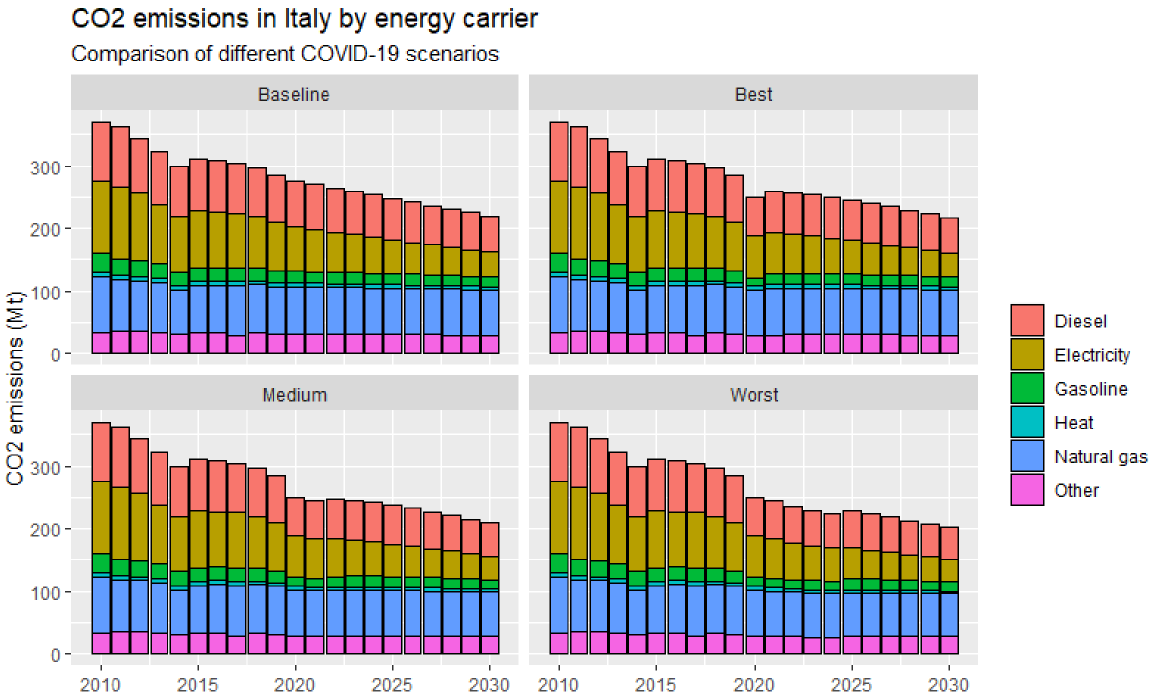

Figure 9 – Future CO_2 direct emissions in Italy by energy carrier (million tonnes).

Considering the different industrial sub-sectors in Italy, the ones with the highest emissions before the pandemic were cement, metals, machinery and chemistry. These industries were accounting together for almost two thirds of the total industrial emissions. The sector with the highest emission decrease from pre-pandemic levels (i.e. 2019) to 2030 is the chemical industry, ranging from -39% (Best scenario) to – 51% (Worst scenario). The other major emitters showed slightly lower decreases, with figures for the ranges 30%-44% for cement, 25%-40% for machinery and 27%-41% for metals. However, a large contribution to these emission reductions comes from the historical improvement of the energy efficiency in industries, with the CO_2 savings in the *Best scenario* that are almost in line with the Baseline scenario. The effect of the pandemic may further contribute to the decrease of industrial emissions in Italy.

4. Discussion

The integrated approach developed for this study allows for defining the main drivers of energy consumption in the different final sectors, which are the economic activity, industry, and mobility demand of citizens. These drivers have been estimated with separate models which are able to address the peculiarities of each of these aspect by defining the relevant parameters and methodologies, based on the common assumptions defined for each future scenario. These models are based on data that are continuously in evolution, and the results can be further updated in the future to reflect the most recent trends.

The results confirm the differences across the scenarios, and the decrease of energy consumption related to a reduced industrial activity as well as a lower mobility demand, which are both lower under COVID-19 than in a baseline scenario where COVID-19 did not happen.

The effects are stronger in the industry sector, in which the economic crisis causes a persistent decreased energy consumption. In transport, especially for the passenger segment, there is a partial recovery of the demand in the long term. The econometric model and expert interviews suggest a shift away from public motorized transport in favour of private motorized transportation modes, but at the same time a modest decrease in overall Italian motorized transport demand until 2030. This likely reflects increased work-from-home practices and increased use of active modes in the post-COVID future.

The effects of the different scenarios on the CO_2 emissions are in line with those observed for energy consumption. Some slight differences from a sector to another are related with the different energy mixes of the final energy consumption. However, throughout our scenarios, the pandemic is causing emission reductions in addition to a decreasing trend that is noticeable already in the Baseline scenario. Such trend is mostly related to energy efficiency measures in both industry and transport, and to an expected increase of electrification of final uses.

The present study has implemented a multi-method, multi-disciplinary modelling approach to assess economic, behaviour, transport, energy and environmental impacts of the still ongoing (at the time of writing this paper) COVID pandemic issues in a holistic way and with a scenario approach to deal with the uncertainties.

