DG DIGIT
Unit D1

Study on informed public policy-making on base of policy modelling and simulation – ANNEX Case studies

Data analytics for Member States and Citizens

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1 PREDICTIVE MODELS TACKLING THE COVID-19 EPIDEMICS

1.1 Introduction

One of the unexpected effects of the lockdown was the widespread attention dedicated to epidemiological curves and exponential models. Topics which looked like obscure, boring and highly specialistic became popularized under concept like "flattening the curve". Indeed, predictive models about the spread have become a strategic asset for understanding and managing the crisis. Having accurate estimates of how the epidemics is evolving, and more importantly, predictions about how it will evolve in the future under different types of lockdown measures, became a fundamental asset not only for ensuring public health, but also for saving the economy. Their importance became clear when the update to the model produced by the Imperial College (as new data became available) led to a complete reversal of policy in the UK and the US. Indeed, accurate models are necessary to move beyond a open/closed model towards a smarter and more nuanced policy approach, or as one popular social media post put it, to move from the "hammer" to "the dance. Every country is using different models to manage the crisis, and many research departments are producing theirs. But how are these models developed, concretely? What predictions do they offer? What data do they use? How influential are they in defining policy choices, and most importantly, are best performing countries using better models? This piece provides an overview of the different models adopted across countries, and tries to extract lessons to be learnt for the future. The findings show that different models have been used for different purposes. For instance, agent based models can be used to assess the impact of mitigation measures, while fitting curve can be used to estimate the magnitude of epidemic dimensions such as the number of deceased and the number of infected individuals. As the saying goes, all models are wrong, but some are useful. And useful they were indeed, as the more data are available, the better are the estimates. Further, several models are able to predict the extent to which mitigation measures affect epidemic and healthcare dimensions, thereby providing tools to the policy makers. On the other hand, having more advanced and sophisticated models is not the magic wand that decides the fate of a country. Indeed, many experts declare that "The mathematical side is pretty textbook". Other related measures are at least as important. First, high quality data. Models are built on estimates, and early stage models were wildly wrong because of the incorrect estimated data put in stemming from assumptions driven by necessity. In fact, when scarce data was available for a single location, models had to be calibrated using data from locations where the epidemics was ongoing. For instance, for the series of Imperial College models, critical assumptions concerned the value of R (reproduction rate), the rate of death, the length of incubation, and the period in which infected and asymptomatics can be infectious. As for a model developed by the University of Oxford, a critical assumption was the suggestion that the infection has reached the UK by December or January, and the figure that only one in 1,000 infections will need hospitalization is removed from reality. This is questionable, as on March 24 (at the time of release of the model) more than one in 1,000 people have already been hospitalised in the Lombardy region of Italy, despite stringent control measures being implemented. But the crucial info hidden from both teams of modellers regards the number of people that have been infected without showing symptoms, and for which a reliable test would be a game changer for modellers as it might significantly alter the predicted path of the pandemics. In fact, it appears that the mortality rate is much lower than official numbers suggest, as many people are infected without knowing it and they do not get tested. By the same token, some countries have better data because of their existing data infrastructure. For instance, Germany has a register of ICU which updates occupancy data on a daily basis. And the main limitations underlying all models is that we don't know how many people are infected in the first place. Secondly, models need to be used properly. They are not commodity that provide a number which the policy makers use to take decisions. There needs to be a full understanding of the subtleties involved, the levels of uncertainty, the risk factors. In other words, you need in-house data and model literacy embedded in the policy making process, in house. You can't outsource that. Indeed, a recent report for the US highlighted the limitations of a process that involved experts on an ad hoc, on demand basis, leaving much arbitrariness to the process: “Expert surge capacity exists in academia but leveraging those resources during times of crisis relies primarily on personal relationships rather than a formal mechanism.” On a similar token, in the UK, a recent article pointed out that experts involved in the SAGE were too "narrowly drawn as scientists from a few institutions". By the same token, there was insufficient in house capacity to manage this input: In the US, “there is currently limited formal capacity within the federal government”, while in the UK, “the criticism levelled at the prime minister may be that, rather than ignoring the advice of his scientific advisers, he failed to question their assumptions”.[1] Further, it is important to ensure transparency in the modelling assumptions, as using models based on assumptions in absence of hard data can lead to over interpretation and exaggeration in the magnitude of the outbreak. Therefore, assumptions must be transparent and clear to the reader and the policy maker in order to be aware of the caveats. Moreover, researchers should perform extensive validation and sensitivity analysis exercises by using different modelling and estimation techniques. By the same token, models should be developed in collaboration with policy makers and practitioners, as in the case at hand, the joint elaboration of simulations and scenarios by policy makers and scientists helps in producing models that are refined to tackle the containment policies adopted. And the researchers/ IT vendors should develop easy to use visualization to help policy makers and citizens to understand the impact of containment policies: interactive visualization is instrumental in making evaluation of policy impact more effective. A final point is to consider carefully the sources of uncertainty in the model, whether statistical (e.g. confidence intervals), parametrical (e.g. the rate of transmission), concerning measurements (e.g. data on fatality), or of a more conceptual level (e.g. assuming a representative agent).

But we must not forget perhaps the most important variable: the quality of the health service itself. For instance, Germany has by far the largest number of ICU beds per head.

1.2 Overview of the models

Several countries are making extensive use of predictive models to forecast the severity of the COVID-19 outbreak and its impact in terms of population affected and strain over the healthcare system. Computer simulations are becoming an increasingly important part of policymaking. However, as they are based on information that is oftentimes estimated or assumed, it is important to be aware of the limitations and possible lack of robust forecasts. The simplest epidemics models (called SIR[2]) aim to understand how an individual passes from being susceptible (S) to the virus, have become infected (I); and then either recover (R) or die. A bit more advanced modelling technique (see the flow in Figure 1) adds the individuals exposed (E) to the virus[3][4].

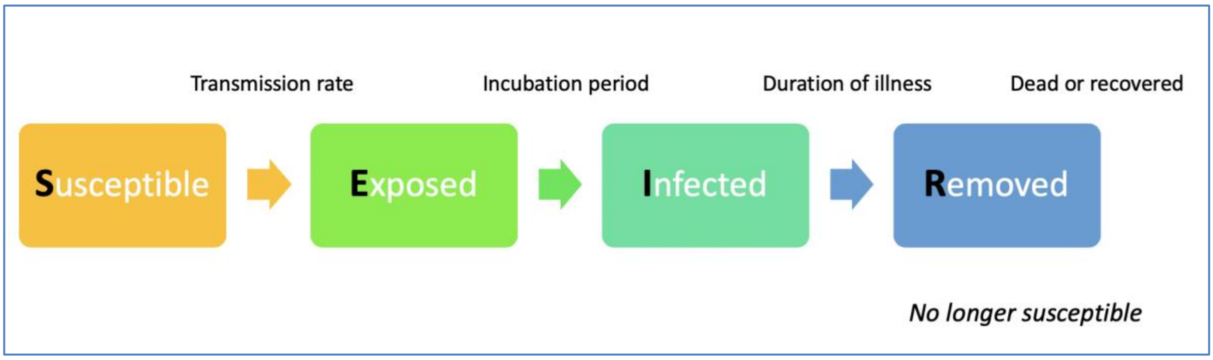
[1] The quotes come from https://mobile.reuters.com/article/amp/idUSKBN21P1VF?__twitter_impression=true and https://www.centerforhealthsecurity.org/our-work/publications/2020/modernizing-and-expanding-outbreak-science-to-support-better-decision-making-during-public-health-crises

[2] https://www.nature.com/articles/d41586-020-01003-6?fbclid=IwAR0WqP_6AH7myk9YJGFeqw0lXlD2KiBPScEX_WQdzrW67n41krXaZYkTV0Q#ref-CR1

[3] https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30260-9/fulltext

[4] https://cmmid.github.io/topics/covid19/current-patterns-transmission/wuhan-early-dynamics.html

Figure 1 – Flow of SEIR Model



Some information can be merely assumed at the start of an epidemic, such as the proportion of infected people who die, and the basic reproduction number (R0), which is the number of people to whom one infected person will transmit the virus. In the same way, also some other parameters have to be assumed, such as the presence or not of natural immunity inside a population. More advanced models make use of stochastics rules, for instance attributing a probability lower than one that someone in the I group infects an S person when they meet, and also the behaviour of agents is modelled in different ways. Most models make use of equations to sort individuals into strata, while others adopt an agent based approach in which each individual moves around and acts according to their own specific rules, and therefore are able to include in the analysis social factors (such as social distancing and travelling), as well as healthcare resources. Further, there are epidemiological models based on mobility matrices (origin-destination) and demographic profiles to understand the extent and direction of the spread of the epidemic, thanks to which it can help to make decisions on the distribution of resources and on hospital logistics, as well as displacement analysis models between municipalities and between geographic areas of the country to identify groups of users with similar displacement patterns, and effectiveness models of lockdown measures, aimed at monitoring the behavior of groups of users before and after the adoption of restrictive measures for mobility. The choice of the model depends on the specific issue at hand: for instance, when testing the effects of social distancing on infection rates, there is no need to use an agent based model as everybody is compelled to behave in the same way, i.e. staying at home.

In total, our analysis depicts a total of 28 different models, 19 of which are used in policy making as reported by the general press as well as by the fact that authors are members of the teams of advisors working for several governments. Further, almost all of the models are published and available for scrutiny (apart from 4, more on that below), while obviously the results of all models are public and available. The study of the models focusses on 6 European countries plus the US: France, Germany, Italy, Spain, United Kingdom, and United States. Most of the models use data collected from the same country, while other integrate the dataset with data from international repositories (e.g. ECDC, WHO, Johns Hopkins CSSE). Interestingly, the models introducing mobility of citizens across regions and countries re-use data on citizens movement collected for other purposes, such as daily origin-destination traffic flows from the Official Aviation Guide (OAG) and International Air Transport Association (IATA) databases, ground mobility flows collected from statistics offices, and mobility data provided by Cuebiq, a location intelligence and measurement company.

From the analytical point of view, the relative majority of models are Susceptible-Exposed-Infected-Recovered (SEIR) models, while there are some spatial epidemic models and some pure statistical models based on maximum likelihood methods and Monte Carlo Markov Chains. Finally, there are strategic models that encompass multiple scenarios assessing the impact of different interventions are able to capture some uncertainty underlying the epidemic outbreak and the behaviour of the population and are the foundation for policy making activity.

As regards the topic of the models, we can distinguish four of them:

- Estimating epidemic variables, such as numbers of infected individuals, number of deceased, and reproduction number (17 models);
- Estimating healthcare variables, such as number of Intensive Care Units Necessary (12 models);
- Assessing the impact on mitigation actions, such as enforcement of lockdowns and social distancing (16 models);
- Assessing the spread of the epidemic model and/or the extent of the mobility of the population (9 models).

A brief illustration of the surveyed models is presented in Table 1.

Table 1 – Brief illustration of the surveyed models

Country	Total	Published	Officially used in policy	Estimating epidemic variables	Est. healthcare	Mitigation actions	Mobility
US	6	6	5	2	2	1	4
UK	5	5	5	3	3	4	1
DE	4	4	3	2	0	4	2
IT	6	4	1	4	2	3	1
ES	4	4	2	3	3	2	1
FR	3	3	3	2	3	2	0
Total	28	26	19	16	13	16	9

1.2.1 Predictive Models used in US and the UK

A number of leading scientists are supporting the decision making process of the White House Coronavirus Task Force by providing results analysis based on predictive epidemic models. One of the primary models used by the White House response team is provided by the Institute for Health Metrics and Evaluation University of Washington (**IHME**)[5][6]. As already mentioned, most epidemiological models look at different populations that interact in an outbreak, which are the people susceptible to infection (S), those who are infectious (I) and those already infected who go on to die or recover (R). The IHME model embraces an entirely different statistical approach, taking the trending curve of deaths from China, and "fitting" that curve to emerging death data from US cities and counties to make its forecasts. The first release of the model predicted a bed excess demand of 64,175 and 17,380 of ICU beds at the peak of COVID-19. Further, the peak ventilator use is predicted to be 19,481 in the second week of April, while the total estimated deaths were 81,114 over the next 4 months. Then, the estimates were amended downwards by predicting the death of 60.400 individuals by August, with a peak on the 12th of April. As for the UK, the model predicted 66,314 fatalities, more than Italy (a total of 23,000) and Spain (19,209).[7] These numbers are consistently lower than other estimates. As transparently recognized by the authors, only one location (Wuhan) has had a generalized epidemics, and therefore modelling the US fitting curve on such location is difficult, especially because the timing and extent of social distancing is difficult to mimic. When more US data will be available, the more will become more precise. Further, even though the model takes into account

[5] https://covid19.healthdata.org/united-states-of-america
[6] https://www.medrxiv.org/content/10.1101/2020.03.27.20043752v1.full.pdf
[7] IHME uses data from the Data Repository by Johns Hopkins CSSE https://github.com/CSSEGISandData/COVID-19

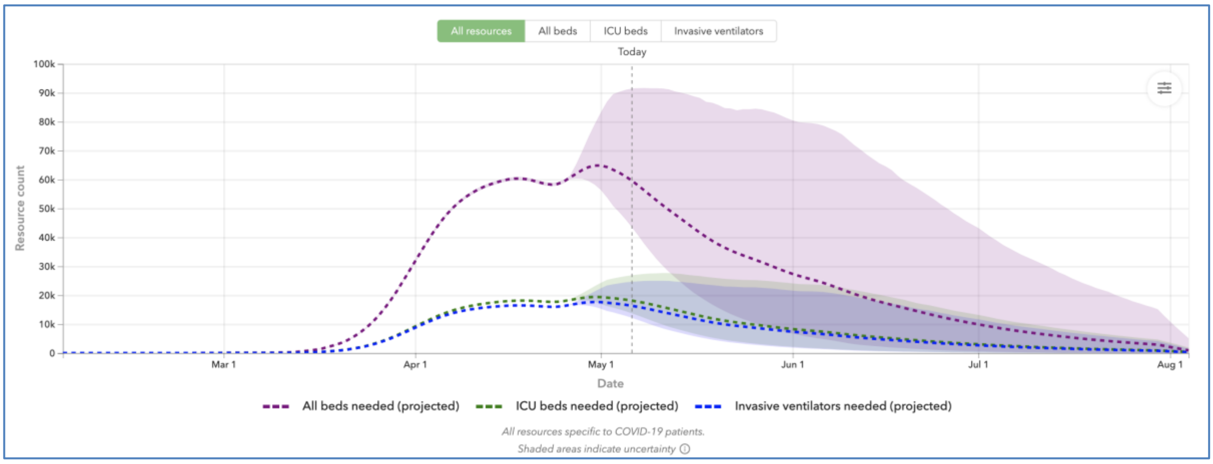
age structure, some other factors are not modelled, such as the prevalence of multi and co-morbidities, chronic lung disease, use of public transport, pollution and population density. On the top of that, the reduction in healthcare quality due to overload is not explicitly taken into account. Other experts consider the estimations to be overly optimistic[8]. In fact, it is argued that actions taken in the US are less drastic than in China, and that while most models assume that social distancing will only slow or reduce transmission, the IHME model assumes that policies such as social distancing are extreme effective at stopping transmission and put the epidemics under control.

Along the same lines, as argued by Siegenfeld, Shen and Bar-Yam[9], the interventions in the US are basically of four typologies: school closures, non-essential business closures, travel restrictions including public transportation closures, and stay-at-home recommendations. It is unlikely that implementing even all four of these measures will yield results like those reported by China, given the multiple steps taken in China's lockdown, many of which have not yet been implemented in the US, such as mandatory masks in public places and quarantine of all suspected cases collectively.

Summarizing, the precision of the IHME model depends a lot on the availability of data as well as on the assumption regarding the extent of interventions. The IHME is planning to continually update its model using new data, so the model will become more accurate over time. In some countries like Italy, for which there is a large amount of data on fatality rates for COVID-19 over time, the accuracy of IMHE is higher. On the other hand in countries such as UK there is a limited timeframe of COVID-19 fatalities and so less data with which to estimate future trends, and therefore the IHME has a widest range of possible outcomes (14,572 to 219,211 deaths in the UK at the time of writing).

At any rate, as of May 6th 2020, examples of projections based on IHME are depicted in the following Figures Figure 2, Figure 3 and Figure 4.

Figure 2 - Hospital Resource use

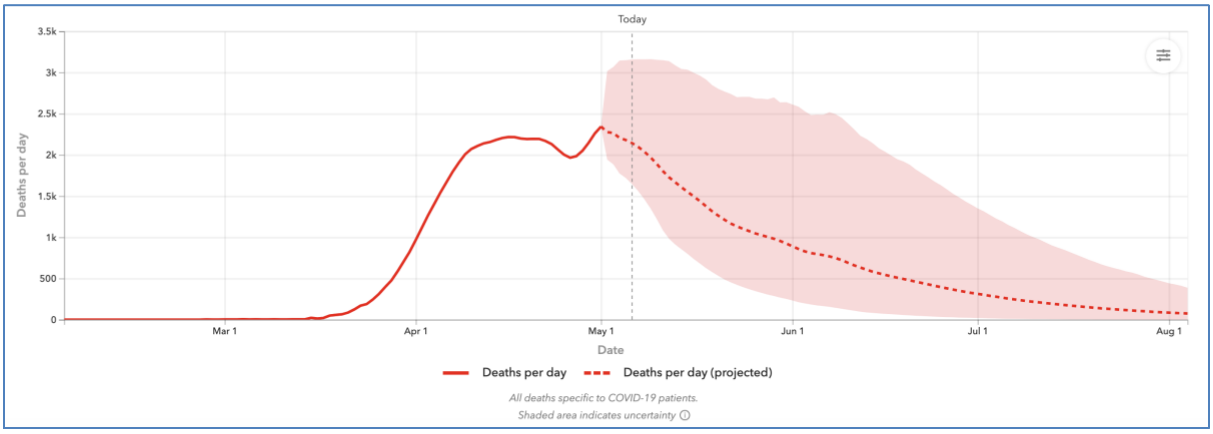


Source: https://covid19.healthdata.org/united-states-of-america

[8] https://www.vox.com/future-perfect/2020/5/2/21241261/coronavirus-modeling-us-deaths-ihme-pandemic

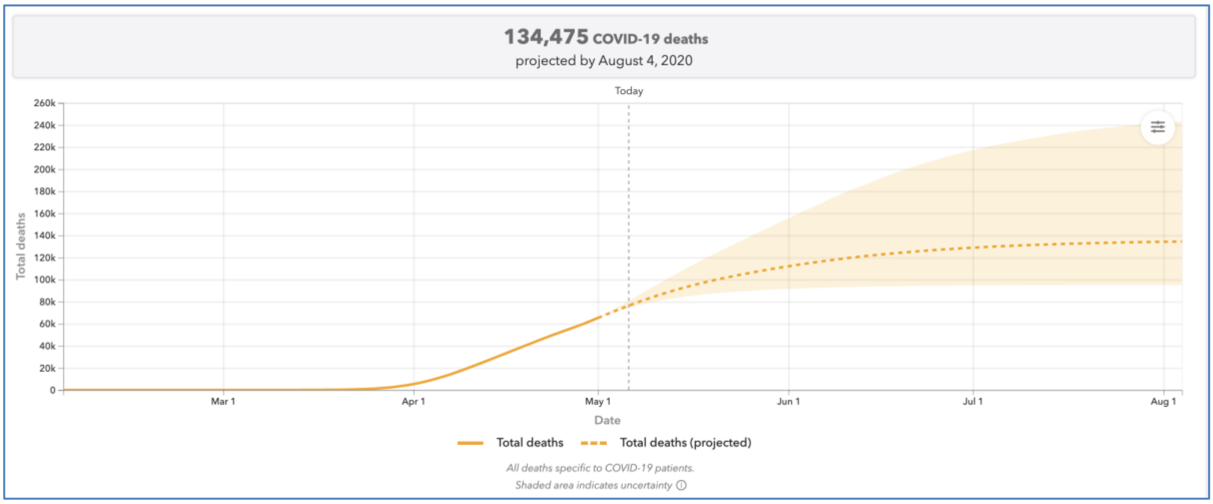
[9] https://necsi.edu/comment-on-forecasting-covid-19-impact-on-hospital-bed-days

Figure 3 – Deaths per day in US



Source: https://covid19.healthdata.org/united-states-of-america

Figure 4 – Total deaths in US



Source: https://covid19.healthdata.org/united-states-of-america

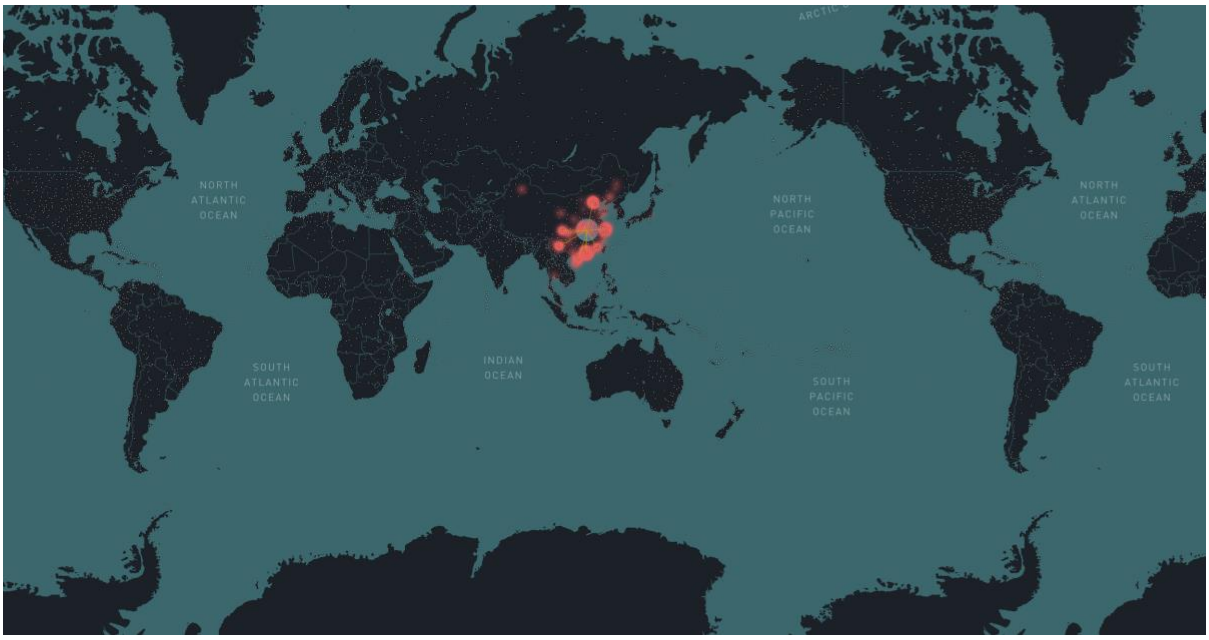
Based on the IHME, other historical model projections for a given country or region (based on data scraping from the John Hopkins dashboard[10] and the IHME website[11]) are produced by the **Los Alamos National Labs**[12][13]. Specifically, they estimate at US state level the number of cases and deaths elaborating two processes: the first process is a statistical model of how the number of COVID-19 infections changes over time, while the second process maps the number of infections to the reported data. Regarding the first process, they model the growth of new cases as the product of a dynamic growth parameter and the underlying numbers of susceptible and infected cases in the population at the previous time step, scaled by the size of the state's starting susceptible population. To model new deaths in the population, they assume that a fraction of the newly generated cases will die and get that fraction from observations. The model can be used to produce short- and long-term forecasts that can help guide situational awareness about what may happen in the near-future. In the model there are two main sources of uncertainty: the primary source of forecast uncertainty is how the growth parameter might change in the future;

10 https://coronavirus.jhu.edu/map.html
11 http://www.healthdata.org/covid/data-downloads
12 http://www.covid-projections.com/
13 https://covid-19.bsvgateway.org/#link%20to%20forecasting%20site

the second is measurement uncertainty, assumed to scale with the number of reported cases and deaths.

Another leading team stems from the collaboration between Northeastern University and ISI Foundation building on the Global Epidemic and Mobility Model (GLEAM) project, an individual-based, stochastic, and spatial epidemic model used to analyze the spatiotemporal spread and magnitude of pandemic outbreaks. The modeling effort produced is based on data on incubation period, methods of transmission, contagiousness and virulence, transportation, human behaviour and social interactions, availability of medical resources in different areas. As for transportation, the model also includes mobile phone data to track changes in people's movement to better understand the effects of various social distancing policies. Further, simple models typically show the start of an epidemic as an exponential curve based on the basic reproductive number, which in reality is not constant and depends on social networks, such as workplaces, households, and communities, and layered them into a larger model. Based on their model, the research team has developed a tool, EpiRisk, aimed at investigating the effectiveness of travel bans. Specifically, the model has been used to achieve situational awareness, then it has been applied to understand how interventions like travel restrictions affect the transmission of the disease. An example of the map of COVID-19 Epidemics as depicted by the EpiRisk Models is provided in Figure 5.

Figure 5 – Map of COVID-19 Epidemics as depicted by the EpiRisk Model



Source: www.epirisk.net

Based on the number of infected, the computational model estimates two quantities:

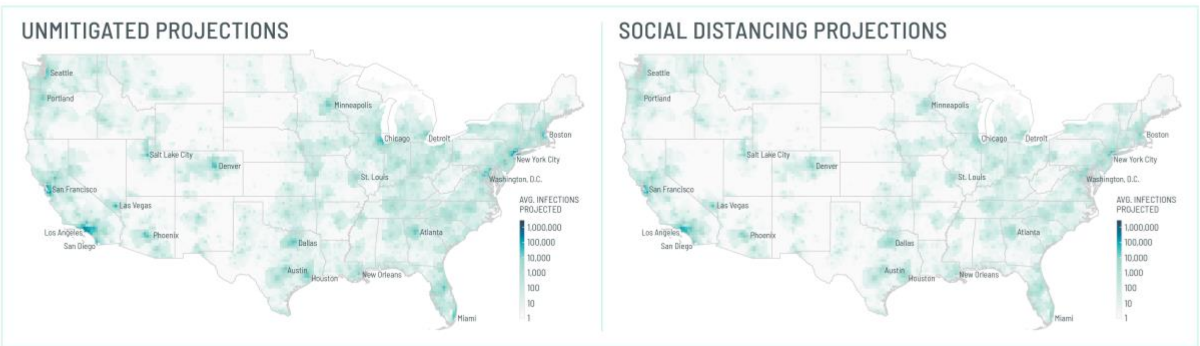
- The probability of "exporting" a given number of cases n from the origin of the disease outbreak;
- Probability that a single infected individual is traveling from the index areas to that specific destination.

As for the data, the airline transportation ones are based on origin-destination traffic flows from the database of the air travel intelligence company OAG.[14] Furthermore, commuting flows are derived by the analysis and modeling of data of over 78,000 administrative regions worldwide and 5,000,000 commuting patterns.

[14] https://www.oag.com/

Another application of the GLEAM models stems from the collaboration between Northeastern University, Fred Hutchinson Cancer Research Center, University of Florida, NIH Fogarty Center, ISI Foundation, and the Bruno Kessler Foundation.[15] The model generates an ensemble of possible epidemic projections described by the number of newly generated infections, times of disease arrival in different regions, and the number of traveling infection carriers. The model points to the days around April 8, 2020 as the peak time for deaths in the US. Based on the last projections, a total of 89795 COVID-19 deaths (range of 63719 to 127002) are currently projected through May 18, 2020. The model uses real-world data where the world is divided into subpopulations centered around major transportation hubs (usually airports). The airline transportation data encompass daily origin-destination traffic flows from the Official Aviation Guide (OAG) and International Air Transport Association (IATA) databases (updated in 2019), whereas ground mobility flows are derived from the analysis and modeling of data collected from the statistics offices of 30 countries on five continents. The unmitigated and social distancing projections of the model are available in the following figure Figure 6.

Figure 6 - Unmitigated and social distancing projections



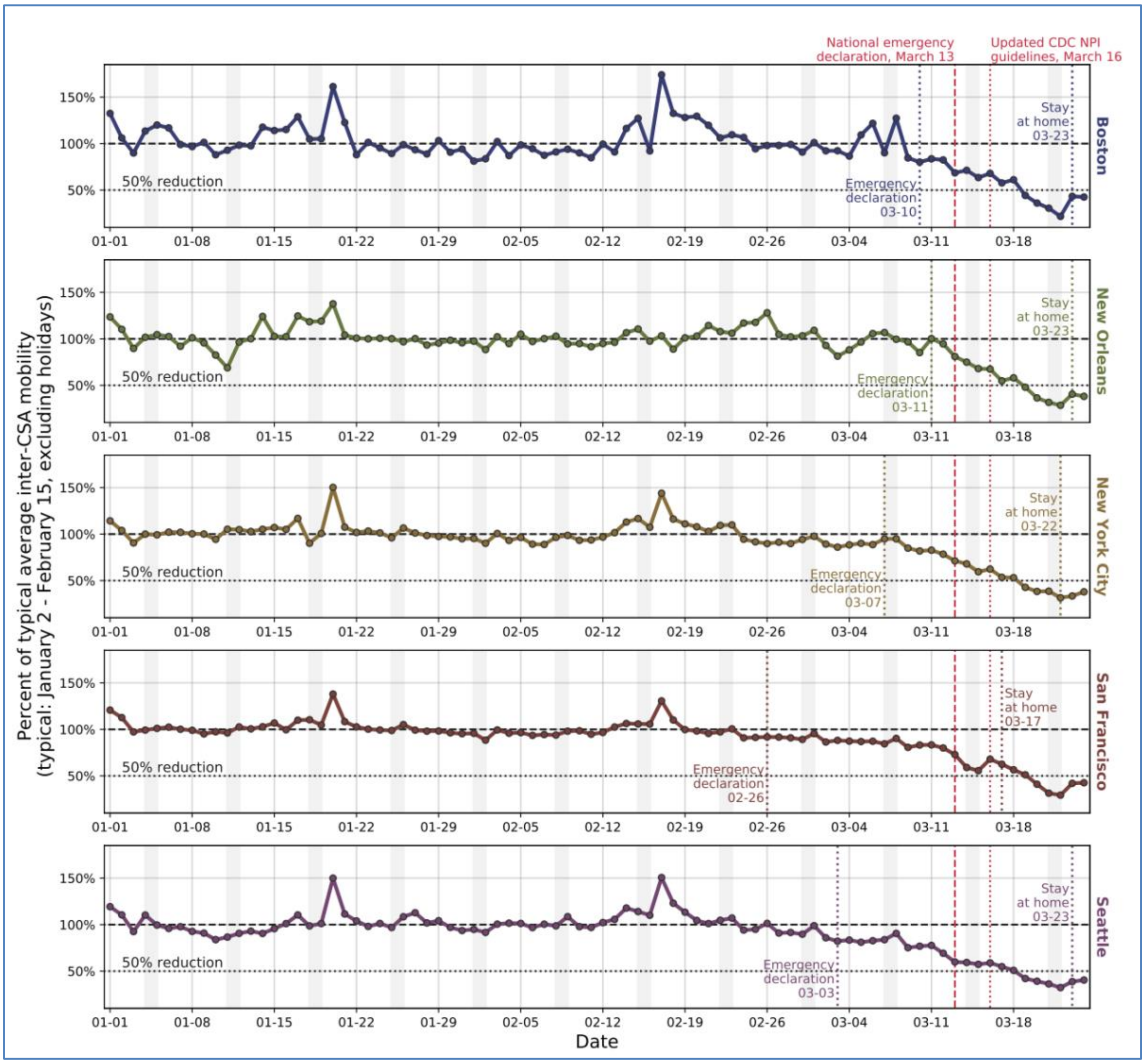
Source: https://covid19.gleamproject.org/

Some other models investigate the effectiveness of social distancing. For instance, **Bakker et al.**[16] make use of mobility data from January 1st 2020 to March 25th 2020 to figure out how has social distancing policy changed mobility and social behavior, how social distancing behavior differs across the physical space of New York City, and how social distancing behavior differs across demographic groups. Mobility data is provided by Cuebiq, a location intelligence and measurement company, and they consist in supplied anonymized records of GPS locations from users who opted-in to share their data anonymously across the U.S. The researchers find that the instance travelled everyday dropped by 70 percent, the number of social contacts in places decreased by 93%, and that the number of people staying home the whole day has increased from 20% to 60%. Very interestingly, they found that the relative differences between different demographic groups for what concerns mobility and social contacts have been dramatically reduced. Finally, they found that supermarkets and grocery stores came to be the most common locations where social contact takes place.

A similar model has used data from Cuebiq to build a preliminary understanding of the effect of work from home policies, mobility restrictions, job loss, and shelter-in-place orders on **urban and inter-urban mobility**.[17] Very interestingly, the model provides an estimation of the decrease in mobility across the U.S. Census Bureau Combined Statistical Areas of Boston, New Orleans, New York city, San Francisco and Seattle (see Figure 7).

Figure 7 – Decrease in mobility across US Census Areas

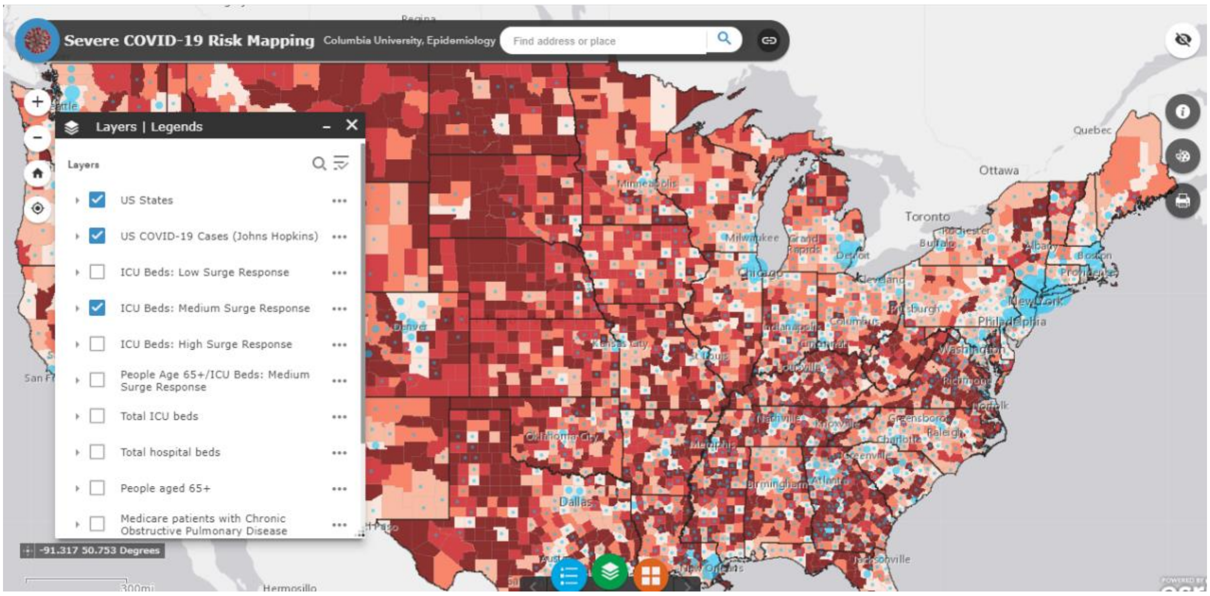
15 https://covid19.gleamproject.org/
16 http://curveflattening.media.mit.edu/Social_Distancing_New_York_City.pdf
17 https://www.mobs-lab.org/uploads/6/7/8/7/6787877/assessing_mobility_changes_in_the_united_states_during_the_covid_19_outbreak.pdf



Source: https://www.mobs-lab.org/uploads/6/7/8/7/6787877/assessing_mobility_changes_in_the_united_states_during_the_covid_19_outbreak.pdf

A final series of models by **Columbia University** in collaboration with Charles Branas in the Department of Epidemiology and colleagues from Patient Insight, the Mount Sinai Health System and MIT, has been used to provide an estimation of the stress on the healthcare system at county level due to the COVID-19 epidemics. Specifically, the team provides an estimate of the number of hospital critical care beds, including ICU beds and other hospital beds used for critical care purposes, that could be made available by hospitals in response to patient surges. Three scenarios of intensity of hospital response were created, taking into account existing ICU bed availability, currently occupied ICU beds that can be made available, other beds such as post-anesthesia care unit bed, operating room beds, and step-down beds that could be converted to critical care beds for COVID-19 patients and the possibility of having two patients use one ventilator in ICU. All civilian acute medical-surgical tertiary care hospitals and long-term acute care hospitals hospitals for which data were available in the US are included. The mapping tool can also display high risk groups such as individuals 65 years and older, Medicare patients with chronic obstructive pulmonary disease, Medicare patients with diabetes, Medicare patients with coronary artery disease and Medicare patients with chronic kidney disease. Specifically, an example of the risk mapping is provided below (Figure 8).

Figure 8 – Example of risk mapping



Source: https://columbia.maps.arcgis.com/apps/webappviewer/index.html?id=ade6ba85450c4325a12a5b9c09ba796c

An online interactive COVID-19 mapping tool is also available on the Columbia website.[18] The simulations displayed in the mapping tool are based on a model[19] simulating the COVID-19 transmission dynamics for all US study counties over the period from February 21, 2020 to April 2, 2020, using an iterated filter-ensemble adjustment Kalman filter framework.[20,21,22] This combined model-inference system estimated the trajectories of susceptible, exposed, documented infected, and undocumented infected populations in each county while simultaneously inferring model parameters for the average latent period, the average duration of infection, the transmission reduction factor for undocumented infections, the transmission rate for documented infections, the fraction of documented infections, and the previously mentioned travel multiplicative factor. To account for delays in infection confirmation, the research team employed a time-to-event observation model using a Gamma distribution with a range of reporting delays and different maximum seeding. Finally, the log-likelihood was used to identify the best fitting model-inference posterior.[23,24]

The model shows that an estimated 77,588-278,850 total critical care beds were available in the US, depending on the level of hospital surge response preparations. Maps of the US showed differences between the 21-day and 42-day projections as more counties outside the Northeast and urban areas, such as in the South, began to exceed their critical care bed capacity limits. Further, the model shows that 185,192 deaths in the Northeast and 33,986 deaths in the Midwest could be averted by reducing contact with actions such as social distancing, as well as that as many as 104,120 deaths could be averted through an

18 https://columbia.maps.arcgis.com/apps/webappviewer/index.html?id=ade6ba85450c4325a12a5b9c09ba796c
19 http://www.columbia.edu/~jls106/branas_etal_preprint.pdf
20 E. L. Ionides, C. Bretó, A. A. King, Inference for nonlinear dynamical systems. Proc. Natl. Acad. Sci. U.S.A. 103, 18438–18443 (2006).
21 A. A. King, E. L. Ionides, M. Pascual, M. J. Bouma, Inapparent infections and cholera dynamics. Nature 454, 877–880 (2008).
22 S. Pei, F. Morone, F. Liljeros, H. Makse, J. L. Shaman, Inference and control of the nosocomial transmission of methicillin-resistant Staphylococcus aureus. eLife 7, e40977 (2018)
23 Hick, J.L., Einav, S., Hanfling, D., Kissoon, N., Dichter, J.R., Devereaux, A.V., Christian, M.D. and Task Force for Mass Critical Care, 2014. Surge capacity principles: care of the critically ill and injured during pandemics and disasters: CHEST consensus statement. Chest, 146(4), e1Se16S.
24 Branas CC, Nance ML, Elliott MR, Richmond TS, Schwab CW. Urban–rural shifts in intentional firearm death: different causes, same results. American journal of public health. 2004 Oct;94(10):1750-5.

aggressive critical care surge response. Such response includes high clearance and preparation of ICU and non-ICU critical care beds and extraordinary measures like using a single ventilator for multiple patients.

The datasets used include:

- The 2020 Centers for Medicare & Medicaid Services (CMS), Health Care Information System (HCRIS) Data File, Sub-System Hospital Cost Report (CMS-2552-96 and CMS-2552-10);
- The 2018 American Hospital Association (AHA) Annual Survey;
- The 2020 US DHHS Health Resources and Services Administration, Area Health Resources Files (AHRF);
- The 2017-2019 CMS Medicare Provider of Services file, Medicare Cost Report, Hospital Compare Files.

Another set of models that has been used both by the UK and the US governments as a basis for policy making has been developed by Neil Ferguson and his team at **Imperial College** London. Specifically, the Imperial College Response Team released on March 16 an individual-based simulation model[25][26] in which individuals reside in areas defined by high-resolution population density data and get into contacts with other individuals in the household, at school, in the workplace and in the wider community. Data on distribution size of households and age are taken from the census, while a synthetic population of schools distributed proportional to local population density is derived from data on average class sizes and staff-student ratios.

The model uses commuting distance to locate workplaces, and general data on the distribution of workplace size. In the model the transmission occurs through contact between infected and susceptible individuals randomly or at work/school/in the household. According to their model, there are two main policy strategies: mitigation, aimed at slowing the epidemic spread in order to reduce peak healthcare demand while protecting those most at risk of severe disease from infection; and suppression, which is aimed to reduce case numbers to low levels and maintaining that situation indefinitely. The model shows that social distancing measures applied to the population as a whole have the largest impact, and that has the potential to suppress transmission (below the threshold of R=1) if combined with other intervention such as home isolation of cases and school and university closure.

The model considers five main scenarios:

- Case isolation at home;
- Voluntary home quarantine;
- Social distancing of those over 70 years;
- Social distancing of the entire population;
- Closure of schools and universities.

As already mentioned, forecasts are affected by assumptions and data availability[27]. In March 16 2016 update the model by the Imperial College reported up to 500K deaths in the UK and up to 2.2 million deaths in the US in case of no action by the government nor population. Further, the estimated figure that 15% of hospital cases would need to be treated in an ICU was then updated to 30%, arguing that the British ICU capacity (4K beds) would be overwhelmed. This prompted the policy response of the UK government, which initiated social distancing measures. But, as already mentioned, the model is based on a series of assumptions. For instance, it was assumed in the 16 March release that

25 https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf

26 The analysis is based on an agent-based model built in 2005 to see what would happen in Thailand if H5N1 avian flu mutated to a version that could spread easily between people available at https://www.ncbi.nlm.nih.gov/pubmed/16079797?dopt=Abstract

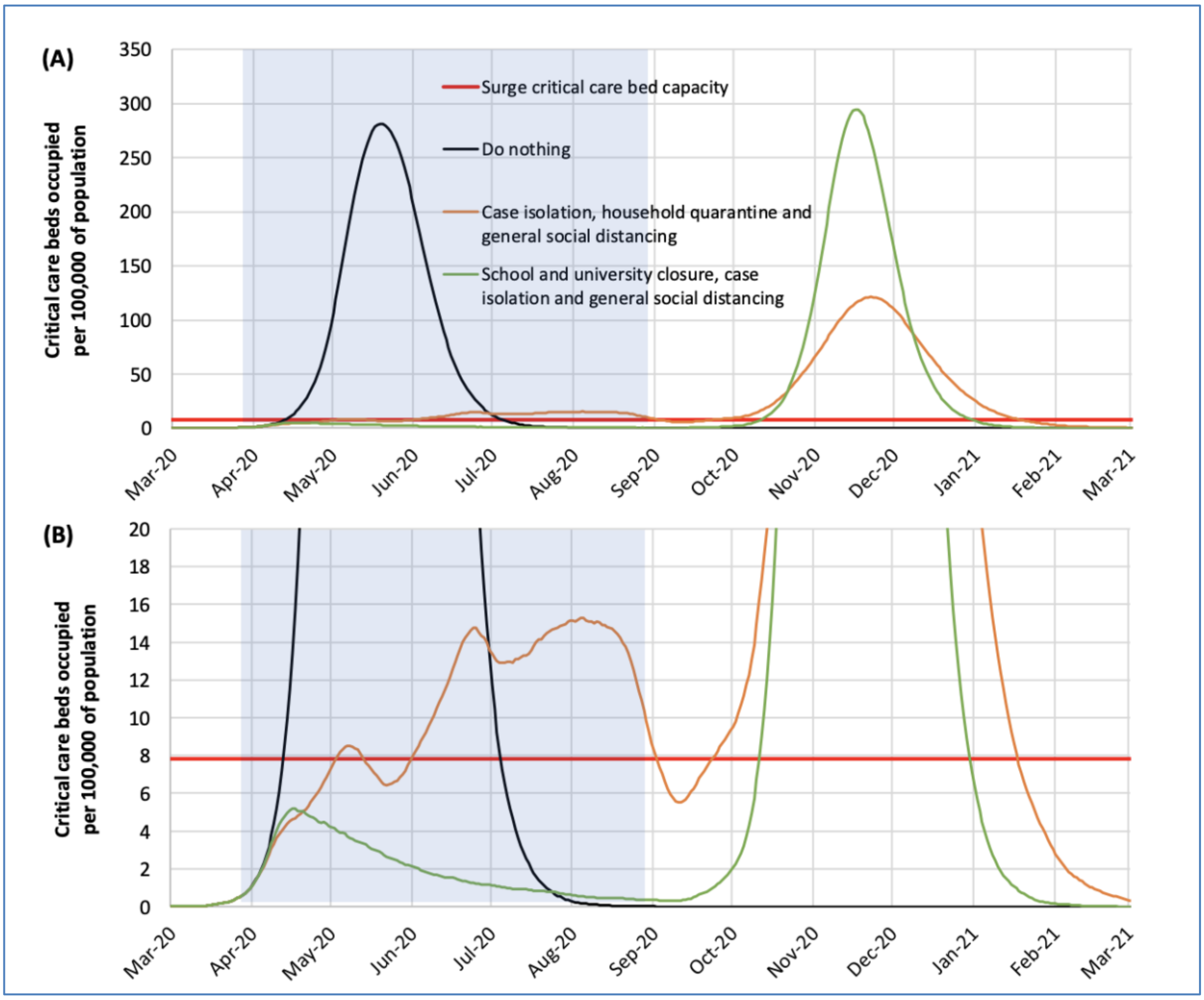
27 https://nucleardiner.wordpress.com/2020/03/21/the-imperial-college-modeling-of-the-coronavirus/

0.9% of patients affected would die, that R0 was between 2 and 2.6, and that incubation was 5.1 days. Further, it was assumed that an individual is infectious for 4.6 days after being infected, and that asymptomatic can be infectious for 12 hours. However, as researchers discover more about the virus, they are updating many key variables, including R0. For instance, in the models released by the Imperial College on the 26th and 30th of March the value of R0 has been updated respectively between 2.4 and 3.3 and between 3 to 4.7. And in any case, the worst case scenario would take place only if the governments would not implement any mitigating action. In fact, in the best case scenario of a reproduction number of 2 and isolation of people with symptoms, home quarantine, and early implementation of school closures, together with social distancing, deaths in the UK will be just 5,600, so much that on the 25th of March Ferguson declared to be "reasonably confident" that total deaths in the United Kingdom will be held below 20,000.[28][29] But how does R0 change? The first value of R0 considered was based on fits to the early growth-rate of the epidemic in Wuhan. However, Ferguson observed a rate of growth of the epidemics in Europe faster than expected looking at the early data from China, and therefore revised the estimate of the reproduction number, implying that the virus has spread more quickly than expected. This boosts the evidence to support intensive social distancing measures, because the higher the reproduction number is, the more intensive the controls need to be to mitigate the epidemic. The difference might be due to the fact that the true number of infections in UK and the rest of Europe is much larger than the official numbers reflect, because many people with mild or nonexistent symptoms will not seek medical treatment or testing. In this regard, a reliable test to see who has been infected without showing symptoms would be a game changer for modellers, and might significantly alter the predicted path of the pandemic. Other assumptions that can be contested are the rate of death, the length of incubation, and the period in which infected and asymptomatics can be infectious.