As far as the economic modelling part is concerned, and differently from CGE models, this approach is not considering the possible feedback loops that may influence the relation between different economic agents. The novelty of the present work is represented by its integrated approach which may contribute at pragmatically overcoming the complexity and implicit shortcomings of CGE-based modelling frameworks. In fact, the pairs of models here employed allows structural relationships to be made explicit in the meso-economic modelling step, without considering substitution of factor of production on the basis of elasticities, market clearing assumptions and price dynamics which may be inconsistent with the outputs obtained in the macroeconomic modelling step. [53]. In this view, recent literature highlights the relevant sensitivity of CGE outputs with respect to shocks, model type and closure rules, which may hinder the applicability of such models for the impact assessment of disasters induced structural changes [54]. Unpacking the causal flows among all the models of the framework brings the advantage of being able to clearly identifying endogenous and exogenous variables, thus isolating the most relevant mechanisms that are affecting the determination of a given modelling step.

The results of this study are affected by some limitations, mostly because it is not an ex-post study but that it is carried out in the middle of the ongoing pandemic with a constantly evolving epidemiological situation but also the political and economic reaction to it. Another limitation is the unavailability of updated data. In some cases, energy consumption trends and parameters are assumed from historical time series, which do not account for the most recent realities of the pandemic. While in most cases those parameters should not be affected by a reduced demand, some structural changes may lead to unforeseen variations in the future. Possible examples include the need of alternative business models to sustain public transport modes in the case of a persistent reduction of demand, modified urban patterns and population distribution after the pandemic (including the role of remote working), accelerated trends of digitalization in specific sectors.

Future evolution of sectoral GDP will be affected by not only transformation in consumer habits, but also by structural change that may occur at intermediate levels of demand. For example, digitalization of work as a favoured response to the pandemic, may boost adoption of software and hardware by firms, while discouraging paper and printing services. Furthermore, increase in electrification and decarbonization rates, in line with national and European efficiency and carbon reduction objectives and strictly linked to economic priorities, may importantly effect results. Speculating on the effects of these complexities on expected Italian energy consumption and emissions is needed in forthcoming studies.

5. Conclusions and policy recommendations

The results of our work show the range of impacts that different COVID-19 scenarios can have on the future energy consumption in Italy, considering a 2030 perspective. Some aspects of the pandemic crisis may result in persistent effects, including non-recovered economic losses and new mobility habits. In our medium scenario, CO_2 emissions in 2030 remain 5% lower than the baseline, with a 33% decrease from 2015 emissions. Sectoral emissions show differentiated contributions, with a 10% decrease of industrial emissions and a 6% decrease of transportation emissions. The duration of the medical emergency has dramatic effects on the results, although with different magnitude in industry and transport sectors and segments. We also included an optimistic scenario that is now out of reach, having considered a full recovery from the virus by January 2021. Still, we believe that the results of this scenario highlight the benefits of a quick recovery from such a crisis, which may be an important lesson when planning resilient measures against future pandemics.

The results of this work are based on the assumption that green investments in renewables and energy efficiency will be in line with the latest confirmed targets presented in national and EU strategies, notably in the European Green Deal [55]. To ensure this positive outcome, it is important that the economic resources of the Recovery Fund will indeed be allocated with a mandatory conditionality on the effectiveness of the projects in ensuring positive climate impacts as it is planned. For the specific context of Italy, which has regularly not been able in the past to allocate all the available EU funds, it is also important to guarantee that the available resources are properly spent within the agreed timelines, which implies both a strengthened administrative system and a lighter bureaucracy to deal with the funds.

The COVID-19 pandemic has had dramatic effects on the economic trajectory of many countries. It is important that the huge resources devoted to recovery from the current economic crisis are used in the most effective way. Such resources should support innovative technologies, solutions and industries to build a new economic and energy system that is less vulnerable to potential disruptions and which prepares for being competitive in a future decarbonized and more digital world. Focusing investments to actions that reinforce existing unsustainable economic, industrial, transport and energy models involves significant risks and would represent a missed opportunity to develop a sustainable, resilient and competitive society in the long run.

Finally, considering urban transport, results show that the COVID-19 pandemic may lead to a persistent, modest increase in demand for private transport modes, and a more substantial decrease in public transport use. This trend may result in a negative impact on congestion as well as on energy consumption and emissions. Therefore, strong targeted policies are needed to provide the citizens with viable alternatives that allow for a more sustainable transportation system and lower environmental impacts while guaranteeing equality in access to transport modes. Good practices supporting active transport modes are already being supported in different European cities, and it is important to avoid losing this positive momentum.

All the aspects discussed above are to be considered in the framework of the European Green Deal, since a just and inclusive transition towards a clean energy system needs to be coupled with a sustainable economic recovery from the current pandemic along a pathway towards net zero carbon emissions by 2050, a stronger digitalization of the economy, and a greater resilience of the energy and economic systems against possible future shocks.

The methods and tools presented for this work can be applied to other European countries and can also be extended to the European Union as a whole.

Author Contributions

Davide Bazzana: conceptualization, economic analysis, writing – original draft, writing – review & editing; **Jed J. Cohen**: conceptualization, transport analysis, writing – original draft, writing – review & editing; **Nicolò Golinucci**: conceptualization, economic analysis, writing – original draft, writing – review & editing; **Manfred Hafner**: conceptualization, writing – review & editing, supervision; **Michel Noussan**: conceptualization, energy analysis, writing – original draft, writing – review & editing; **Johannes Reichl**: conceptualization, transport analysis, writing – original draft, writing – review & editing; **Matteo Vincenzo Rocco**: conceptualization, economic analysis, writing – review & editing; **Alessandro Sciullo**: conceptualization, transport analysis, writing – original draft, writing – review & editing; **Sergio Vergalli**: conceptualization, economic analysis, writing – review & editing.

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