An example of the forecasts of the critical care bed occupied per 10,000 of population provided by the model based on the March 16 update is depicted in Figure 9, in which the red line is the estimated surge ICU bed capacity in UK, the black line shows the unmitigated epidemic, the orange one shows a containment strategy (i.e. case isolation, household quarantine and social distancing), and the green shows a suppression strategy (closure of schools and universities, case isolation and social distancing) beginning in late March 2020.

28 https://media.nature.com/original/magazine-assets/d41586-020-01003-6/d41586-020-01003-6.pdf
29 https://parliamentlive.tv/Event/Index/2b1c71d4-bdf4-44f1-98fe-1563e67060eehttps://parliamentlive.tv/Event/Index/2b1c71d4-bdf4-44f1-98fe-1563e67060ee

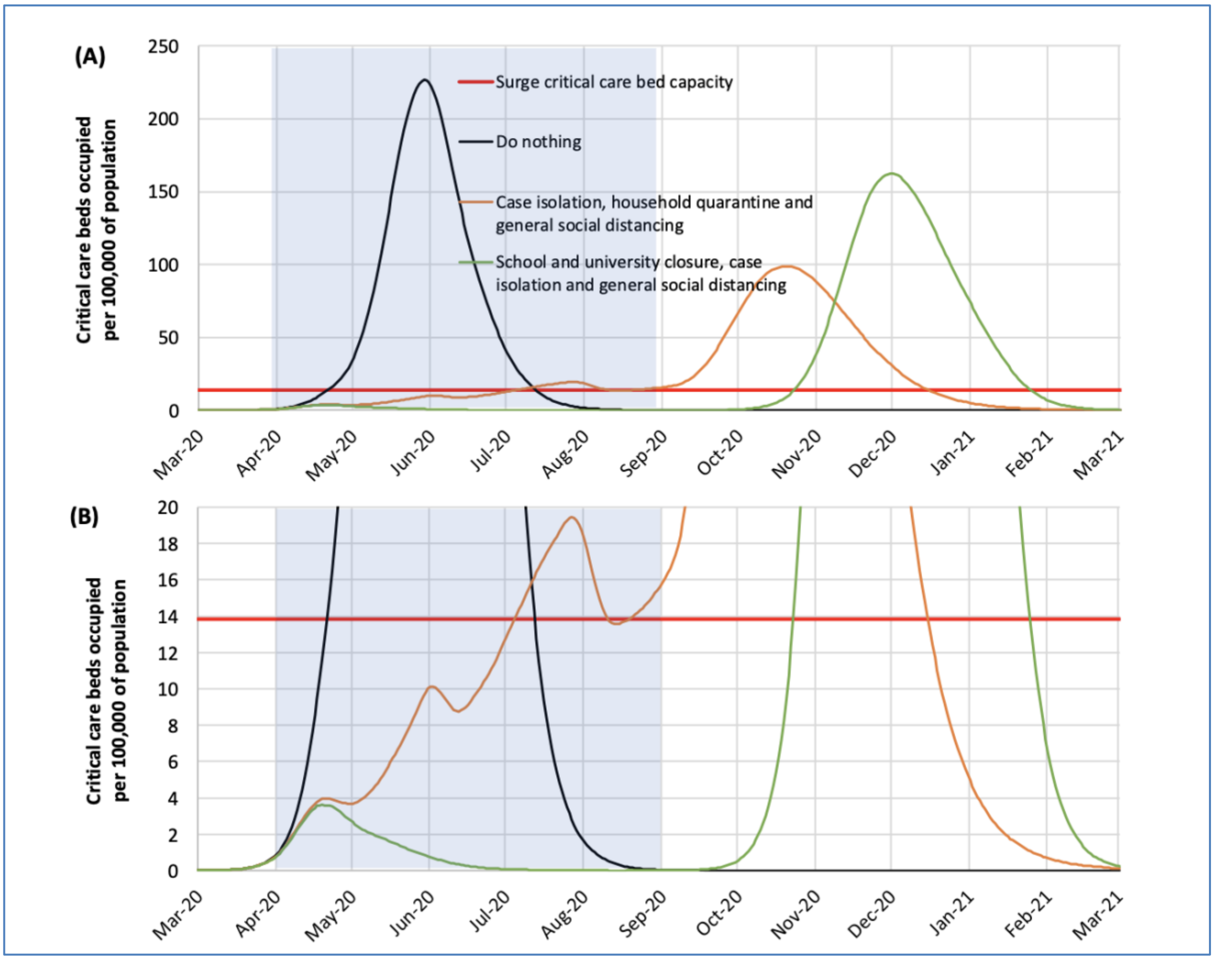
Figure 9 - Suppression strategy scenarios for GB showing ICU bed requirements



Source: https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf

An example of the forecasts provided by the model based on the March 16 update for UK is depicted in Figure 10.

Figure 10 - Suppression strategy scenarios for UK showing ICU bed requirements



Source: https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf

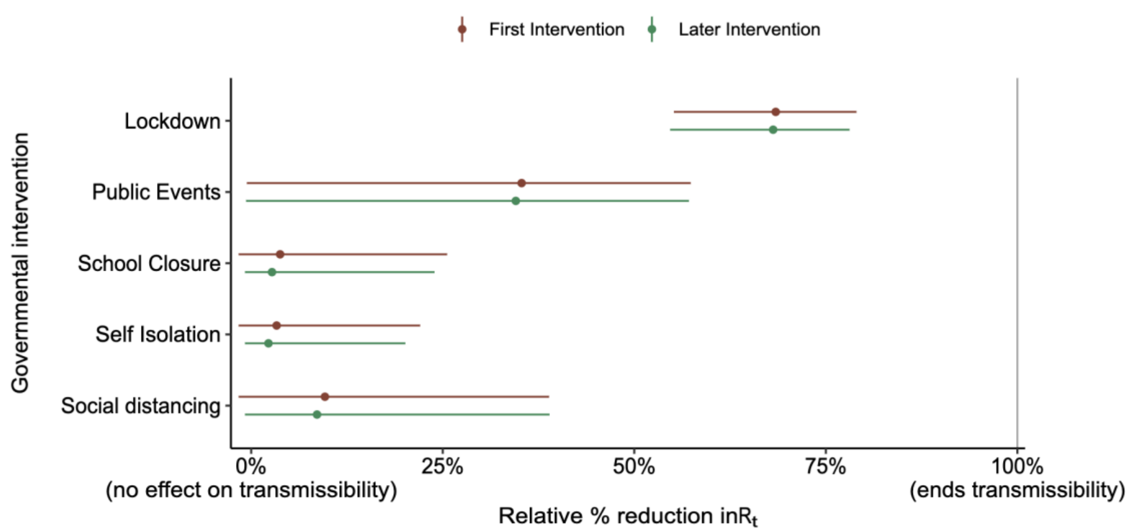
On the other hand, the global projections released on March 26 are based on an equation based approach.[30] There the population is divided into four groups: susceptibles (S), infected (I), either recover (R) or die, and those who have been exposed, but who are not yet infectious (E), postulating the mpact of an unmitigated scenario in the UK and the USA for a reproduction number R0 of 2.4 up to 490,000 deaths and 2,180,000 deaths respectively, , and estimate that in the absence of interventions, COVID-19 would have resulted in 7.0 billion infections and 40 million deaths globally this year.

Finally, on the March 30[31] release the modellers adopted a semi-mechanistic Bayesian hierarchical model to attempt to infer the impact of policy interventions across 11 European countries. They assume that the reproductive number is an immediate response to the interventions being implemented rather than broader gradual changes in behaviour. It is important to notice that one of the key assumptions of the model is that each intervention has the same effect on the reproduction number across countries and over time. In this way the researchers are able to leverage on a higher amount of data. Their estimate that the intervention has averted 59,000 deaths up to 31 March across all 11 countries, that between 7 and 43 million individuals have been infected, and that the

30 https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-Global-Impact-26-03-2020v2.pdf
31 https://spiral.imperial.ac.uk:8443/handle/10044/1/77731

proportion of the population infected to date is the highest in Spain followed by Italy and lowest in Germany and Norway, reflecting the relative stages of the epidemics. Specifically, they estimated that in Italy and Spain, respectively 38,000 and 16,000 deaths have been avoided. More in depth, the Imperial College team has estimated the estimated impact of interventions on the reproductive number, as displayed in Figure 11.

Figure 11 – Impact of the policy intervention on the reproductive number



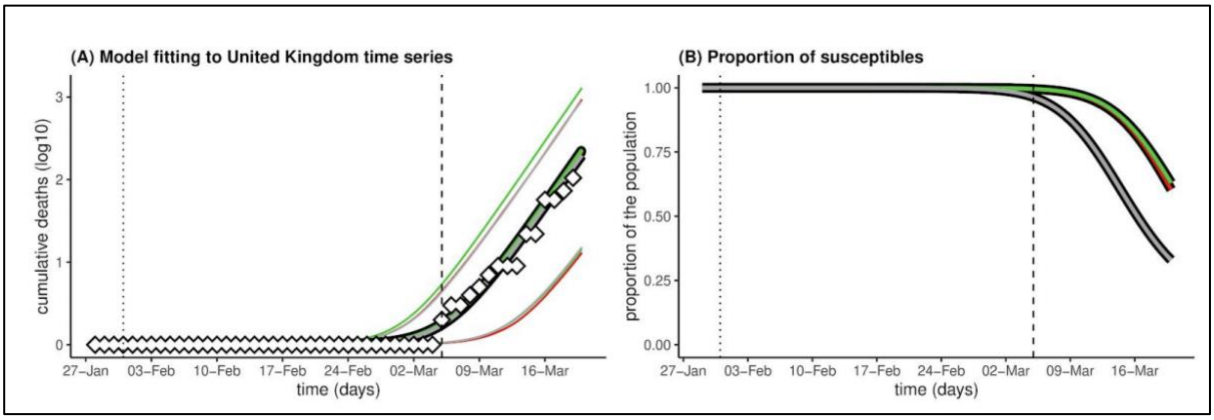
Mean relative percentage reduction in R_t is shown with 95% posterior credible intervals. If 100% reduction is achieved, R_t = 0 and there is no more transmission of COVID-19.

Source: https://spiral.imperial.ac.uk:8443/handle/10044/1/77731

Another model that has been discussed at length is the one developed by the university of **Oxford (UO)**[32]. Specifically, the researchers calibrated a susceptible-infected-recovered (SIR) model to data on cumulative deaths from the UK and Italy, building on the assumption that such deaths are well reported events that occur only in a vulnerable fraction of the population. The authors also assume estimates of critical epidemiological parameters such as the basic reproduction number (R0), infectious period and time from infection to death, probability of death in the vulnerable fraction of the population. This with the aim to assess the sensitivity of the system to the actual fraction of the population vulnerable to severe disease and death. The estimations of the model for the UK and Italy are reported in the figures below. Results are given for three scenarios: R0 = 2.25 and p=0.001, R0 = 2.25 and p= 0.01 (green), and R0 = 2.75 and p=0.01[33] (red). In the part (A) the model shows reported (diamonds) and model (lines) cumulative death counts. In part (B) the model shows the mean proportion of the population still susceptible to infection. In parts (A-B) the vertical lines mark the date of the first confirmed case (dotted) and date of first confirmed death (dashed). The chart shows that in R0 scenarios, by the time the first death was reported (05/03/2020), thousands of individuals would have already been infected with the virus. By 19 March, approximately 36% (R0=2.25) and 40% (R0=2.75) of the population would have already been exposed. Running the same model with R0=2.25 and the proportion of the population at risk of severe disease p being distributed around 0.1%, states that places the start of transmission at 4 days prior to first case detection and 38 days before the first confirmed death and suggests that 68% would have been infected by 19 March (see Figure 12 and Figure 13).

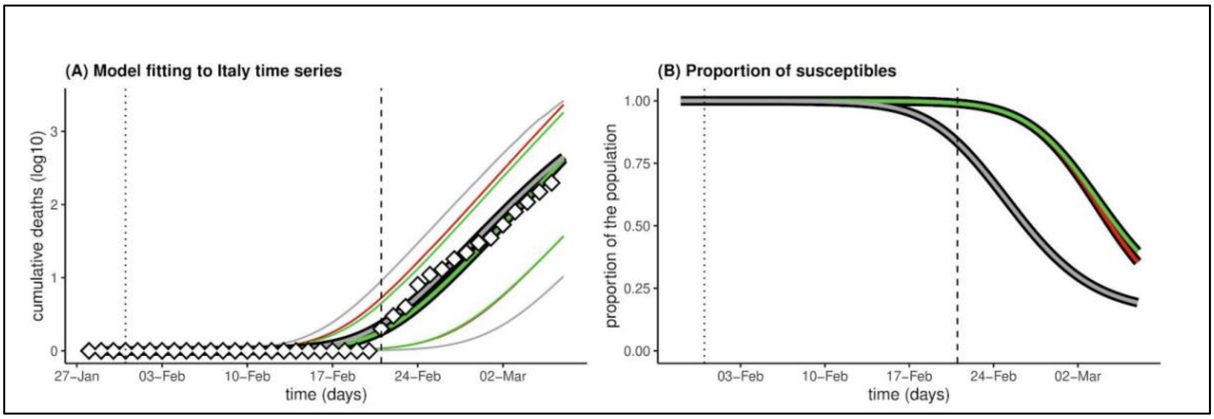
32 https://www.medrxiv.org/content/10.1101/2020.03.24.20042291v1
33 Proportion of the population at risk of severe disease

Figure 12 – Results for UK



Source: https://www.medrxiv.org/content/10.1101/2020.03.24.20042291v1.full.pdf

Figure 13 – Results for Italy



Source: https://www.medrxiv.org/content/10.1101/2020.03.24.20042291v1.full.pdf

In summary, the model suggests that the new coronavirus may already have infected far more people in the UK than scientists had previously estimated (maybe half of the population), and that thereby the mortality rate from the virus is much lower than what is generally thought to be, as the vast majority of infected individuals develop mild symptoms or not at all. The model suggests that the infection has reached the UK by December or January, and that therefore people started to be infected in huge numbers before the first official case was reported. Clearly the model presents a very different view from the one produced by the Imperial College one. In fact the Oxford model puts the focus on herd immunity, and concludes that the country had already acquired substantial herd immunity through the unrecognised spread of Covid-19 over more than two months. In any case, the Oxford team is not critic with the measures of social distancing put into place by the UK government, which will reduce the number of people becoming seriously ill and relieve severe pressure on the NHS during the peak of the epidemic. And the UK has abandoned the herd immunity policy after its scientific advisers said this would swamp the National Health Service with critically ill patients.

However, also this model is criticized as far as its assumptions are concerned. First of all, the assumption that the infection has reached the UK by December or January it is not shared by most epidemiologists. Further, the figure that only one in 1,000 infections will need hospitalization is removed from reality, as on March 24 (at the time of release of the model) more than one in 1,000 people have already been hospitalised in the Lombardy region of Italy, despite stringent control measures being implemented (population of Lombardy: 10,060,574; hospitalised: 10,905; hospitalisation rate per 1,000 population: 1.08; deaths: 4,178; deaths per 1,000 population: 0.42).[34]

As we have seen, the results of the model forecasts are influenced by the underlying assumption and data availability. But the crucial info hidden from the modellers regards the number of people that have been infected without showing symptoms, and for which a reliable test would be a game changer for modellers as it might significantly alter the predicted path of the pandemics. In fact, it appears that the mortality rate is much lower than official numbers suggest, as many people are infected without knowing it and they do not get tested. As suggested by three federal public health officials the "overall clinical consequences of COVID-19 may ultimately be more akin to those of a severe seasonal influenza (which has a case fatality rate of approximately 0.1 percent) or a pandemic influenza (similar to those in 1957 and 1968) rather than a disease similar to SARS or MERS, which have had case fatality rates of 9 to 10% and 36%, respectively."[35] This view was also argued by a study estimating that in China that 86 percent of all infections were undocumented in the early stages of the epidemics, and therefore the actual number of infections was roughly six times as high as the official number.[36] This would imply lower estimates for mortality also in case of the US.

Another modelling team consulted by the UK government works at the **London School of Hygiene and Tropical Medicine**.[37] The team used population contact patterns for United Kingdom based self-reported contact data from over 36,000 volunteers that participated in the citizen science project BBC Pandemic. The team leveraged on the data collected to generate fine-scale age-specific population contact matrices by context (home, work, school, other) and type (conversational or physical) of contact. The matrices have then been used to evaluate social distancing and population mixing reduction strategies (e.g. school closures and smart working). The analysis of the team have also focussed on the impact of social distancing and travel restrictions, as well as on the necessity to focus on risk groups, i.e. those are the ones who get the vaccines or the expensive treatments. In this regard, a potential strategy for COVID-19 is to try to cocoon those most affected, meaning complete isolation of the elderly population from our society as much as possible.[38] The same team has also assessed the effect of control strategies to reduce social mixing on outcomes of the COVID-19 epidemic in Wuhan[39]. Specifically, the research team has built an age-specific and location-specific transmission model to assess progression of the Wuhan outbreak under different scenarios of school and workplace closure, showing that changes to contact patterns are likely to have substantially delayed the epidemic peak and reduced the number of COVID-19 cases in Wuhan. Furthermore, the authors show that if these restrictions are lifted in March 2020, a second peak of cases might occur in late August 2020, and if the restrictions were to be delayed by 2 months, also the peak would be delayed. In summary, the research shows that the measures put in place to reduce contacts in school and work are helping to control the COVID-19 outbreak by affording health-care systems time to expand and respond, and especially that authorities need to carefully consider epidemiological and modelling evidence before lifting these measures to mitigate the impact of a second peak.

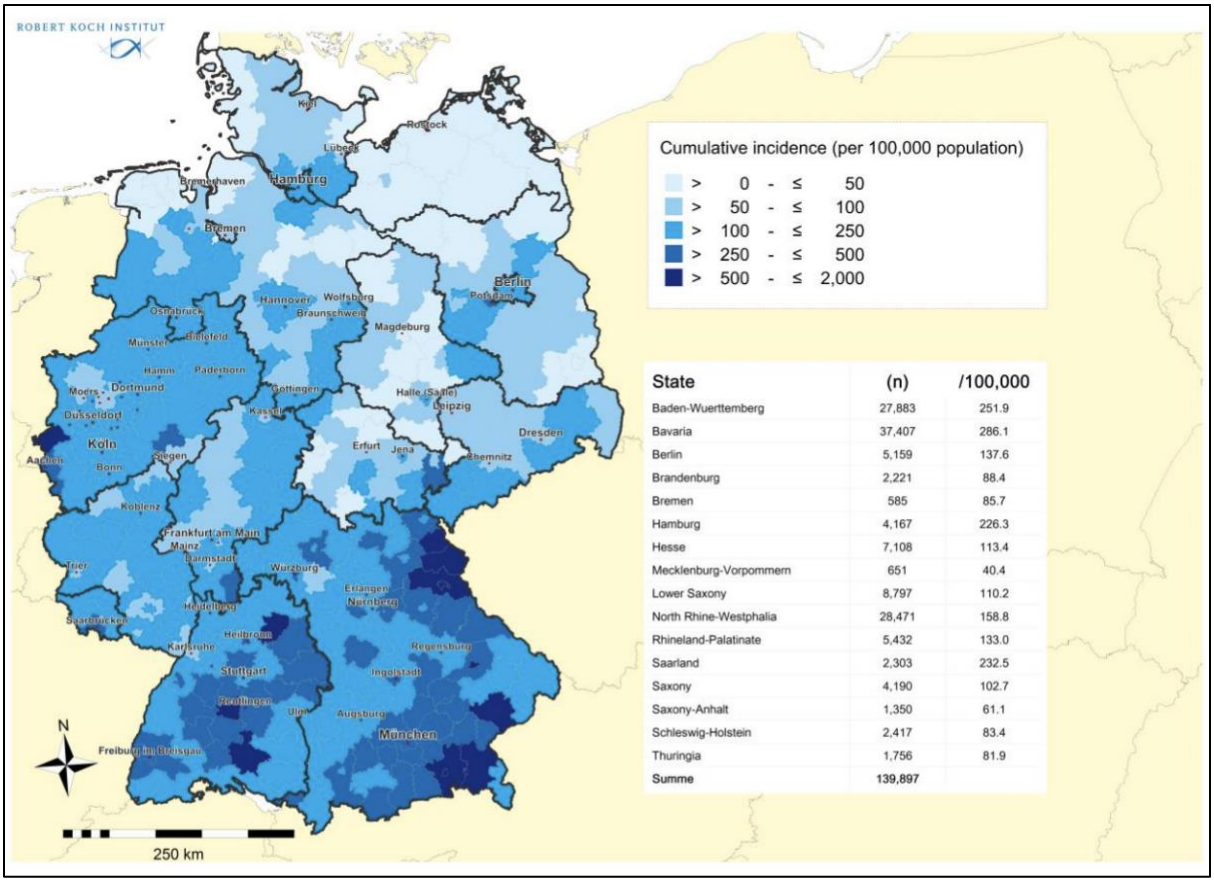
1.2.2 Predictive Models used in Continental Europe

The German disease and epidemic control is advised by the **Robert Koch Institute (RKI)** within the scope of a national pandemic plan. RKI is a German federal government agency and research institute responsible for disease control and prevention. The RKI is a federal government agency and research institute responsible for disease control and prevention, subordinate to the Federal Ministry of Health. The RKI provides daily updates on the

34 https://www.ft.com/content/ebab9fcc-6e8d-11ea-9bca-bf503995cd6f
35 https://www.nejm.org/doi/full/10.1056/NEJMe2002387
36 https://science.sciencemag.org/content/early/2020/03/24/science.abb3221
37 https://www.medrxiv.org/content/10.1101/2020.02.16.20023754v2.full.pdf
38 https://www.dw.com/en/coronavirus-code-computer-modeling-could-help-fight-the-virus/a-52795025
39 https://www.thelancet.com/action/showPdf?pii=S2468-2667%2820%2930073-6

situation of the COVID-19 outbreak, as well as projections and predictions on the future development of the epidemics. Specifically, the RKI provides a dashboard with the number and geographical distribution of active cases, critical cases, deaths and recovered patients, as well as a daily report. As the RKI is public, the common barrier to data innovation stemming from the difficulty in getting modelers to speak to policy makers is mitigated. This is a major factor in the success of German mitigation strategy. An example of the charts produced by the dashboard is depicted in Figure 14.

Figure 14 – Cumulative incidence of COVID-19 by lander



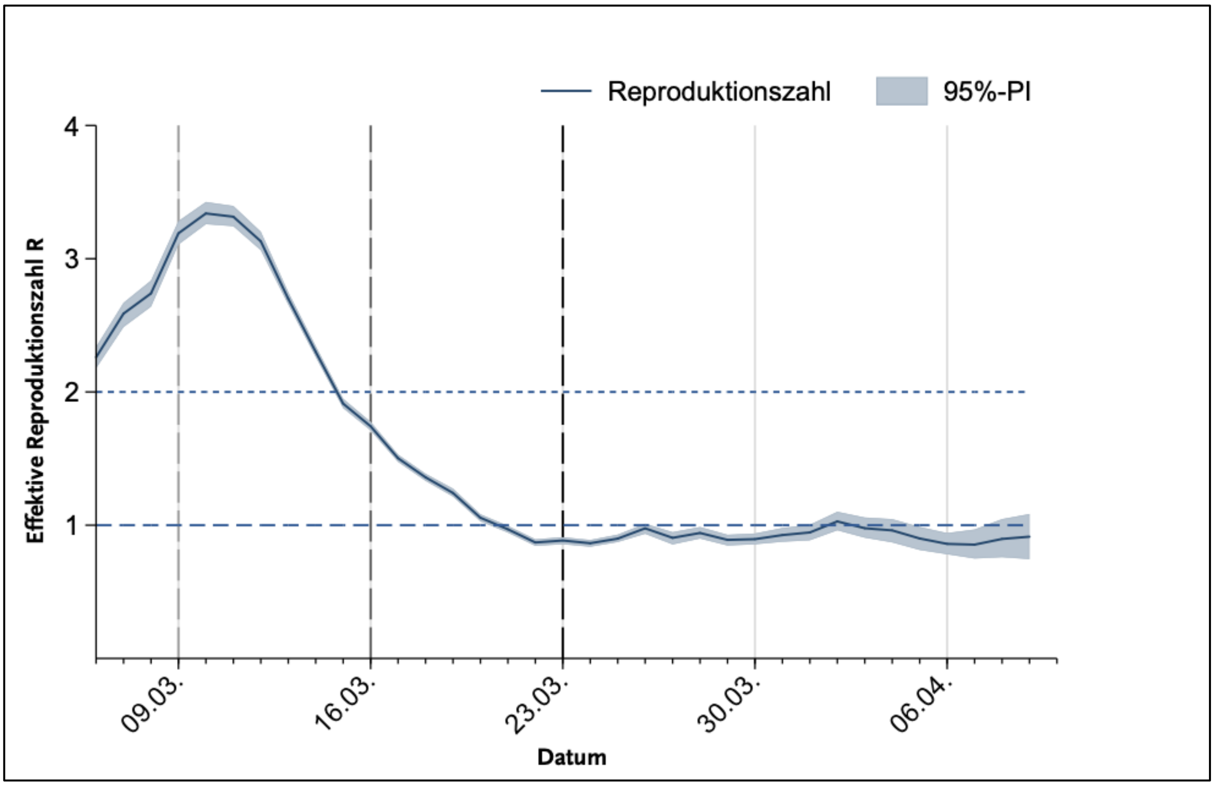
State	(n)	/100,000
Baden-Wuerttemberg	27,883	251.9
Bavaria	37,407	286.1
Berlin	5,159	137.6
Brandenburg	2,221	88.4
Bremen	585	85.7
Hamburg	4,167	226.3
Hesse	7,108	113.4
Mecklenburg-Vorpommern	651	40.4
Lower Saxony	8,797	110.2
North Rhine-Westphalia	28,471	158.8
Rhineland-Palatinate	5,432	133.0
Saarland	2,303	232.5
Saxony	4,190	102.7
Saxony-Anhalt	1,350	61.1
Schleswig-Holstein	2,417	83.4
Thuringia	1,756	81.9
Summe	139,897	

Source: https://experience.arcgis.com/experience/478220a4c454480e823b17327b2bf1d4

What is very interesting, the RKI makes available on an almost daily basis the estimation of the reproduction number, R, which is the mean number of persons infected by a case.[40] The current estimate is R= 0.8 and is based on current electronically notified cases (18/04/2020, 12:00 A.M.) and an assumed mean generation time of 4 days. The development of the effective reproduction number R for an assumed generation time of 4 days is depicted in Figure 15.

40 https://www.rki.de/DE/Content/Infekt/EpidBull/Archiv/2020/Ausgaben/17_20_SARS-CoV2_vorab.pdf?__blob=publicationFile

Figure 15 - Development of the effective reproduction number R



Source: https://www.rki.de/DE/Content/Infekt/EpidBull/Archiv/2020/Ausgaben/17_20.pdf?__blob=publicationFile

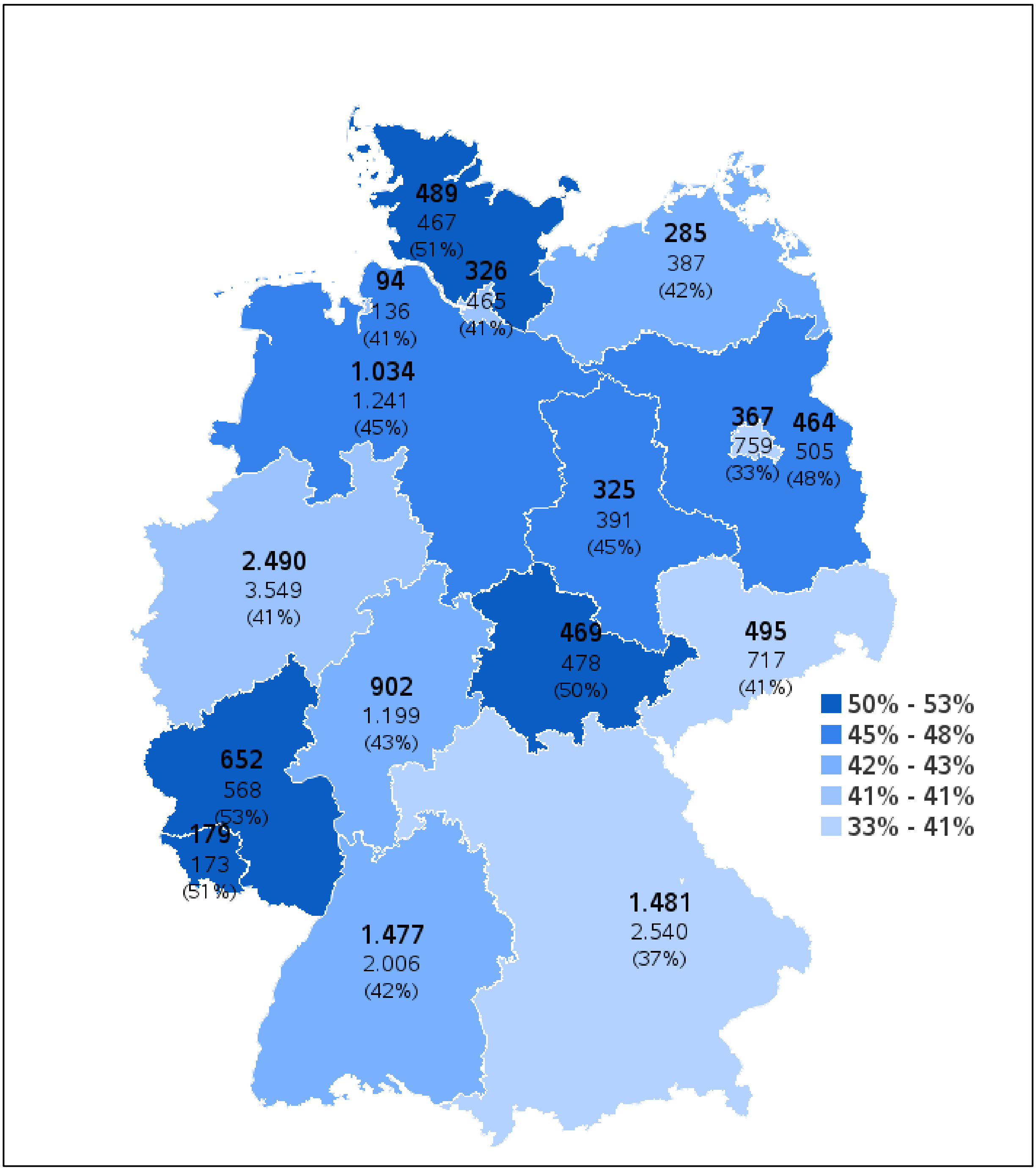
The vertical lines represent the policies carried out by the Federal Government, i.e. the cancellation of major events in different federal states (with more than 1,000 participants) on March 9 2020, the Federal-State Agreement on guidelines against the spread of the coronavirus on March 16 2020, and the nationwide extensive ban on contacts on March 23 2020. There is a clear decrease in the number over time.

Another interesting aspect is the Intensive Care Register, which to the best of our knowledge is a case unique to Germany. The German Interdisciplinary Association for Intensive and Emergency Medicine (DIVI), the RKI and the German Hospital Federation (DKG) have established the register to document the capacities for intensive care as well as the number of COVID-19 cases treated in participating hospitals. Specifically, the DIVI intensive care register documents the number of available intensive care beds in the reporting hospitals on a daily basis. What is very interesting about the register, and what makes it very precise, is the fact that a hospital location can have several reporting areas: this gives the hospital locations the opportunity to report directly from individual wards / departments.[41] A map view with the number of free and occupied intensive care beds & share of free beds in the total number of intensive care beds (

Figure 16).

[41] https://www.intensivregister.de/#/intensivregister

Figure 16 – ICU capacity in Germany



Source: https://www.intensivregister.de/#/intensivregister

Another interesting collaborative effort is carried out by RKI together with the the Research on Complex Systems Group (ROCS) at the Institute for Theoretical Biology and IRI Life

Sciences at Humboldt University of Berlin. The core of the data used come from RKI together with data from the worldwide air transportation network (WAN).[42] This network has 3893 nodes (airports) that are connected by 51476 directed links (flight routes). Each link is weighted by the traffic flux between nodes, i.e. the average number of passengers that travel each route per day.[43] Specifically, the team employs a SIR-X model, in which the transmission rate changes over time, inspired by the assumption that susceptible individuals are continuously removed from the transmission process due to interventions such as social distancing, public shutdowns, quarantines, and curfews.[44] This is complemented by an import risk model, which displays the likelihood of importing a case from an affected location to an airport or country distant from the outbreak location. This model is used to assess the If an infected individual boards a plane at airport A in an affected region, the relative import risk P(B|A) at airport B quantifies the probability that airport B is the final destination for that individual (irrespective of non-direct travel routes).

Say, 1000 infected individuals board planes at Hangzhou Airport. An import risk of 0.2% in Germany means that, of those 1000 individuals, only 2 are expected to have Germany as their final destination. By mean of the model it has been possible to describe the situation at the start of the pandemic (see

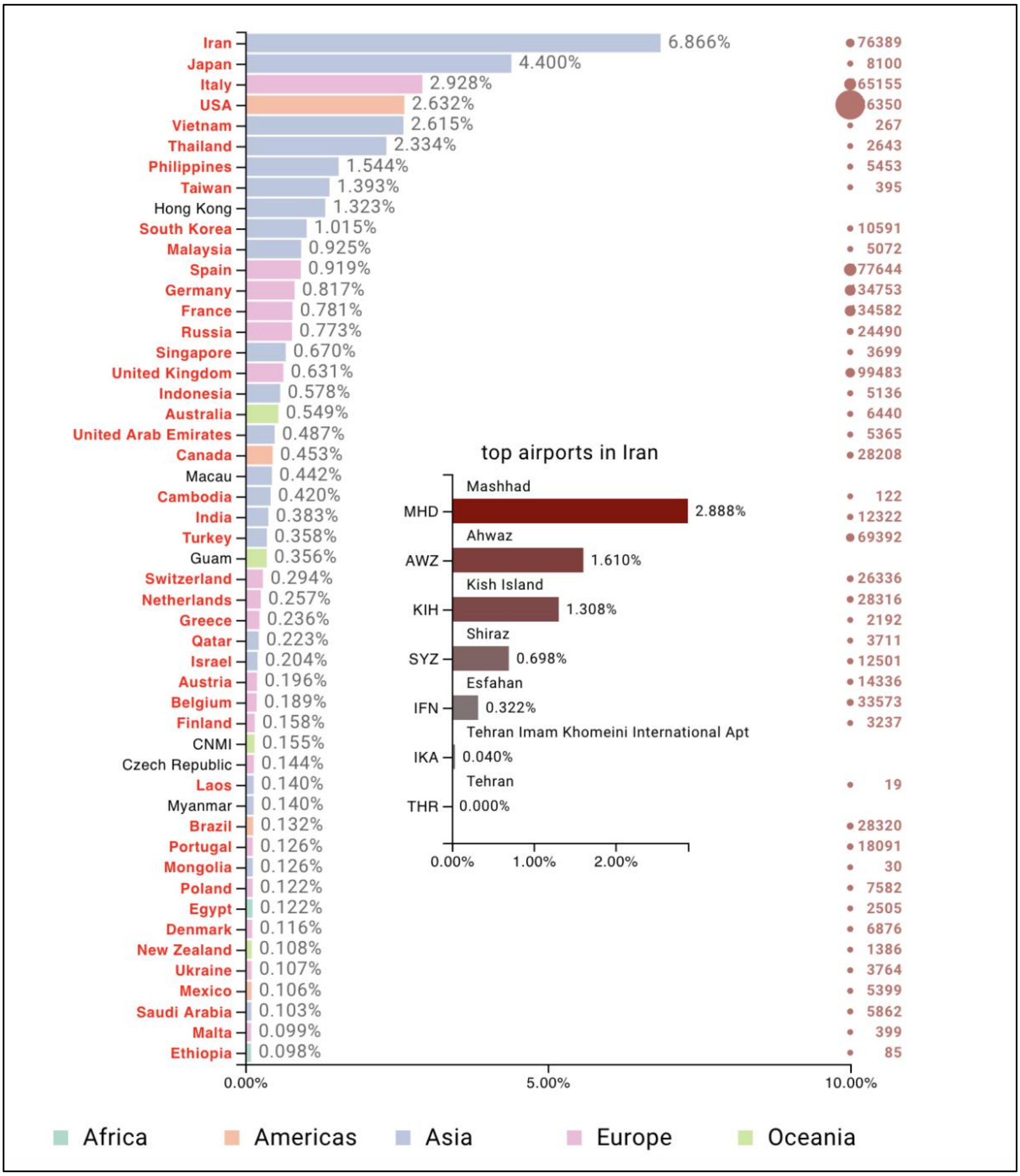
42 http://rocs.hu-berlin.de/corona/docs/analysis/importrisk/

43 The underlying network theoretic model is based on the concept of effective distance and is an extension of a model introduced in the 2013 paper The Hidden Geometry of Complex, Network-Driven Contagion Phenomena, D. Brockmann & D. Helbing, Science: 342, 1337-1342 (2013).

44 SIR-X model is described in detail here: Effective containment explains sub-exponential growth in confirmed cases of recent COVID-19 outbreak in China, B. F. Maier & D. Brockmann, Science, eabb4557, DOI: 10.1126/science.abb4557, (2020)

Figure 17).

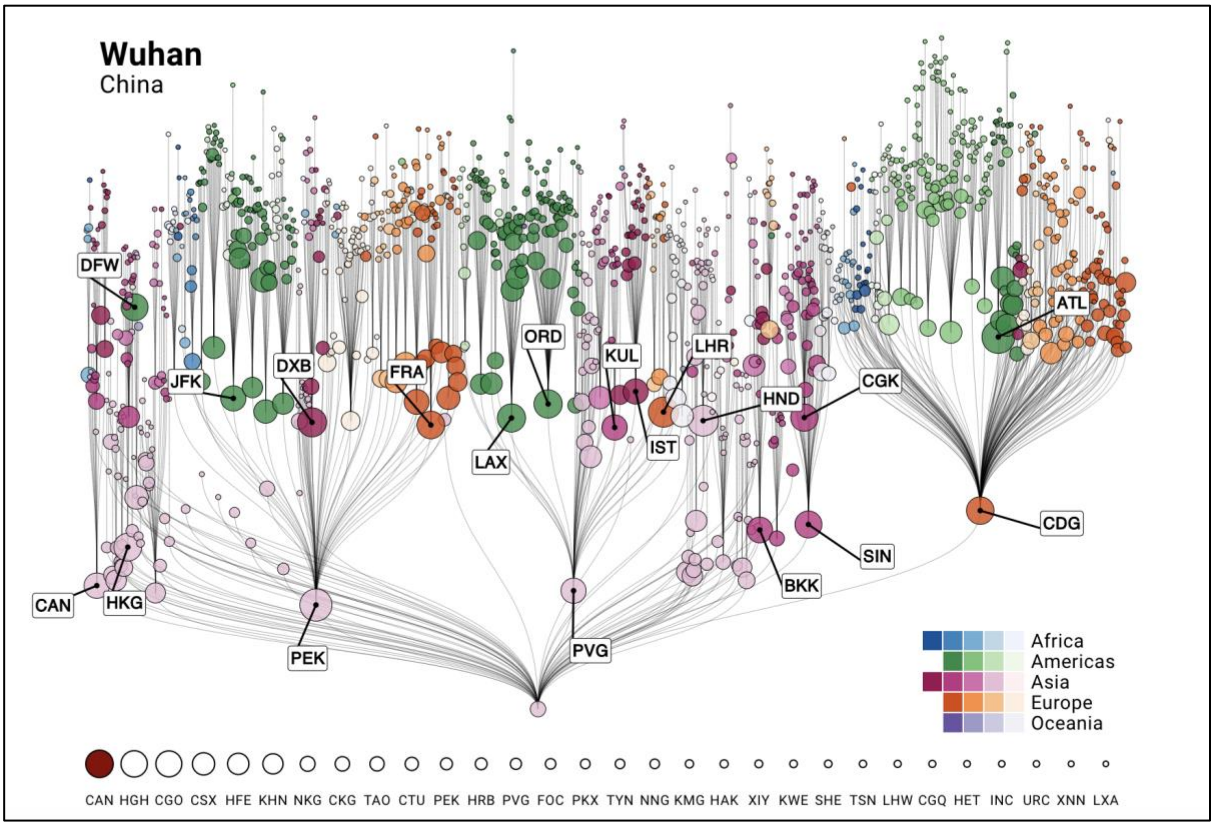
Figure 17 – Import risk at the beginning of the pandemics



Source: http://rocs.hu-berlin.de/corona/docs/analysis/importrisk/

Current import risk estimates for the top 50 countries (excluding Mainland China) at highest risk of importation. The national import risk is the cumulative import risk of all airports in that country. Countries with confirmed cases of COVID-19 at the time are depicted in red; the current number of cases per country are listed on the right-hand side. The import risk model also provides information on the most probable spreading routes from a location in the affected region, i.e. root node in the air transportation network. Figure 18 provides an understanding of the distribution of import risk and the most probable spreading routes from a selected set of airports in affected regions in Mainland China.

Figure 18 - Distribution of import risk and most probable spreading routes



Source: http://rocs.hu-berlin.de/corona/docs/analysis/importrisk/

The tree represents the most probable spreading routes from the root node to all other airports in the network, while the vertical length between nodes represents the effective distance between airports.

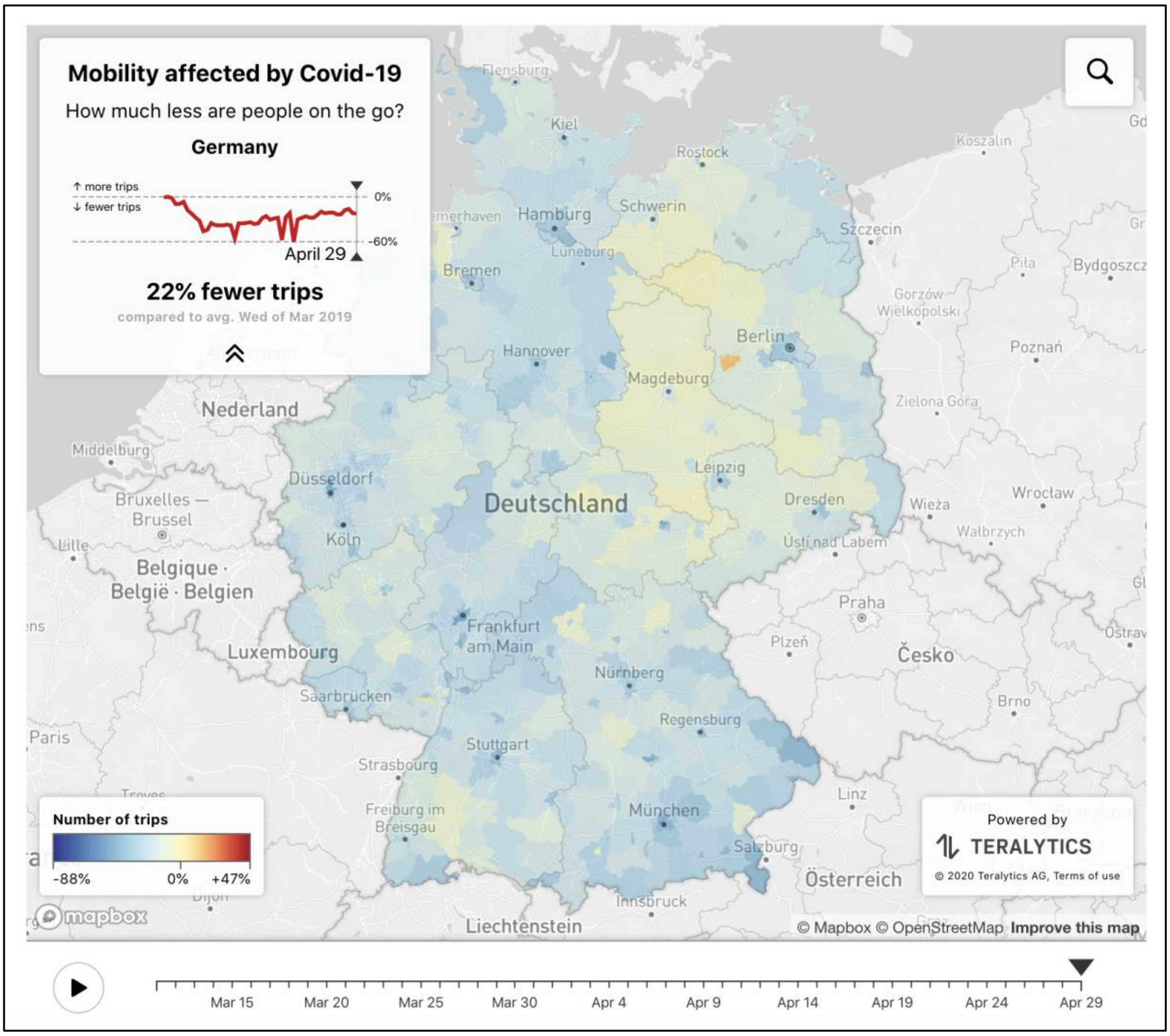
Along the same line the COVID Mobility Project[45] provides a general picture of mobility reduction in Germany due to Covid-19 mobility restrictions. Specifically, the model depicts three phases:

- Initial drop in mobility: mobility fell to -39% below normal in mid-March 2020, after the majority of restrictions in Germany took effect.
- Slow recovery of mobility: in late March mobility slowly increased and finally plateaued at -27% in the second week of April. As restriction policies hardly changed during this time, this increase might be attributed mostly to a relaxing of self-imposed, individual mobility restrictions, paired with increased mobility due to warmer weather.
- Beginnings of an opening: starting April 20th, some mobility restriction policies have been lifted. We observe an immediate increase in mobility to -21% in the week starting April 20th.

Mobility flows of this kind are collected by many mobile phone providers. The team uses data from the German Telekom, which is distributed by the company Motionlogic, as well as data from Telefónica, which is analyzed and aggregated by the company Teralytics. This kind of data is commercially available and is used, for example, by public transportation companies, for predicting traffic or to improve road infrastructure. The live mobility monitor is depicted in Figure 19.

Figure 19 – Change in mobility due to COVID-19

45 http://rocs.hu-berlin.de/covid-19-mobility/mobility-monitor/



Source: http://rocs.hu-berlin.de/covid-19-mobility/mobility-monitor/

Finally, a team of researchers (**Hartl et al.**) has measured the impact of the German public shutdown on the spread of COVID-19 by making use of data from Johns Hopkins University (2020), which links data from the Robert Koch Institute, the World Health Organization, and the European Centre for Disease Prevention and Control. Specifically, the researchers tested for a trend break in the cumulated confirmed Covid-19 cases by means of maximum likelihood.[46][47] They carried out a first estimation finding a trend break around 20 March.[48] Their finding is that confirmed Covid-19 cases in Germany grew at a daily rate of 26.7% until 19 March. From March 20 onwards, the growth rate drops by half to 13.8%, which is in line with the lagged impact of the policies implemented by the German administration on 13 March and implies a doubling of confirmed cases every 5.35 days. Before 20 March, cases doubled every 2.93 days. In their update of the model they test the impact of the 22 March policies.[49] From 30 March on, the estimated average growth rate is 5.8%, so that the cases double every 12.20 days, therefore the containment policies are being effective.

The Italian response to COVID-19 is supported by several teams of experts, among which the Task Force for the Covid-19 Emergency established by the Italian Ministry for

46 Bai, J (1997), "Estimation Of A Change Point In Multiple Regression Models", The Review of Economics and Statistics 79(4): 551–563.
47 Bai, J and P Perron (1998), "Estimating and Testing Linear Models with Multiple Structural Changes", Econometrica 66(1): 47–78.
48 https://cepr.org/sites/default/files/news/CovidEcon1%20final.pdf
49 https://voxeu.org/article/measuring-impact-german-public-shutdown-spread-covid-19

Technological Innovation and Digitization, and the data utilised are those of the Italian Civil Protection, which in turn are the result of the data collection effort through the Italian integrated COVID-19 surveillance system and aggregated at the national, regional and provincial level. There is no specific and explicit information regarding which models are used by the Italian authorities to take their decisions. According to confidential sources, the Italian National Institute of Health and the Italian Scientific and Technical Committee, in agreement with the Italian Ministry of Health and Italian Civil Protection, are collaborating with Bruno Kessler Foundation in developing the models used by the Italian authorities in taking their policy decisions. The model will be available only when published.

At any rate, on the basis of the modelling effort, members of the Italian Scientific and Technical committee and the Italian National Institute of Health have carried out an assessment of the risks of epidemic spread for COVID-19 disease associated with various scenarios of the release of the lockdown introduced on 11 March on the national territory. Some anticipated results according to which restarting all the sectors without teleworking and with schools open, the country would need 151 thousand intensive care units already in June and a number of hospitalizations, by the end of the year, equal to 430,866.[50]

Some other results obtained suggest that:

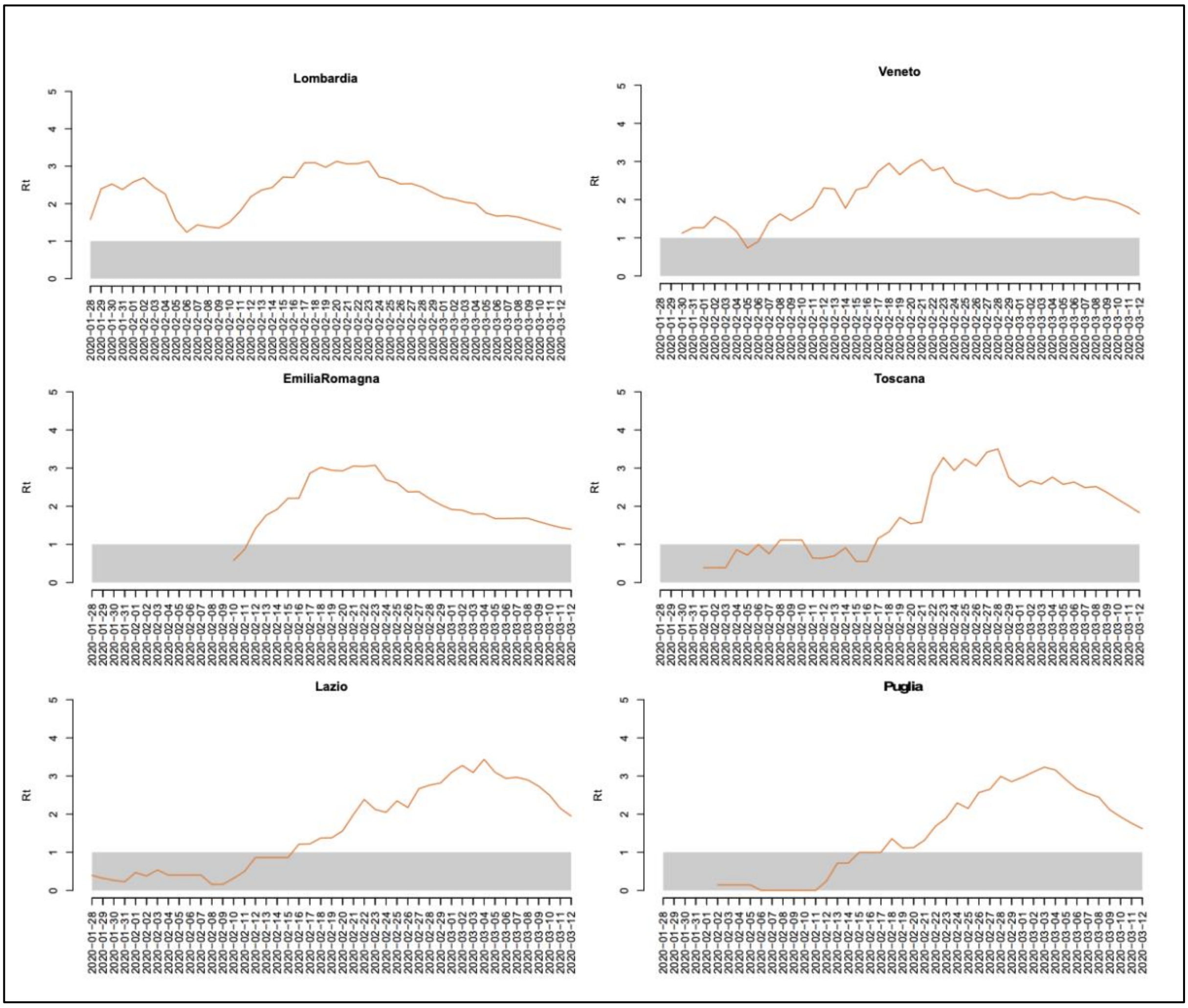
1. The reopening of schools would significantly increase the risk of a new epidemic wave with potentially very critical consequences on the stability of the national health system;
2. For all reopening scenarios in which an increase in community contacts is expected, transmissibility crosses the epidemic threshold, thus triggering a new epidemic wave;
3. In most re-opening scenarios of the professional sectors (in the presence of closed schools), even if transmissibility exceeds the epidemic threshold, the expected number of intensive therapies at the peak it would be lower than the current availability of beds at national level (about 9000);
4. If the widespread adoption of personal protective equipment reduces the transmissibility by 15%, the scenarios reopening the commercial sector to the community could allow containment below the threshold epidemic only managing to limit transmission in the community for over 60 years old;
5. If the widespread adoption of personal protective equipment reduces the transmissibility by 25%, the scenarios the reopening of the commercial sector and of the restaurant sector to the community could allow containment below the threshold only managing to limit the transmission in the community over 65 years.

Further, researchers from the **COVID-19 working group, National Institute of Health, Bruno Kessler Foundation and Cyprus University of Technology** have estimated the reproductive numbers one month into the epidemic.[51] Specifically, they analysed data from the national case-based integrated surveillance system of all COVID-19 infections as of March 24th 2020, collected from all Italian regions and autonomous provinces in order to provide a descriptive epidemiological summary on the first 62,843 COVID-19 cases in Italy as well as estimates of the basic and net reproductive numbers by region. Estimates of R0 varied between 2.5 in Toscana and 3 in Lazio, with epidemic doubling time of 3.2 days and 2.9 days, respectively. The net reproduction number showed a decreasing trend starting around February 20-25, 2020 in Northern regions. Initially R0 was at 2.96 in Lombardia, which explains the high case-load and rapid geographical spread observed. As it can be seen from Figure X, In Lombardia, the Rt started to oscillate reaching maximum values around 3 over the week from February 17 to 23. Starting from February 24, with the enforcement of a quarantined area around the most affected municipalities of the region, Rt was estimated to follow a constantly decreasing trend. The second and third most affected regions in February (Veneto and Emilia Romagna) show

50 https://drive.google.com/file/d/1pe1gEp4-UAPxLW_vnqntAa4AT5D_nyR1/view
51 https://www.medrxiv.org/content/10.1101/2020.04.08.20056861v1.full.pdf

an increasing trend of Rt until about February 24. On the other hand, in Tuscany, Lazio, and Apulia are located, the epidemic spread was largely undetected until early March, and after an initial increase, Rt remained nearly constant at values around 2.5-3 until March 4-8, when physical distancing measures began being implemented (Figure 20).

Figure 20 - Estimated reproduction number in selected Italian regions, February-March 2020, over a 4-day moving average



Source: https://www.medrxiv.org/content/10.1101/2020.04.08.20056861v1.full.pdf

Overall the reproductive number in Italian regions is currently decreasing, supporting the importance and effectiveness of combined non-pharmacological control measures. Along the same line, researchers and consultants to the Italian Government from the National Observatory on Health in the Italian Regions have estimated the timing according to which the number of new cases in each Italian region will amount to zero. Specifically, they find that the regions with zero new cases will be Basilicata and Umbria on April 21st, while the last will be Tuscany on May 30th.[52]

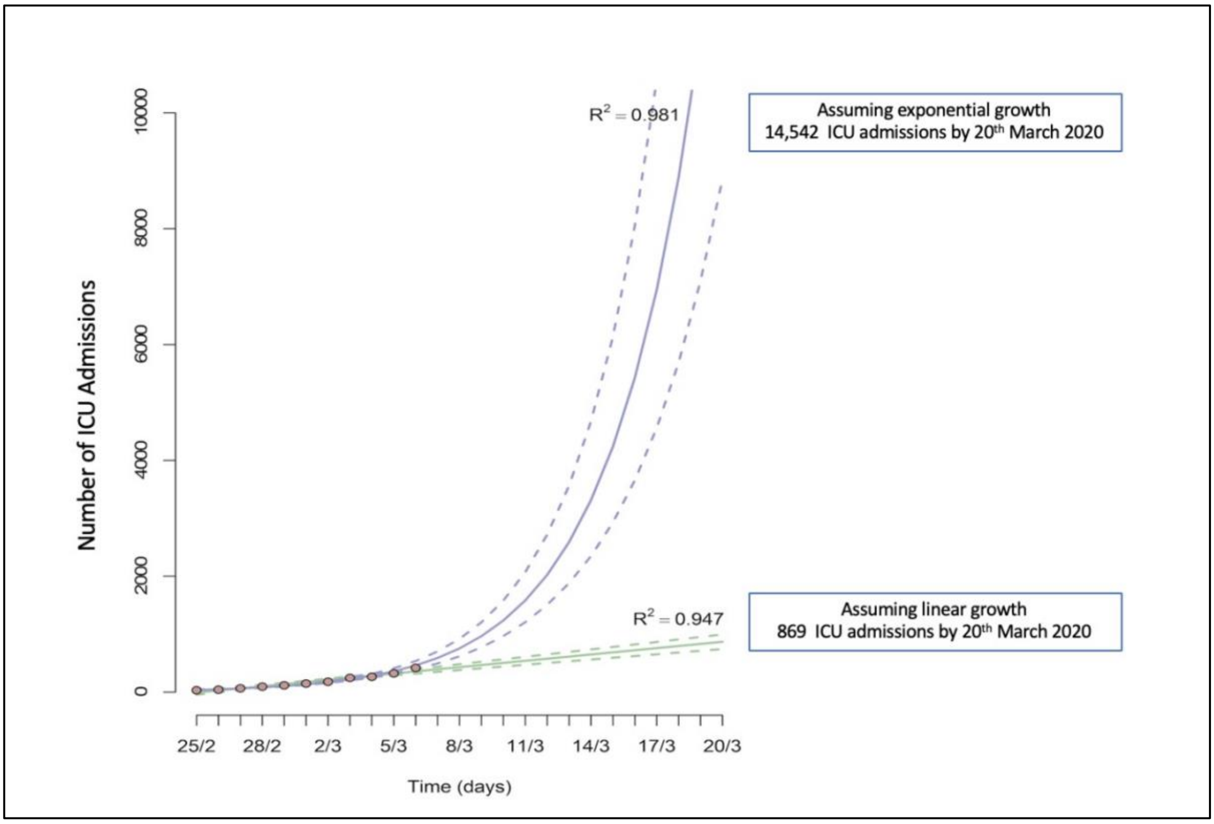
The impact of containment measures is assessed by another research team by Signorelli et al.[53] that concludes that suspending flights from China and air-ports' checkpoints with thermos-scan did not have a significant effect in containing the epidemic, the

[52] https://www.osservatoriosullasalute.it/wp-content/uploads/2020/04/new-19-aprile-Definitivo-CS-COVID-19-Osservatorio.pdf
[53] https://www.mattioli1885journals.com/index.php/actabiomedica/article/view/9511/8735

implementation of a “red zone” in Lombardy effectively contained the spread of the infection within that area, even though it did not have the same effect in the neighboring provinces (Bergamo, Brescia, and Piacenza); the failure to establish a second “red zone” near Bergamo in the Municipalities of Alzano and Nembro despite the proposal of local authorities (on March 3rd), led to a dramatic out-break with about 10,000 cases in Bergamo with over 1,000 death toll and similar figures in the neighbouring areas (Brescia and Piacenza); and finally that General mitigation measures seem to be effective to flatten the epidemic curve of new notified infections.

An Italian team of researchers (**Grasselli et al.**) was the first to address the consequences of the COVID-19 outbreak on critical care capacity outside China.[54] The article shows that despite prompt response of the local and regional ICU network, health authorities, and the government to try to contain the initial cluster, the surge in patients requiring ICU admission has been overwhelming. Therefore, other health care systems should prepare for a massive increase in ICU demand during an uncontained outbreak of COVID-19. This experience would suggest that only an ICU network can provide the initial immediate surge response to allow every patient in need to be cared for. In Figure 21 a linear and an exponential model were fitted to the number of ICU admissions to March 20, 2020.

Figure 21 - Linear and an exponential model fitted to the number of ICU admissions



Source: https://jamanetwork.com/journals/jama/fullarticle/2763188

The predicted number of ICU admissions on March 20, 2020, was estimated to be 869 with the linear model and 14,542 with the exponential model.

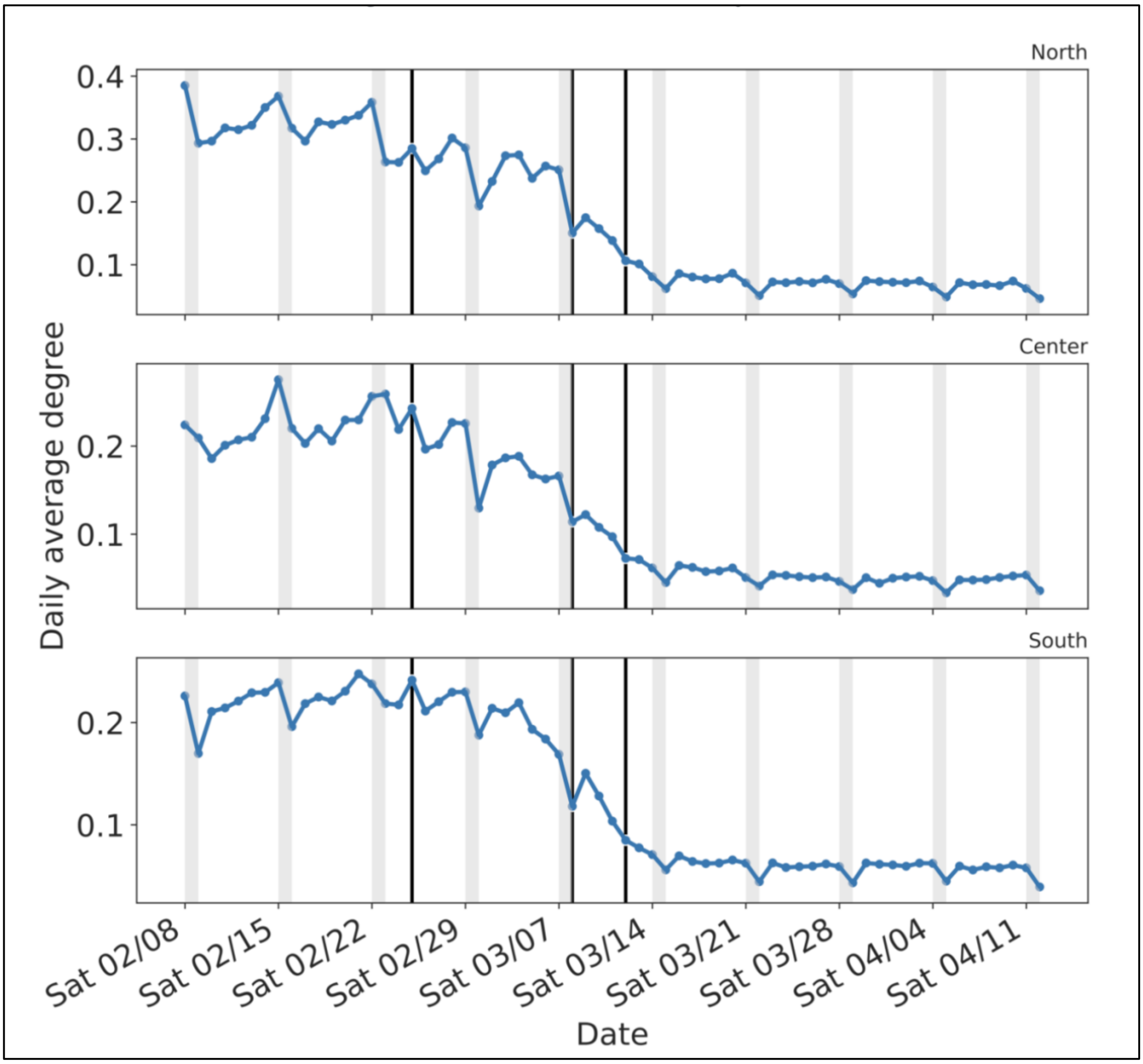
Another interesting case is the **COVID-19 Mobility Monitoring project**, which is an on-going project work carried out through a Data Collaborative between the ISI Foundation and Cuebiq Inc, aimed to analyse anonymized location data to understand the effect of mobility restrictions and behavioral changes on the current international COVID-19

54 https://jamanetwork.com/journals/jama/fullarticle/2763188

outbreak.[55] In their last exercise, they quantitatively assess the impact of non-pharmaceutical interventions like mobility restrictions and social distancing, to better understand the ensuing reduction of mobility flows, individual mobility changes, and impact on contact patterns, leveraging on the aggregated and privacy-safe mobility data provided by the Cuebiq programme Data for Good.[56] Specifically, they investigate the number of unique contacts made by a person on a typical day, and evaluate the effect of interventions on the social mixing of our users' sample by defining a proxy of the potential encounters each user could have in one hour. In order to do that, the researchers build a proximity network among users based on the locations they visited and the hour of the day when these visits occurred. The network is built by asserting the proximity between any two users in the same province who were seen within a circle of radius R = 50 m in a 1-hour period. The results of the exercise show that on April 12, Easter Day, the average degree of all users was 86% lower than the pre-outbreak averages in the North, 83% in the Center and 82% in the South and the Islands. In conclusion, in the past 4 weeks, the adherence to the mobility restrictions imposed since March 12 has remained high and constant all over the country. Specifically, in Figure 22 vertical lines highlight the start of three major interventions by the government: school closure and mobility restrictions imposed on Lombardy, Veneto, Piedmont, Emilia-Romagna, Liguria and Friuli on February 25, 2020; lockdown of the Lombardy region and additional provinces in Piedmont, Veneto, Emilia-Romagna, Marche on March 8, 2020; national lockdown on March 12, 2020.

Figure 22 – Effect of the major policy interventions on mobility

55 https://covid19mm.github.io/
56 https://covid19mm.github.io/in-progress/2020/04/17/third-report.html

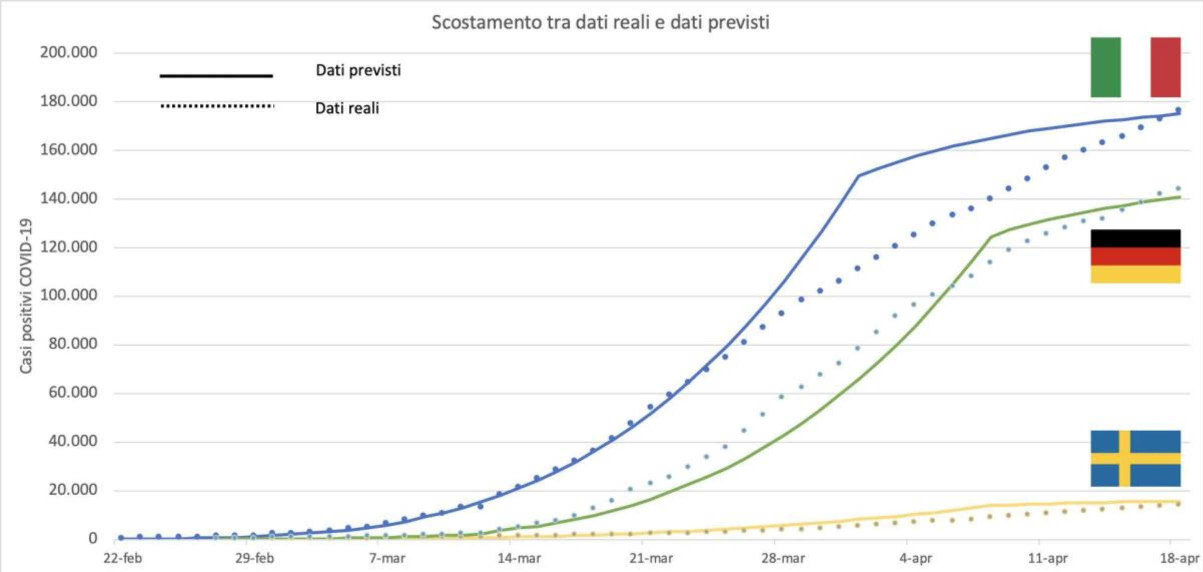


Source: https://covid19mm.github.io/in-progress/2020/04/17/third-report.html

Another Italian based team (**PREDICT COVID-19**) has developed a predictive model on the development of positive and dead cases due to COVID-19.[57] The study assumes that the first 17 days of infection are those that determine the slope of the curve, the duration of the epidemic depends on when the daily peak is reached which depends in turn on the containment strategies, and the curve can be divided into two different sections, before and after daily peak. The model, which is applicable at every level (city, province, region, country, macro-area, continent, etc.) shows that although the peak is close, in some regions the positive cases are underestimated, and also that containment strategies are working. As it can be seen from Figure 23 below, the model seems to be very precise in its predictions.

Figure 23 – Prediction of the development of new cases and deaths

57 https://www.predictcovid19.com/model.html



Source: https://www.predictcovid19.com/model.html

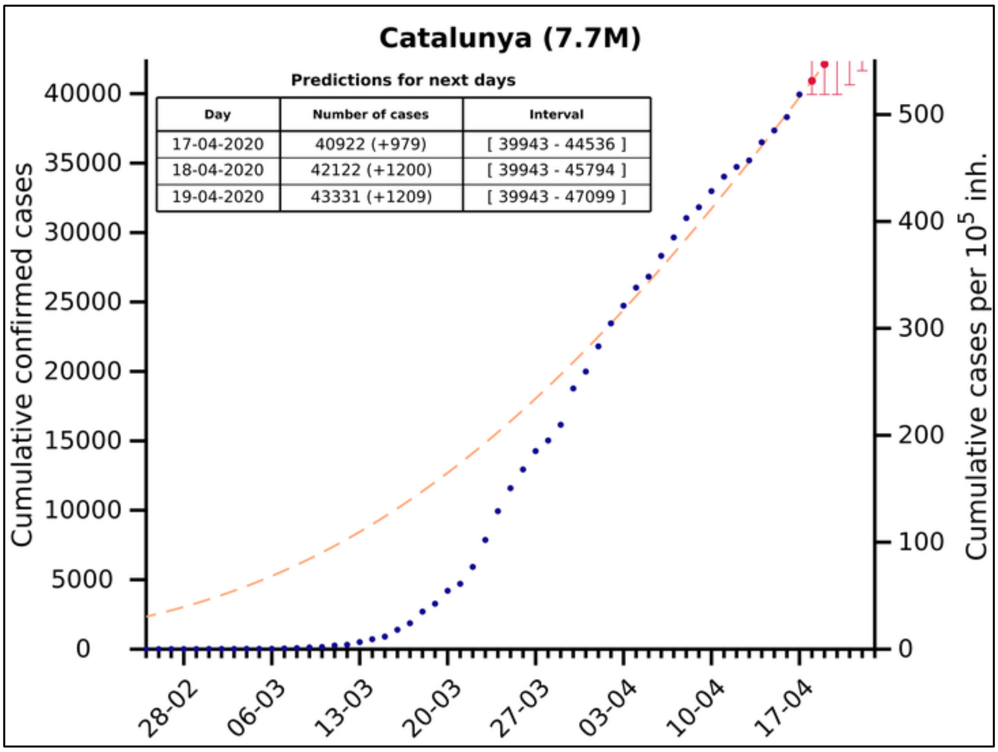
Also for what concerns the Spanish government there is no much explicit information about the models that are used by the government for policy making aimed to mitigate the COVID-19 outbreak. One of the advisors to the Spanish emergency departments is **Juan Luis Fernández Martínez**, a professor of applied mathematics from the University of Oviedo who has developed a short term prediction tool predicting how many patients will need to be admitted in intensive care units.[58] His model uses data at regional level from Asturias, Cantabria and Castile Leon, together with data from the Spanish ministry of health since March 18th, and the estimations issued by Johns Hopkins University. Other models adopted include the one by Polytechnic University of Catalonia, which employs an empirical model verified with the evolution of the number of confirmed cases in previous countries where the epidemic is close to conclude, including all provinces of China.[59] The model permits the evaluation of the quality of control measures made in each state and a short-term prediction of tendencies. Specifically, the model and predictions are based on two parameters: the rate at which the specific propagation rate slows down and the final number of expected cumulative cases. The model is then fit to countries and regions with at least 4 days with more than 100 confirmed cases and a current burden of more than 200 cases with forecasts of up to 3 days. The predicted period of a country depends on the number of datapoints over this 100 cases threshold:

- Group A - countries that have reported more than 100 cumulated cases for 10 consecutive days or more - 3 days prediction;
- Group B - countries that have reported more than 100 cumulated cases for 7 to 9 consecutive days - 2 days prediction;
- Group C - countries that have reported more than 100 cumulated cases for 4 to 6 days - 1 day prediction.

The data sources of the model are World Health Organization (WHO) surveillance reports[60], the European Centre for Disease Prevention and Control (ECDC)[61] and the Spanish Ministry of Health.[62] The short term predictions for Catalonia, Spain and European Union are depicted in figures Figure 24Figure 25 and Figure 26.

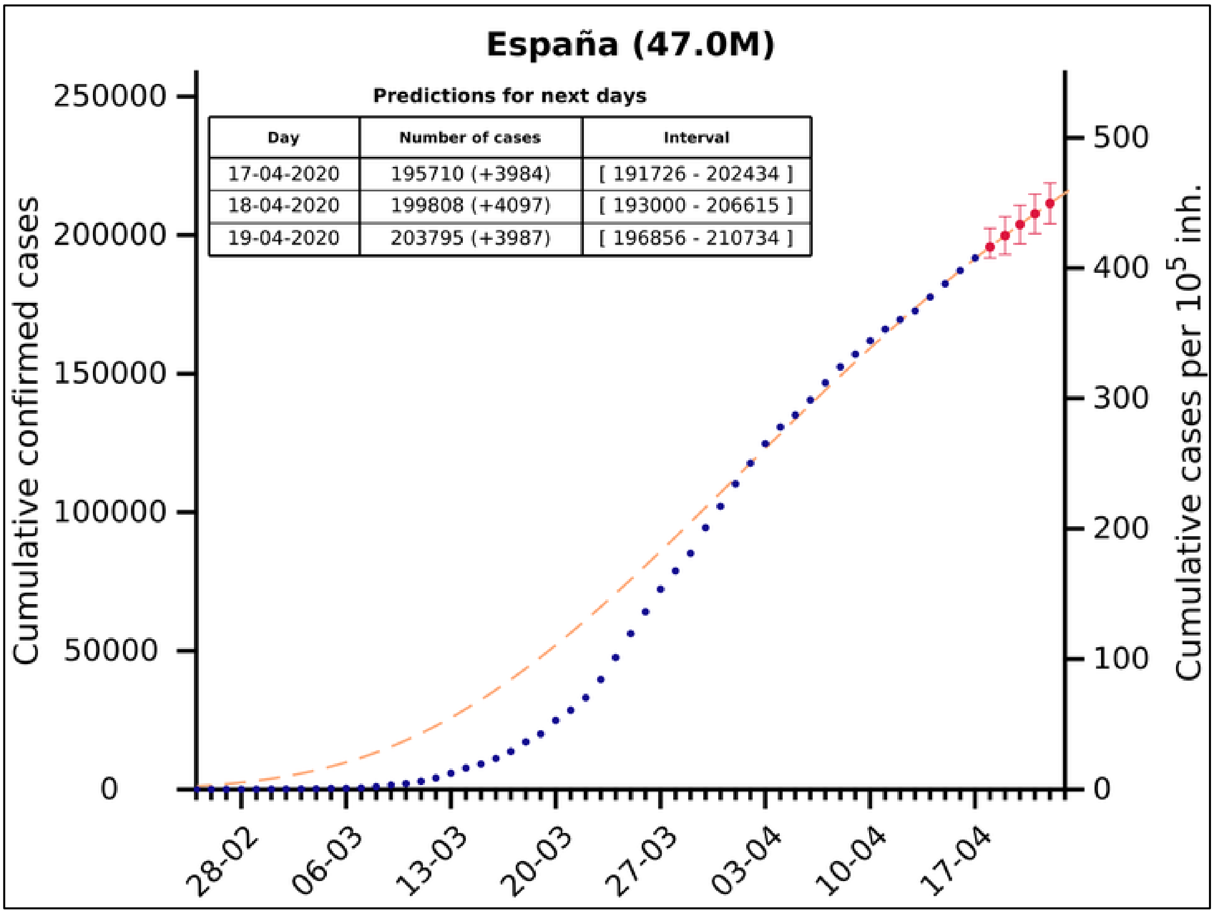
Figure 24 – Prediction for Catalonia

58 https://healthcare-in-europe.com/en/news/predicting-the-future-of-the-covid-19-pandemic-with-data.html
59 https://biocomsc.upc.edu/en/covid-19/Methods.pdf/view
60 https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports
61 https://www.ecdc.europa.eu/en/geographical-distribution-2019-ncov-cases
62 https://www.mscbs.gob.es/profesionales/saludPublica/ccayes/alertasActual/nCov-China/situacionActual.htm



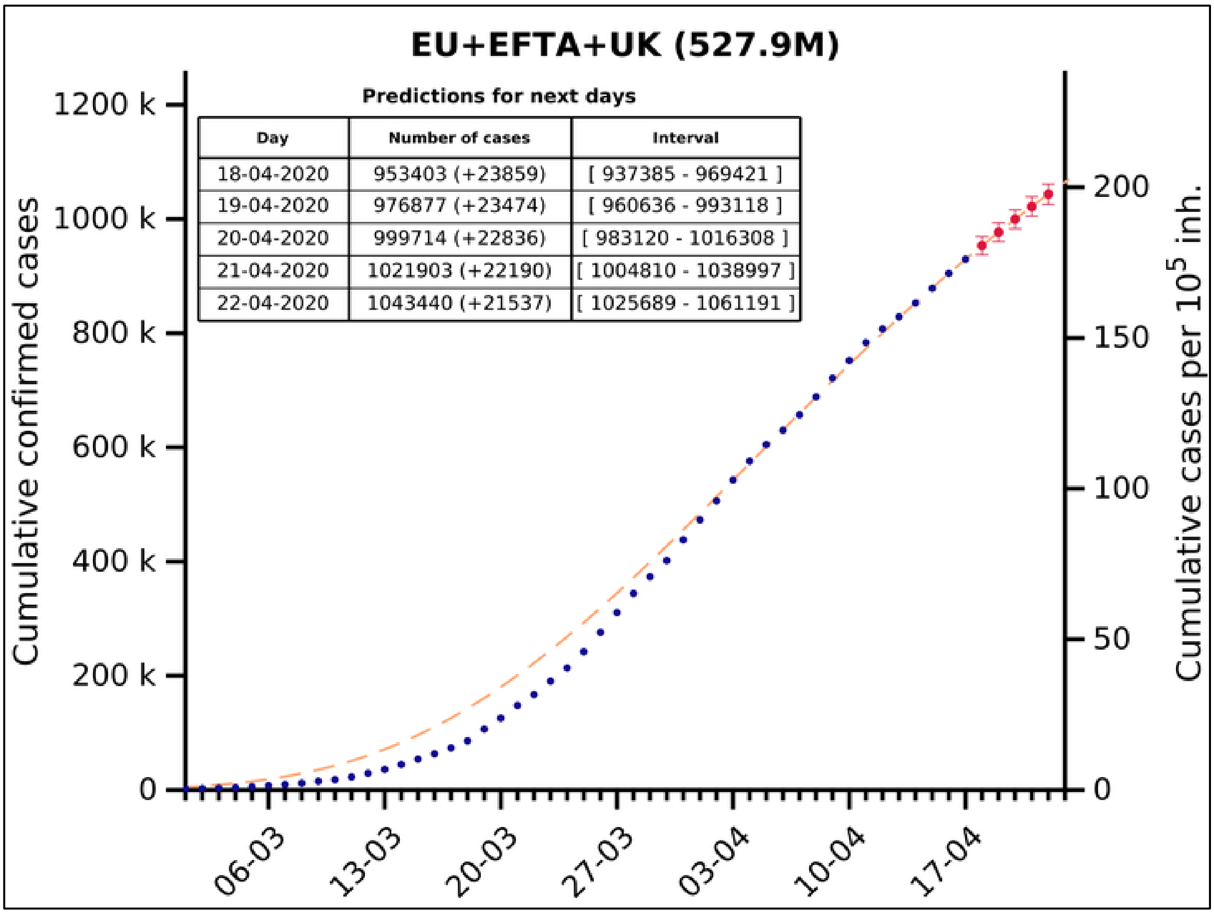
Source: https://biocomsc.upc.edu/en/covid-19/Methods.pdf/view

Figure 25 – Prediction for Spain



Source: https://biocomsc.upc.edu/en/covid-19/Methods.pdf/view

Figure 26 – Prediction for EU/EFTA/UK

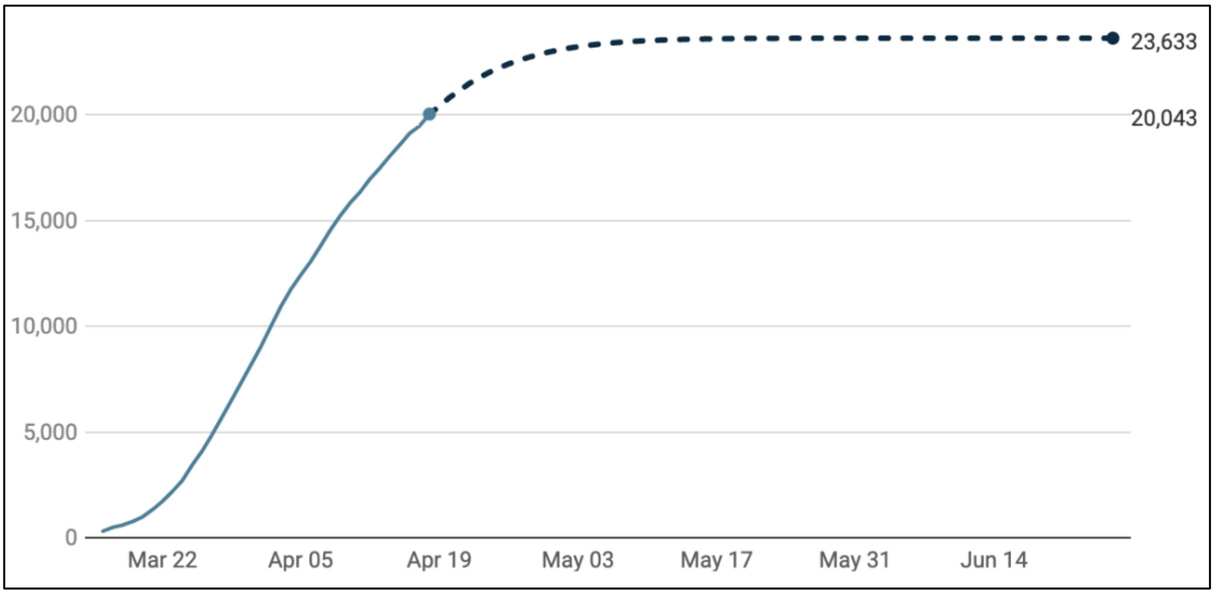


Source: https://biocomsc.upc.edu/en/covid-19/Methods.pdf/view

Another interesting modelling exercise is carried out by **Inverence**[63], which has developed predictive models based on Bayesian time series analysis building on data released by Spain's Ministry of Health. The modelling strategy considered the number of daily ICU admissions in every region and linking it, via a transfer function, to the number of deaths, assuming that the number of ICU admissions is a good indicator of the number of infected individuals in critical condition. The regional models are then combined with a nation-wide model to produce consistent forecasts that consider the covariance structure of all different forecasts. Later on, the research team has developed models for the number of infected cases, based on a dynamical transmission rate model, which allows to understand in a straightforward way the effect of public authorities' actions, which are aimed precisely at reducing this transmission rate. These models for total detected cases have then been coupled to transfer functions for deaths, recoveries, hospitalizations, and ICU admissions. The modelling activity produced a series of forecasts, out of which some examples are provided in the figures Figure 27Figure 28 and Figure 28.

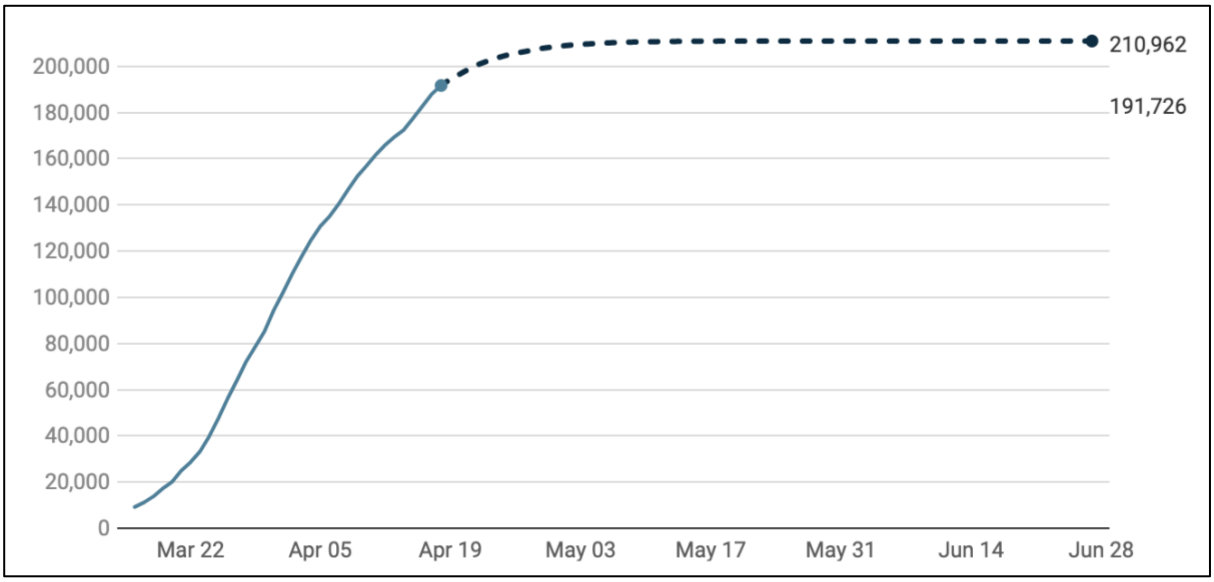
Figure 27 - Cumulative Number of Deaths in Spain

63 https://covid19.inverence.com/



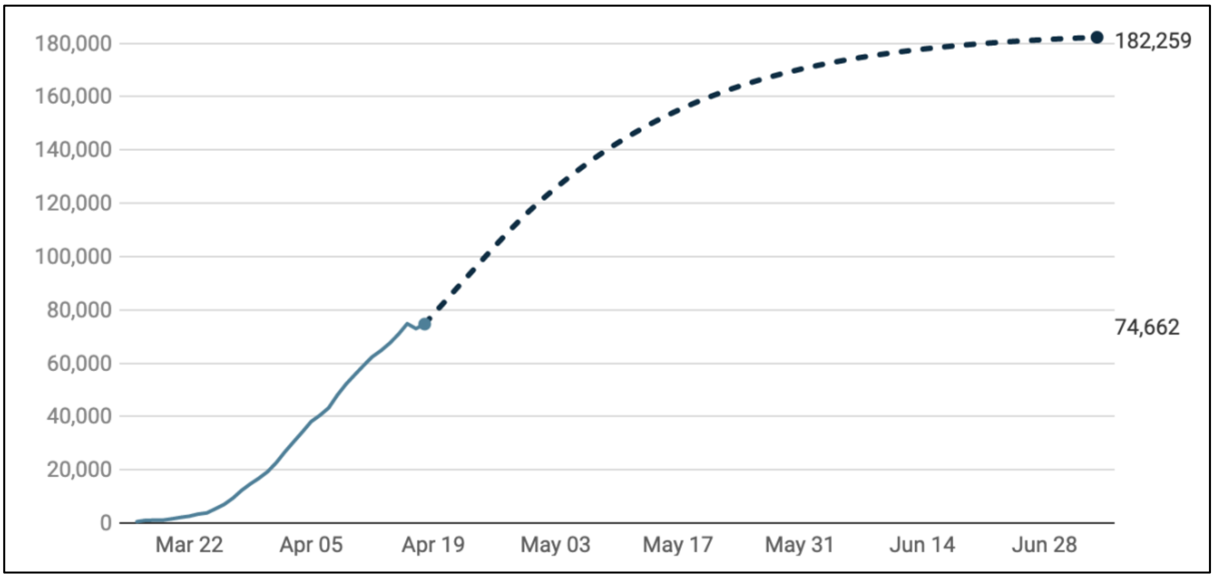
Source: https://covid19.inverence.com/#articulos

Figure 28 - Cumulative Confirmed Cases in Spain



Source: https://covid19.inverence.com/#articulos

Figure 29 - Cumulative Confirmed Recoveries in Spain



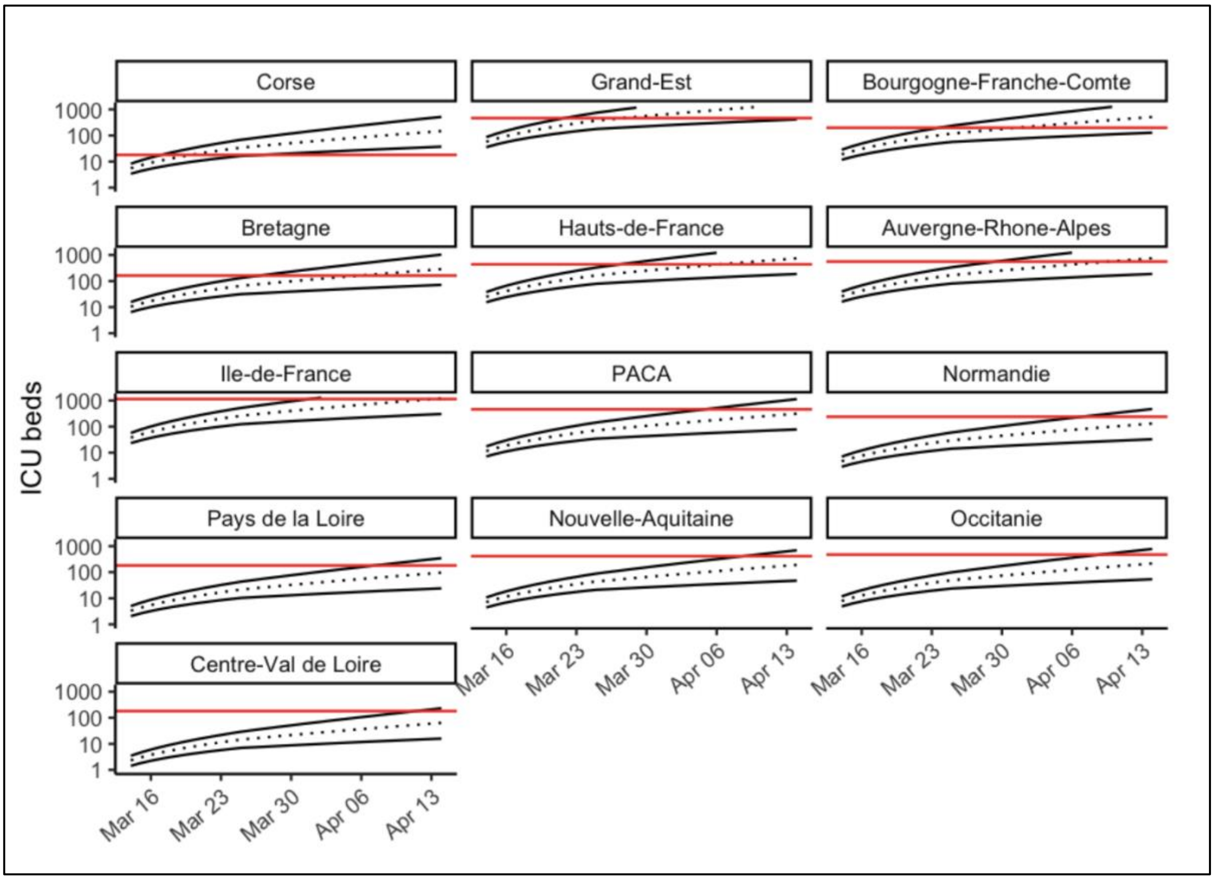
Source: https://covid19.inverence.com/#articulos

A final interesting and advanced modelling approach implemented by the University of Zaragoza[64] to describe the propagation of COVID–19 in Spain. The research team adapted a Microscopic Markov Chain Approach (MMCA) metapopulation mobility model to capture the spread of COVID-19 that stratifies the population by ages, and accounts for the different incidences of the disease at each strata. The model is used to predict the incidence of the epidemics in a spatial population through time, permitting investigation of control measures. Specifically, the model makes use of the estimates of the epidemiological parameters and the mobility and demographic census data of the Spanish national institute of statistics (INE) to define human behavior features such as age strata, age-structured contact patterns, the urban demography, and daily recurrent mobility flows. In this application, the model is used to evaluate different containment policies and shows that at the current stage of the epidemics the application of stricter containment measures of social distance are urgent to avoid the collapse of the health system. Furthermore, it also shows that the complete lockdown appears as the only possible measure to avoid the collapse.

As for France, **Massonnaud and his team**[65] have developed a deterministic SEIR model for hospital areas with predictions at one month and 17 five-year age groups (last 80 and over) to estimate the ICU resource deficit. Specifically, the model is based on country-specific contact matrices (social interactions) between age groups.[66] The team modeled the propagation of COVID-19 from March 10 to April 14, across all metropolitan French Regions. At the national level, the total number of infected cases was expected to range from 22,872 in the best case (R0 = 1.5) to 161,832 in the worst considered case (R0 = 3). Regarding the total number of deaths, it was expected to vary from 1,021 to 11,032, respectively. Clearly the real data regarding mortality rate are higher. What is interesting, it is also that they estimated the timing according to which the capacity limit of French ICU would be overrun, building on data retrieved from the "Statistique Annuelle des Etablissements de Santé" (SAE).[67] The predicted ICU capacity limit, is depicted in figure Figure 30, where the dotted line stands for the scenario with R0 = 2.25, the black lines for the worst and best case scenarios (R0 = 3 and R0 = 1.5, respectively). Panels for each French Region are ordered by time of overrun (left to right and top to bottom).

64 https://www.medrxiv.org/content/10.1101/2020.03.21.20040022v1.full.pdf
65 https://www.ea-reperes.com/wp-content/uploads/2020/03/PredictedFrenchHospitNeeds-EHESP-20200316.pdf
66 The model builds on the study by Prem K, Cook AR, Jit M. Projecting social contact matrices in 152 countries using contact surveys and demographic data. PLOS Computational Biology 2017; 13: 1–21.
67 DREES. Statistique annuelle des établissements de santé (SAE). https://www.sae-diffusion.sante.gouv.fr/sae-diffusion/accueil.htm.

Figure 30 - Predicted needs of ICU beds in the 13 French Regions



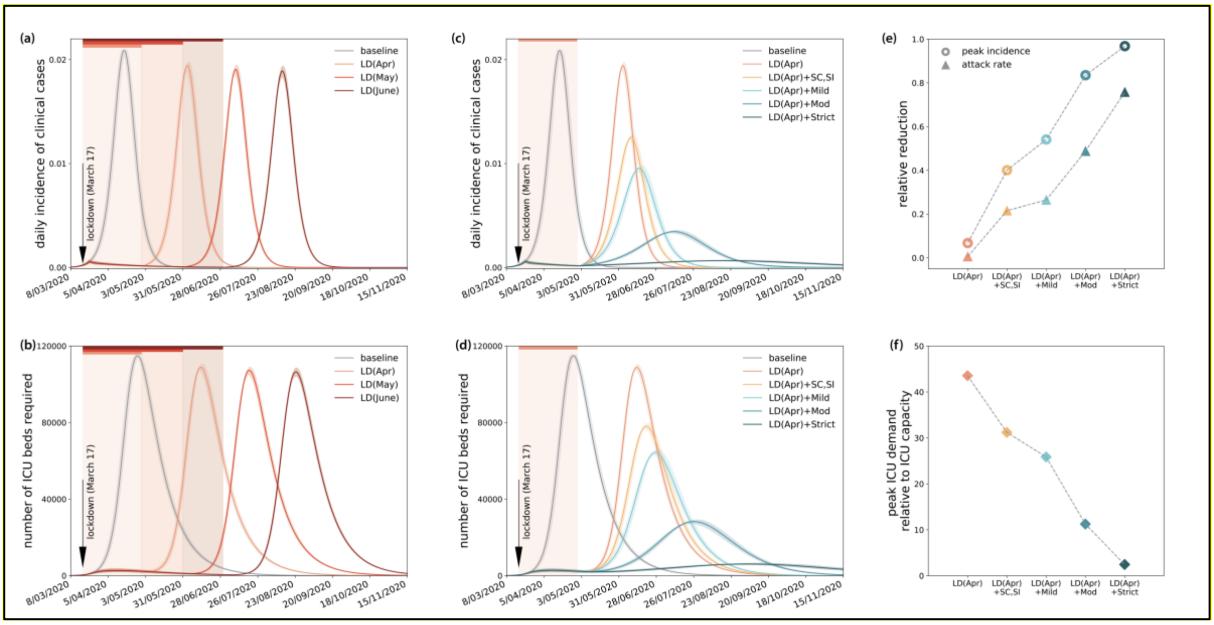
Source: https://www.ea-reperes.com/wp-content/uploads/2020/03/PredictedFrenchHospitNeeds-EHESP-20200316.pdf

Luckily, the French healthcare system was able to react and not be overwhelmed, most probably because the government reacted based on this model. Another team of researchers that is advising the French government works at the **EPIcx-lab of INSERM** - (Institut national de la santé et de la recherche médicale) at the Pierre Louis Institute of Epidemiology and Public Health, Sorbonne Université. In one study they use a stochastic age-structured transmission model integrating data on age profile and social contacts in the Île-de-France region to assess the current epidemic situation, evaluate the expected impact of the lockdown implemented in France on March 17, and finally to estimate the effectiveness of exit strategies, building on hospital admission data of the region before lockdown.[68] Within this scope, they simulate different types and durations of social distancing interventions as well as a progressive lifting of the lockdown targeted on specific classes of individuals joint with large-scale testing. The authors also estimate the basic reproductive number at 3.0 prior to lockdown and assume that the population infected by April 5 to be in the range 1% to 6%. Further, they estimated that the average number of contacts is predicted to be reduced by 80% during lockdown, leading to the reduction of the reproductive number to 0.68. They show that the epidemic curve reaches ICU system capacity and slowly decreases during lockdown, and that lifting the lockdown with no exit strategy would cause a second wave. They also show that testing and social distancing strategies that gradually relax current constraints while keeping schools closed and seniors isolated will avoid a second wave and healthcare demand exceeding capacity. Figure 31 reports the simulated impact of lockdown of different durations and exit strategies: (a) Simulated daily incidence of clinical cases assuming lockdown till end of April, end of May, end of June; (b) Corresponding demand of ICU beds; (c) Simulated daily incidence of clinical cases assuming lockdown till end of April, followed by interventions of varying degree of intensity; (d) Corresponding demand of ICU beds. (e) Relative reduction of peak

68 https://www.epicx-lab.com/uploads/9/6/9/4/9694133/inserm-covid-19_report_lockdown_idf-20200412.pdf

incidence and epidemic size after 1 year for each scenario; (f) Peak ICU demand relative to ICU capacity of the region.

Figure 31 - Simulated impact of lockdown of different durations and exit strategies



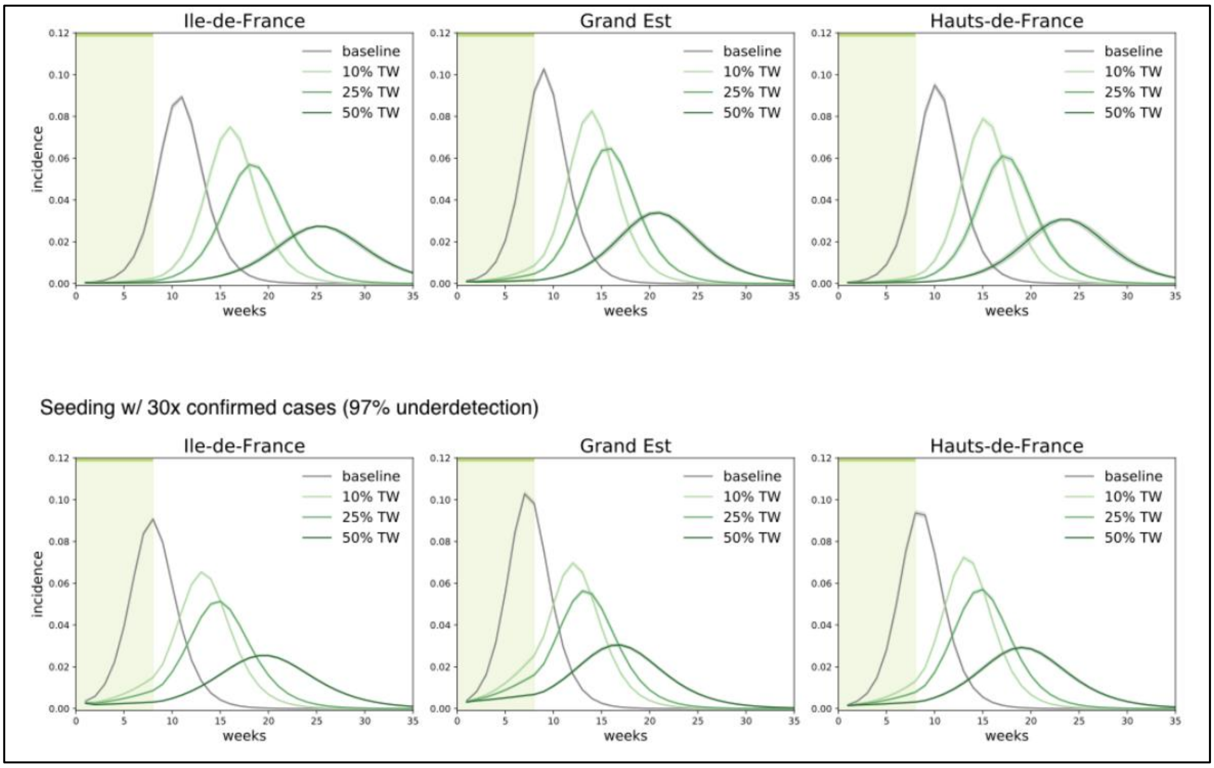
Source: https://www.epicx-lab.com/uploads/9/6/9/4/9694133/inserm-covid-19_report_lockdown_idf-20200412.pdf

Another work from the institute aims to assess the expected impact of school closure and telework to mitigate COVID-19 epidemic in France[69]. The model builds on social contact data between children and adults for each region, and accounts for current uncertainties in the relative susceptibility and transmissibility of children. According to the model, mere school closure would have limited effects (i.e. <10% reduction with 8-week school closure for regions in the early phase of the epidemic), while coupled with teleworking for 25% adults there would be a delay of the peak by almost 2 months with an approximately 40% reduction of the case incidence at the peak. Therefore, explicit guidance on telework and interventions to facilitate its application to all professional categories who can adopt it should be urgently provided.

Figure 32 reports the incidence curves in case of no intervention (grey line) and the 8-week school closure scenario for Île-de-France (left), Grand Est (center), and Hauts-de-France (right), with 10%, 25%, and 50% of adult population teleworking. It has to be noticed that the shaded area indicates the 8-week period during which the school closure is implemented. The model is seeded with four times the number of confirmed cases (75% under-reporting at the top) and 30x the number of confirmed cases (97% under-reporting at the bottom).

Figure 32 - Incidence curves for the baseline scenarios and for several interventions

69 https://www.epicx-lab.com/uploads/9/6/9/4/9694133/inserm_covid-19-school-closure-french-regions_20200313.pdf



Source: https://www.epicx-lab.com/uploads/9/6/9/4/9694133/inserm_covid-19-school-closure-french-regions_20200313.pdf

1.3 In depth Analysis

All over the world predictive models are used as background and guide for policy making. However, as widely documented, there are several caveats to be taken into account when stemming from data and modelling assumption, particularly when the phenomena studied are still ongoing.[70] Considering the simplest SIR model, in principle the number of deaths from an infectious disease is given by the susceptible population times the infection rate times the fatality rate. Starting from the fatality rate, it is difficult to have an average single dimension as it depends on the age of individuals and the presence of comorbidities, and therefore it changes from cohort to cohort and from country to country. Furthermore, even in the same subset of individuals, there are many uncertainties. In fact, the fatality rate is the ratio of the number of people who have died from the disease and the number of people infected with the disease. Now, it is first of all difficult to state how many people died from COVID-19, in particular in the presence of comorbidities. There are in fact differences in how countries record Covid-19 deaths.[71] Secondly, it is extremely impractical to determine the number of people that are infected at any given moment. This suggests that there are a lot of people walking around with COVID-19 who do not know it, and therefore the fatality rates are lower than what is currently argued in many countries. On the other hand, there are also several studies that suggest a higher mortality of the COVID-19 outbreak by looking at "excess mortality", i.e. the gap between the total number of people who died from any cause, and the historical average for the same place and time of year, as well as that many individuals were killed by conditions that might normally have been treated, had hospitals not been overwhelmed by a surge of patients needing intensive care.[72][73][74] Further, it is not easy to estimate to what extent fatality rate is influence by the hospital capacity, e.g. access to the best care (ICU). It is also difficult

70 https://fivethirtyeight.com/features/why-its-so-freaking-hard-to-make-a-good-covid-19-model/
71 https://www.bbc.com/news/52311014
72 https://www.economist.com/graphic-detail/2020/04/16/tracking-covid-19-excess-deaths-across-countries?fsrc=scn/fb/te/bl/ed/covid19datatrackingcovid19excessdeathsacrosscountriesgraphicdetail&fbclid=IwAR2AqP18VghCYmX5PKH8ns0a-2yPXhzzNId01Ge7PWxg5HLjhaeD0yOPDng
73 https://www.ispionline.it/it/pubblicazione/fase-2-morti-sommerse-eccesso-di-zelo-25878
74 https://www.medrxiv.org/content/10.1101/2020.04.15.20067074v2

to have a precise estimation of the symptomaticity ratio, which calculates how many people are symptomatic versus asymptomatic. In fact, it is clear that in case the healthcare capacity of a country (or a region) is overwhelmed, the fatality rate goes up. The infection rate depends on the basic reproduction number (R0), which is the average number of new infections traced back to each infected person in a population where everyone is susceptible to the disease. This is influenced by the rate of contact, which is given by how many people an infected person interacts with in a given period of time and that depends on the circumstances, and by the rate of transmission per contact, which is basically how many of the people an infected person meets will become infected themselves. In turns, there are other variables that influence the infection rate: how long the virus can survive on a given surface, how far it can be flung through the air, the duration of infectiousness, and the extent to which asymptomatic individuals are infectious in comparison with symptomatic ones. And finally, all these dimensions are influenced by interventions such as social distancing and school closing, as well as of the modelling technique and the stage of the epidemics. Taking into account more concrete cases, different assumptions and modelling approaches can lead to different results and policy recommendations. In that regard, an interesting comparison[75] can be done between top down and bottom up approaches. The top down approach consists in fitting a curve to the data set and then to extrapolate the future data points. A bottom up approach consists in modelling a series of components mimicking the progress of the epidemics such as social distancing, allowing to separate the different mechanisms of the transmission process. The models by the Imperial College is based on the bottom up approach. In fact, they model the ways in which the virus can be transmitted, and then assess how social distance and transportation influence the process. On the other hand, the model by IHME fits curves representing deaths in various locations with a series of parameters, and then extrapolates the numbers of deaths and the need for hospitalization and equipment. This leads to uncertainty at the beginning of the outbreak in which less location-specific data is available. Another important issue is that the IHME model assumes that the US has had a lockdown as strict as Wuhan, but this seems not to be the case. Further, only one location Wuhan has had a generalized epidemics, and therefore modelling the US fitting curve on such location is difficult, especially because the timing and extent of social distancing is difficult to mimic. When more US data will be available, the more will become more precise. Further, even though the model takes into account age structure, some other factors are not modelled, such as the prevalence of multi and co-morbidities, chronic lung disease, use of public transport, pollution and population density. On the top of that, the reduction in healthcare quality due to overload is not explicitly taken into account.

Another interesting comparison lies in recommendations stemming from the models. For instance, the first version (16 March) of the Imperial College model has grim predictions for what concerns the death toll in US and UK (respectively up to 500K and 2.2 million deaths) and the strain on ICU capacity, prompting the government to put in place mitigation measures. On the other hand, the Oxford model suggests that the new coronavirus may already have infected far more people in the UK than scientists had previously estimated (maybe half of the population), and that thereby the mortality rate from the virus is much lower than what is generally thought to be, as the vast majority of infected individuals develop mild symptoms or not at all.

However, both models are built on a series of extreme assumptions: for the Imperial College model the value of R0, the rate of death, the length of incubation, and the period in which infected and asymptomatics can be infectious. For the Oxford model the suggestion that the infection has reached the UK by December or January, and the figure that only one in 1,000 infections will need hospitalization is removed from reality. Clearly the two models provide different recommendations: the Oxford model recommends to put more effort in trying to achieve herd immunity, and concludes that the country had already acquired substantial herd immunity through the unrecognised spread of Covid-19 over

75 https://nucleardiner.wordpress.com/2020/04/07/the-ihme-epidemiological-model/amp/?__twitter_impression=true

more than two months, while the model by the Imperial College recommends to put more effort on containment measures. However, both models agree with the measures of social distancing put into place by the UK government, and the only point of argument concerns the timing of removing such restrictions. In that regard, the crucial info hidden from the modellers regards the number of people that have been infected without showing symptoms, and for which a reliable test would be a game changer for modellers as it might significantly alter the predicted path of the pandemics. A final consideration is linked to the availability of data and the data collection activity. In this regard, there is a huge difference across the countries. Very interestingly, the German central register for ICU beds is based on voluntary contributions from all hospitals seems to be a unique platform and maybe something to replicate in other countries[76]. In the following tables Table 2Table 3, and Table 4, an in depth classification of the models is provided.

[76] https://www.intensivregister.de/#/intensivregister

Table 2 – Model Description: Source, Country, Usage and Publication

Model	Source	Country	Is it published?	Are the results published?	Usage
IHME	https://www.medrxiv.org/content/10.1101/2020.03.27.20043752v1.full.pdf	US	Yes	Yes	Used in Policy Making
Los Alamos	https://covid-19.bsvgateway.org/#link%20to%20forecasting%20site	US	Yes	Yes	Used in Policy Making
COVID-19 Modelling	https://covid19.gleamproject.org/	US	Yes	Yes	Used in Policy Making
Epirisk	https://epirisk.net/	US	Yes	Yes	Used in Policy Making
Bakker et al.	http://curveflattening.media.mit.edu/Social_Distancing_New_York_City.pdf	US	Yes	Yes	Not clear
Columbia University	http://www.columbia.edu/~jls106/branas_etal_preprint.pdf	US	Yes	Yes	Used in Policy Making
Imperial College (1)	https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf	UK	Yes	Yes	Used in Policy Making
Imperial College (2)	https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-Global-Impact-26-03-2020v2.pdf	UK	Yes	Yes	Used in Policy Making
Imperial College (3)	https://spiral.imperial.ac.uk:8443/handle/10044/1/77731	UK	Yes	Yes	Used in Policy Making
UO	https://www.medrxiv.org/content/10.1101/2020.03.24.20042291v1	UK	Yes	Yes	Used in Policy Making
LSHTM	https://www.medrxiv.org/content/10.1101/2020.02.16.20023754v2.full.pdf	UK	Yes	Yes	Used in Policy Making
RKI (1)	https://www.rki.de/DE/Content/Infekt/EpidBull/Archiv/2020/Ausgaben/17_20_SARS-	DE	Yes	Yes	Used in Policy

	CoV2_vorab.pdf?__blob=publicationFile				Making
RKI (2)	http://rocs.hu-berlin.de/corona/docs/analysis/importrisk/	DE	Yes	Yes	Used in Policy Making
COVID Mobility Project	http://rocs.hu-berlin.de/covid-19-mobility/mobility-monitor/	DE	Yes	Yes	Used in Policy Making
Hartl et al.	https://cepr.org/sites/default/files/news/CovidEcon1%20final.pdf	DE	Yes	Yes	Not clear
Italian STC	https://drive.google.com/file/d/1pe1gEp4-UAPxLW_vnqntAa4AT5D_nyR1/view	IT	No[77]	Yes	Used in Policy Making
COVID-19 working group et al.	https://www.medrxiv.org/content/10.1101/2020.04.08.20056861v1.full.pdf	IT	Yes	Yes	Not clear
Signorelli et al.	https://www.mattioli1885journals.com/index.php/actabiomedica/article/view/9511/8735	IT	Yes	Yes	Not clear
Grasselli et al.	https://jamanetwork.com/journals/jama/fullarticle/2763188	IT	Yes	Yes	Not clear
COVID-19 MMP	https://covid19mm.github.io/in-progress/2020/04/17/third-report.html	IT	Yes	Yes	Not clear
PREDICT COVID-19	https://www.predictcovid19.com/model.html	IT	No	Yes	Not clear
Martinez et al.	https://healthcare-in-europe.com/en/news/predicting-the-future-of-the-covid-19-pandemic-with-data.html	ES	No	Yes	Used in Policy Making
Uni Cat	https://biocomsc.upc.edu/en/covid-19/Methods.pdf/view	ES	Yes	Yes	Used in Policy Making
Inverence	https://covid19.inverence.com/	ES	No	Yes	Not clear
University of Zaragoza	https://www.medrxiv.org/content/10.1101/2020.03.21.20040022v1.full.pdf	ES	Yes	Yes	Not clear
Massonnaud et al.	https://www.ea-reperes.com/wp-content/uploads/2020/03/PredictedFrenchHospitNeeds-EHESP-20200316.pdf	FR	Yes	Yes	Used in Policy Making

[77] There is no specific and explicit information regarding which models are used by the Italian authorities to take their decisions. According to confidential sources, the Italian National Institute of Health and the Italian Scientific and Technical Committee, in agreement with the Italian Ministry of Health and Italian Civil Protection, are collaborating with Bruno Kessler Foundation in developing the models used by the Italian authorities in taking their policy decisions. The model will be available only when published.

EPIcx-lab of INSERM (1)	https://www.epicx-lab.com/uploads/9/6/9/4/9694133/inserm-covid-19_report_lockdown_idf-20200412.pdf	FR	Yes	Yes	Used in Policy Making
EPIcx-lab of INSERM (2)	https://www.epicx-lab.com/uploads/9/6/9/4/9694133/inserm_covid-19-school-closure-french-regions_20200313.pdf	FR	Yes	Yes	Used in Policy Making

Table 3 - Model Description: Typology, Topic, Predictions and Data

Model name	Type of model	Topic	Predictions	Data
IHME	Statistical model for the cumulative death rate developing a curve-fitting tool to fit a nonlinear mixed effects model to the available administrative cumulative death data. From the projected death rates, it is estimated the hospital service utilization using an individual-level microsimulation model. Deaths by age are simulate using the average age pattern from Italy, China, South Korea, and the US.	Epidemic and healthcare variables such as number of infected, deaths, hospital beds, ICU, and invasive ventilation needed	US: bed excess demand of 64,175 and 17,380 of ICU beds at the peak of COVID-19. Further, the peak ventilator use is predicted to be 19,481 in the second week of April, while the total estimated deaths were 81,114 over the next 4 months. Then, the estimates were amended downwards by predicting the death of 60.400 individuals by August, with a peak on the 12th of April. As for the UK, the model predicted 66,314 fatalities, more than Italy (a total of 23,000) and Spain (19,209)	Data Repository by Johns Hopkins CSSE
Los Alamos	The model consists of two processes. The first process is a statistical model of how the number of COVID-19 infections changes over time. The second process maps the number of infections to the reported data. It is a forecast model and does not produce projections, meaning it does not explicitly model the effects of interventions or other "what-if" scenarios.	Estimate at US state level the number of cases and deaths	For instance, for the state of New York the daily death where expected to peak at 3215 on the 19^{th} of April	Data from the John Hopkins dashboard and the IHME website
Epirisk	Global Epidemic and Mobility Model (GLEAM), an individual-based, stochastic, and spatial epidemic model used to analyze the spatiotemporal spread and magnitude of the COVID-19 epidemic in the continental US.	EpiRisk is a computational platform designed to allow a quick estimate of the probability of exporting infected individuals from sites affected by a disease outbreak to other areas in the world through the airline transportation network and the daily commuting patterns. It also lets the user to explore the effects of potential restrictions	There are many predictions related to exported cases (probability of exporting a given number of cases) and relative importation risk (probability that a single infected individual is traveling from the index areas to that specific destination).	The airline transportation data used in the platform are based on origin-destination traffic flows from the OAG database that are aggregated at specific time and spatial. Commuting flows are derived by the analysis and modeling of data for more than 5,000,000 commuting patterns

		applied to airline traffic and commuting flows.		among 78,000 administrative regions in five continents.
COVID-19 Modelling	Based on the GLEAM model.	Global Epidemic and Mobility Model (GLEAM), an individual-based, stochastic, and spatial epidemic model used to analyze the spatiotemporal spread and magnitude of the COVID-19 epidemic in the continental US. The model generates an ensemble of possible epidemic projections described by the number of newly generated infections, times of disease arrival in different regions, and the number of traveling infection carriers.	The model points to the days around April 8, 2020 as the peak time for deaths in the US. Based on the last projections, a total of 89795 COVID-19 deaths (range of 63719 to 127002) are currently projected through May 18, 2020.	Real-world data where the world is divided into subpopulations centered around major transportation hubs (usually airports). The airline transportation data encompass daily origin-destination traffic flows from the Official Aviation Guide (OAG) and International Air Transport Association (IATA) databases, whereas ground mobility flows are derived from the analysis and modeling of data collected from the statistics offices of 30 countries on five continents.
Bakker et al.	Network analysis by mean of metrics such as mobility, which refers to how people move around a city (distance traveled, radius of gyration, number of people staying home, number of stays in public places, which we call visits); and contacts, which refers to how many people each person comes into contact with.	Use of mobility data from January 1st 2020 to March 25th 2020 to figure out how has social distancing policy changed mobility and social behavior, how social distancing behavior differs across the physical space of New York City, and how social distancing behavior differs across demographic groups	The researchers find that the instance travelled everyday dropped by 70 percent, the number of social contacts in places decreased by 93%, and that the number of people staying home the whole day has increased from 20% to 60%. Very interestingly, they found that the relative differences between different demographic groups for what concerns mobility and social contacts have been dramatically reduced. Finally, they found that supermarkets and grocery stores came to be the most common locations where social contact takes place.	Mobility data is provided by Cuebiq, a location intelligence and measurement company, and they consist in supplied anonymized records of GPS locations from users who opted-in to share their data anonymously across the U.S.
Columbia University	Metapopulation SEIR model1 to simulate the transmission of COVID-19 among 3,108 US counties. Two types of movement: daily work commuting and random movement. Information on county-to-county work commuting is publicly available from the US Census Bureau. Number of random visitors between two counties is assumed to be proportional to the average number of commuters between them. As population present in each county is different during daytime and nighttime, the transmission dynamics of COVID-19 is modelled separately for these two time periods as a discrete Markov process during both day and night times.	Estimate of the number of hospital critical care beds, including ICU beds and other hospital beds used for critical care purposes, that could be made available by hospitals in response to patient surges. Various scenarios are considered.	As many as 104,120 deaths could be averted through an aggressive critical care surge response, including roughly 55% through high clearance and preparation of ICU and non-ICU critical care beds and roughly 45% through extraordinary measures like using a single ventilator for multiple patients.	2020 Centers for Medicare & Medicaid Services (CMS), Health Care Information System (HCRIS) Data File, Sub-System Hospital Cost Report (CMS-2552-96 and CMS-2552-10), Section S-3, Part 1, Column 2; the 2018 American Hospital Association (AHA) Annual Survey; the 2020 US DHHS Health Resources and Services Administration, Area Health Resources Files (AHRF); and the 2017-2019 CMS Medicare Provider of Services file, Medicare Cost Report, Hospital Compare Files.
Imperial College (1)	Individual-based simulation model developed to support pandemic influenza planning to explore scenarios for COVID-19 in GB. The basic structure of the model remains as previously published. In brief, individuals reside in areas defined by high-resolution population density data.	Assess the potential role of a number of public health measures – so-called non-pharmaceutical interventions aimed at reducing contact rates in the population and thereby reducing	In March 2016 update the model by the Imperial College reported up to 500K deaths in the UK and up to 2.2 million deaths in the US in case of no action by the government nor population. Further, the estimated figure that 15% of hospital cases would need to be	Data on distribution size of households and age are taken from the census, while a synthetic population of schools distributed proportional to local population density is

	Contacts with other individuals in the population are made within the household, at school, in the workplace and in the wider community. Transmission events occur through contacts made between susceptible and infectious individuals in either the household, workplace, school or randomly in the community, with the latter depending on spatial distance between contacts.	transmission of the virus	treated in an ICU was then updated to 30%, arguing that the British ICU capacity (4K beds) would be overwhelmed.	derived from data on average class sizes and staff-student ratios.
Imperial College (2)	Estimation of the final epidemic size from an age-structured Susceptible-Infected Recovered model incorporating both the demographic structure of the population and the rates of contact between different individuals across different age groups. The impact of the different scenarios on the dynamics of likely healthcare demand over time was assessed by using an age-structured stochastic Susceptible-Exposed-Infected-Recovered (SEIR) model parameterised to match best estimates of key parameters determining the dynamics of spread of COVID-19.	Combine data on age-specific contact patterns and COVID-19 severity to project the health impact of the pandemic in 202 countries in the view to compare predicted mortality impacts in the absence of interventions or spontaneous social distancing with what might be achieved with policies aimed at mitigating or suppressing transmission	Impact of an unmitigated scenario in the UK and the USA up to 490,000 deaths and 2,180,000 deaths respectively, and up to 7.0 billion infections and 40 million deaths globally this year	Population sizes and age distributions by country were taken from the 2020 World Population Prospects. Estimates of household size and the age of members of each household were extracted from The Demographic and Health Surveys (DHS) Program using the rDHS package. Patterns of contact across different populations and countries were drawn from several sources, including previously published estimates of mixing from a number of HICs and a recent systematic review of social contact surveys including MICs and LMICs.
Imperial College (3)	Use of a semi-mechanistic Bayesian hierarchical model to attempt to infer the impact of mitigation interventions across 11 European countries. The methods assume that changes in the reproductive number are an immediate response to these interventions being implemented rather than broader gradual changes in behaviour. The model estimates these changes by calculating backwards from the deaths observed over time to estimate transmission that occurred several weeks prior, allowing for the time lag between infection and death.	Attempt to infer the impact of policy interventions across 11 European countries.	They estimate that the intervention has averted 59,000 deaths up to 31 March across all 11 countries, that between 7 and 43 million individuals have been infected, and that the proportion of the population infected to date is the highest in Spain followed by Italy and lowest in Germany and Norway, reflecting the relative stages of the epidemics. Specifically, they estimated that in Italy and Spain, respectively 38,000 and 16,000 deaths have been avoided.	Real-time death data from the ECDC, as well as data on the nature and type of major non-pharmaceutical interventions, excerpted from the government webpages from each country as well as their official public health division/information webpages.
UO	The researchers calibrated a susceptible-infected-recovered (SIR) model to data on cumulative deaths from the UK and Italy, building on the assumption that such deaths are well reported events that occur only in a vulnerable fraction of the population. The authors also assume estimates of critical epidemiological parameters such as the basic reproduction number (R0), infectious period and time from infection to death, probability of death in the vulnerable fraction of the population. This with the aim to assess the sensitivity of the system to the actual fraction of the population vulnerable to severe disease and death.	Percentage of population exposed to the virus.	In summary, the model suggests that the new coronavirus may already have infected far more people in the UK than scientists had previously estimated (maybe half of the population), and that thereby the mortality rate from the virus is much lower than what is generally thought to be, as the vast majority of infected individuals develop mild symptoms or not at all. The model suggests that the infection has reached the UK by December or January, and that therefore people started to be infected in huge numbers before the first official case was reported.	For Italy, a time series was obtained from the Italian Department of Civil Protection GitHub repository. For UK, a time series was obtained from the John Hopkins University Centre for Systems Science and Engineering COVID-19 GitHub repository.

LSHTM	Generation of fine-scale age-specific population contact matrices by context (home, work, school, other) and type (conversational or physical) of contact that took place.	Age specific social mixing patterns by encounter context (home, work, school or other, in respective rows) and type of contact (physical only shown with dashed lines or all contacts in solid line).	Estimation of high resolution age-specific social mixing matrices based on data from over 40,000 participants, stratified by key characteristics such as contact type and setting. The matrices generated are highly relevant for informing prevention and control of new outbreaks, and evaluating strategies that reduce the amount of mixing in the population (such as school closures, social distancing, or working from home). In addition, they finally provide the possibility to use multiple sources of social mixing data to evaluate the uncertainty that stems from social mixing when designing public health interventions.	Population contact patterns for United Kingdom based self-reported contact data from over 36,000 volunteers that participated in the massive citizen science project BBC Pandemic.
RKI (1)	The number of incident cases is estimated using the nowcasting approach and is presented as a moving 4-day average to compensate for random effects of individual days. With this approach, the point estimate of R for a given day is estimated as the quotient of the number of incident cases on this day divided by the number of incident cases four days earlier.	Estimation of the impact of mitigation measures on the reproduction number.	The policies carried out by the Federal Government, i.e. the cancellation of major events in different federal states (with more than 1,000 participants) on March 9 2020, the Federal-State Agreement on guidelines against the spread of the coronavirus on March 16 2020, and the nationwide extensive ban on contacts on March 23 2020, have had a great impact on the reproduction number.	Ministry of Health and data from the Intensive Care Register produced by the German Interdisciplinary Association for Intensive and Emergency Medicine (DIVI), the RKI and the German Hospital Federation (DKG)
RKI (2)	Stochastic network dynamic modelling of an import risk model and relative import risk analysis.	Relative import risk at the airport, country and continental levels, as predicted by the computational model and the worldwide air transportation network.	The implementation of mitigation measures altered the infection pattern and spread of the disease and helped to keep it under control.	The core of the data used come from the worldwide air transportation network (WAN). This network has 3893 nodes (airports) that are connected by 51476 directed links (flight routes). Each link is weighted by the traffic flux between nodes, i.e. the average number of passengers that travel each route per day.
COVID Mobility Project	Analysis of the deviation in mobility from a “normal” baseline by counting all movements and compare them to the number to bee expect in a usual, comparable timeframe.	General picture of mobility reduction in Germany due to Covid-19 mobility restrictions.	Initial drop in mobility: mobility fell to -39% below normal in mid-March 2020, after the majority of restrictions in Germany took effect. Slow recovery of mobility: in late March mobility slowly increased and finally plateaued at -27% in the second week of April. As restriction policies hardly changed during this time, this increase might be attributed mostly to a relaxing of self-imposed, individual mobility restrictions, paired with increased mobility due to warmer weather. Beginnings of an opening: starting April 20th, some mobility restriction policies have been lifted. We observe an immediate increase in mobility to -21% in the week starting April 20th.	Mobility flows of this kind are collected by many mobile phone providers. The team uses data from the German Telekom, which is distributed by the company Motionlogic, as well as data from Telefónica, which is analyzed and aggregated by the company Teralytics. This kind of data is commercially available and is used, for example, by public transportation companies, for predicting traffic or to improve road infrastructure.

Hartl et al.	Search for a trend break in cumulated confirmed Covid-19 cases as reported by the Johns Hopkins University (2020). The trend break has been estimated though maximum likelihood methods.	The impact of the German public shutdown on the spread of COVID-19.	Their finding is that confirmed Covid-19 cases in Germany grew at a daily rate of 26.7% until 19 March. From March 20 onwards, the growth rate drops by half to 13.8%, which is in line with the lagged impact of the policies implemented by the German administration on 13 March and implies a doubling of confirmed cases every 5.35 days. Before 20 March, cases doubled every 2.93 days. In their update of the model they test the impact of the 22 March policies. From 30 March on, the estimated average growth rate is 5.8%, so that the cases double every 12.20 days, therefore the containment policies are being effective.	Data from Johns Hopkins University (2020), which links data from the Robert Koch Institute, the World Health Organization, and the European Centre for Disease Prevention and Control.
Italian STC	?	Assessment of the risks of epidemic spread for COVID-19 disease associated with various scenarios for the release of the lockdown introduced on 11 March on national territory.	Restarting all the sectors without teleworking and with schools open, the country would need 151 thousand intensive care units already in June and a number of hospitalizations, by the end of the year, equal to 430,866	?
COVID-19 working group et al.	In depth review of the first month of the Italian outbreak through descriptive and analytic epidemiology and an estimation of the R0 and Rt taking into account the diversity of transmission across the country.	It is provided a descriptive epidemiological summary on the first 62,843 COVID-19 cases in Italy as well as estimates of the basic and net reproductive numbers by region.	The COVID-19 infection in Italy emerged with a clustering onset similar to the one described in Wuhan, China and likewise showed worse outcomes in older males with comorbidities. Initial R0 at 2·96 in Lombardia, explains the high case-load and rapid geographical spread observed. Overall Rt in Italian regions is currently decreasing albeit with large diversities across the country, supporting the importance of combined non-pharmacological control measures.	The team analysed data from the national case-based integrated surveillance system of all RT-PCR confirmed COVID-19 infections as of March 24th 2020, collected from all Italian regions and autonomous provinces.
Signorelli et al.	Statistical estimate of period-prevalence of the disease.	Impact of mitigation measures.	The team concludes that suspending flights from China and airports' checkpoints with thermos-scan did not have a significant effect in containing the epidemic, the implementation of a "red zone" in Lombardy effectively contained the spread of the infection within that area, even though it did not have the same effect in the neighboring provinces (Bergamo, Brescia, and Piacenza); the failure to establish a second "red zone" near Bergamo in the Municipalities of Alzano and Nembro despite the proposal of local authorities (on March 3rd), led to a dramatic out-break with about 10,000 cases in Bergamo with over 1,000 death toll and similar figures in the neighbouring areas (Brescia and Piacenza); and finally that General mitigation measures seem to be effective to flatten the epidemic curve of new notified infections	Data from Italian Civil Protection and from Local Authorities
Grasselli et	Based on data to March 7, when 556 COVID-19–positive	Estimation of ICU capacity and admissions.	The article shows that despite prompt response of the	Patients in 15 first-responder hub

al.	ICU patients had been admitted to hospitals over the previous 15 days, linear and exponential models were created to estimate further ICU demand.		local and regional ICU network, health authorities, and the government to try to contain the initial cluster, the surge in patients requiring ICU admission has been overwhelming. Therefore, other health care systems should prepare for a massive increase in ICU demand during an uncontained outbreak of COVID-19. This experience would suggest that only an ICU network can provide the initial immediate surge response to allow every patient in need to be cared for.	hospitals, chosen because they either had expertise in infectious disease or were part of the Venous-Venous ECMO Respiratory Failure Network (RESPIRA).
COVID-19 MMP	The researchers built a proximity network among users based on the locations they visited and the hour of the day when these visits occurred. In this way, they assess the effect of intervention on the average contact rate, or the number of unique contacts made by a person on a typical day.	Investigate the number of unique contacts made by a person on a typical day, and evaluate the effect of interventions on the social mixing of our users' sample by defining a proxy of the potential encounters each user could have in one hour. In order to do that, the researchers build a proximity network among users based on the locations they visited and the hour of the day when these visits occurred.	The results of the exercise show that on April 12, Easter Day, the average degree of all users was 86% lower than the pre-outbreak averages in the North, 83% in the Center and 82% in the South and the Islands. In conclusion, in the past 4 weeks, the adherence to the mobility restrictions imposed since March 12 has remained high and constant all over the country.	Mobility data is provided by Cuebiq, a location intelligence, and measurement platform.
PREDICT COVID-19	?	Predictive model on the development of positive and death cases due to COVID-19. The study assumes that the first 17 days of infection are those that determine the slope of the curve, the duration of the epidemic depends on when the daily peak is reached which depends in turn on the containment strategies, and the curve can be divided into two different sections, before and after daily peak.	The model shows that although the peak is close, in some regions the positive cases are underestimated, and also that containment strategies are working.	Data from Italian Civil Protection and from Local Authorities
Martinez et al.	Verhulst model, a population growth scale that looks at the initial population to identify velocity and propagation constant. This approach enables to calculate the level of uncertainty in the short run, by adjusting epidemics history and identifying parameters.	Prediction tool that is helping Spanish emergency departments know how many patients with Covid-19 will need to be admitted in intensive care units (ICU) and prepare adequately.	The total number could oscillate between 90,000 and 160,000, depending on the data received every day.	Data at regional level from Asturias, Cantabria and Castile Leon, together with data from the Spanish ministry of health since March 18th, and the estimations issued by Johns Hopkins University.
Uni Cat	Empirical model, verified with the evolution of the number of confirmed cases in previous countries where the epidemic is close to conclude, including all provinces of China. The model and predictions are based on two parameters that are daily fitted to available data: the velocity at which spreading specific rate slows down; the higher the value, the better the control; the final number of expected cumulated cases, which cannot be evaluated at the initial stages because growth is still exponential.	The model estimates the number of cases, and permits the evaluation of the quality of control measures made in each state and a short-term prediction of tendencies.	The model predicted 203795 cases for Spain on April 19 2020.	The data sources of the model are World Health Organization (WHO) surveillance reports the European Centre for Disease Prevention and Control (ECDC) and the Spanish Ministry of Health.

Inverence	Based on data released by Spain's Ministry of Health (Ministerio de Sanidad), predictive models have been developed based on Bayesian time series analysis.	The modelling strategy considered the number of daily ICU admissions in every region and linking it, via a transfer function, to the number of deaths, assuming that the number of ICU admissions is a good indicator of the number of infected individuals in critical condition. Later on, the research team has developed models for the number of infected cases, based on a dynamical transmission rate model, which allows to understand in a straightforward way the effect of public authorities' actions, which are aimed precisely at reducing this transmission rate.	The number of deaths per million people shows the pandemic's different spreading velocities in different countries. Spain appears as the country with the largest epidemic spreading velocity among the set of countries considered.	Data released by Spain's Ministry of Health.
University of Zaragoza	The research team adapted a Microscopic Markov Chain Approach (MMCA) metapopulation mobility model to capture the spread of COVID-19 that stratifies the population by ages, and accounts for the different incidences of the disease at each stratum.	The model is used to predict the incidence of the epidemics in a spatial population through time, permitting investigation of control measures.	We have applied the results to the validation and projection of the propagation of COVID–19 in Spain. Our results reveal that, at the current stage of the epidemics, the application of stricter containment measures of social distance are urgent to avoid the collapse of the health system. Moreover, we are close to a scenario in which the complete lockdown appears as the only possible measure to avoid the former situation. Other scenarios can be prescribed and analyzed after lockdown, as for example pulsating open-closing strategies or targeted herd immunity.	Estimates of the epidemiological parameters and the mobility and demographic census data of the national institute of statistics (INE).
Massonnaud et al.	Deterministic SEIR model for hospital areas with predictions at one month and 17 five-year age groups (last 80 and over) to estimate the ICU resource deficit. Specifically, the model is based on country-specific contact matrices (social interactions) between age groups.	Estimation of the daily number of COVID-19 cases, hospitalizations and deaths, the needs in ICU beds per Region and the reaching date of ICU capacity limits.	At the national level, the total number of infected cases was expected to range from 22,872 in the best case (R0 = 1.5) to 161,832 in the worst considered case (R0 = 3). Regarding the total number of deaths, it was expected to vary from 1,021 to 11,032, respectively. Clearly the real data regarding mortality rate are higher. What is interesting, it is also that they estimated the timing according to which the capacity limit of French ICU would be overrun.	Population structure was inferred for each catchment area from 2016 and 2017 census data provided by the French National Institute of Statistics and Economic Studies (Insee). Catchment areas were then aggregated by metropolitan Regions [13 French administrative areas with an averaged population of 4.75 millions ranging from 300,000 (Corse) to 12.55 millions (Ile-de-France)]. Data on ICU beds capacity per French Region were retrieved from the "Statistique Annuelle des Etablissements de Santé" (SAE)
EPIcx-lab of INSERM (1)	Stochastic age-structured transmission model integrating data on age profile and social contacts in the Île-de-France region to assess the current epidemic situation, and estimate the effectiveness of possible exit strategies. The model is calibrated on hospital admission data of the region before lockdown and validated on syndromic and virological surveillance data.	In one study they use a stochastic age-structured transmission model integrating data on age profile and social contacts in the Île-de-France region to assess the current epidemic situation, evaluate the expected impact of the lockdown implemented in France on March 17, and finally to estimate the effectiveness of exit strategies, building on hospital admission data of the region	They estimated that the average number of contacts is predicted to be reduced by 80% during lockdown, leading to the reduction of the reproductive number to 0.68. They show that the epidemic curve reaches ICU system capacity and slowly decreases during lockdown, and that lifting the lockdown with no exit strategy would cause a second wave. They also show that testing and social distancing strategies that gradually relax current	The model is calibrated on hospital data specifying the number of COVID-19 positive hospital admissions in Île-de-France prior to lockdown. Data for that period was consolidated up to April 3, to account for delays in reporting. The simulated incidence of clinical cases (mild and severe symptoms) is compared to the

		before lockdown.	constraints while keeping schools closed and seniors isolated will avoid a second wave and healthcare demand exceeding capacity.	regional incidence of COVID-19 cases estimated by the syndromic and virological surveillance system for the weeks 12 (March 16 to 22, 2020) and 13 (March 23 to 29).
EPIcx-lab of INSERM (2)	Stochastic age-structured data-driven epidemic model based on demographic and social contact data between children and adults for each region, and is parameterized to COVID-19 epidemic, accounting for current uncertainties in the relative susceptibility and transmissibility of children.	Assess the expected impact of school closure and telework to mitigate COVID-19 epidemic in France by mean of a stochastic age-structured epidemic model integrating data on age profile and social contacts of individuals.	According to the model, mere school closure would have limited effects (i.e. <10% reduction with 8-week school closure for regions in the early phase of the epidemic), while coupled with teleworking for 25% adults there would be a delay of the peak by almost 2 months with an approximately 40% reduction of the case incidence at the peak. Therefore, explicit guidance on telework and interventions to facilitate its application to all professional categories who can adopt it should be urgently provided.	Demographic and age profiles of the regions of Île-de-France, Hauts-de-France, Grand Est

Table 4 – Estimates and Assessments of the Model Studied

Model name	Estimating epidemic variables[78]	Estimating healthcare variables[79]	Assessing mitigation actions[80]	Assessing Epidemic spread/mobility of population[81]
IHME	X	X		
Los Alamos	X			
Epirisk				X
COVID-19 Modelling				X
Bakker et al.			X	X
Columbia University		X		X
Imperial College (1)	X	X	X	
Imperial College (2)	X	X	X	
Imperial College (3)	X		X	
UO		X		
LSHTM			X	X
RKI (1)	X		X	
RKI (2)			X	X
COVID Mobility Project			X	X
Hartl et al.	X		X	
Italian STC	X	X	X	
COVID-19 working group et al.	X			
Signorelli et al.	X		X	
Grasselli et al.		X		
COVID-19 MMP			X	X
PREDICT COVID-19	X			
Martinez et al.		X		
Uni Cat	X		X	
Inverence	X	X	X	
University of Zaragoza	X	X		X
Massonnaud et al.	X	X		
EPIcx-lab of INSERM (1)	X	X	X	
EPIcx-lab of INSERM (2)		X	X	

78 E.g.: number of infected and deceased individuals
79 E.g.: number of ICU available
80 E.g.: limits to circulation
81 E.g.: spread of epidemic across countries and regions, extent of population mobility in the country

1.4 Policy Take-Outs

The exercise carried out allows to draw a set of assumptions on governance of modelling:

1 **Ensure transparency in the modelling assumptions**. Using models based on assumptions in absence of hard data can lead to over interpretation and exaggeration in the magnitude of the outbreak. As an example, the aforementioned model elaborated by UO in its most extreme scenario suggests that 68% of the UK population had been exposed to the virus. Likewise, the aforementioned model from the Imperial College, based on the code developed 13 years ago for describing an influenza pandemic, assumed that the demand for intensive care units would be the same for both infections, thereby leading to the belief that herd immunity could be reached at a small cost. However, data from both Italy and China show that COVID-19 leads to a much higher percentage of admissions to ICU (5-10%). Therefore, assumptions must be transparent and clear to the reader and the policy maker in order to be aware of the caveats.

2 **Collect data from different sources in a standardized fashion.** Some experts argued that the initial spread of the virus might have been due to the incapability to recognize anomalous infections in some hospitals at the beginning of the epidemics. Further, other experts argue that the inconsistency in mortality rates between Italy and other countries and within Italian regions may be driven by different data collection approaches, while some others argue that mortality rates are underestimated.[82] Overall a system for standardized data collection across regions and at macro and micro level is needed in order to ensure comparability among statistics and modeling results and therefore boost increase situational awareness. A survey of the data sources available to download is presented in the annex.

3 **Perform validation and sensitivity analysis exercises.** As we have seen, the results of many modeling exercises have been deeply influenced by the modeling and estimation techniques used. In this respect, a core activity ensuring the robustness of the modelling exercises performed consists in applied different modelling and estimation techniques to the same set of data, as well as changing the values of the input and internal parameters of a model to determine the effect upon the model output. Related to this issue is the necessity to validate the models by employing them on comparable but different data sources to see how the model results change, and to keep them open in order to scrutiny and criticisms by other researchers. Last but not least, also keeping data open allows to carry out different modelling and estimation techniques by different researchers.

4 **Generate collaborative model simulations and scenarios.** Clearly the collaboration of several individuals in the simulation and scenario generation allows for policies and impact thereof to be better understood by non-specialists and even by citizens, ensuring a higher acceptance and take up. On the other hand, modelling co-creation has also other advantages: no person typically understands all requirements and understanding tends to be distributed across a number of individuals; a group is better capable of pointing out shortcomings than an individual; individuals who participate during analysis and design are more likely to cooperate during implementation. In the case at hand, the joint elaboration of simulations and scenarios by policy makers and scientists helps in producing models that are refined to tackle the containment policies adopted.

5 **Develop easy to use visualizations.** As we have seen there are several data aggregators that visualize the data coming from the field every day and that improve the situational awareness of the policy makers. Further, an interesting feature of many models that have been developed and used by policy makers to tackle the COVID-19 pandemic is the use of visualization tools depicted the results of the underlying simulation models. In this regard, policy makers should be able to independently visualize results of analysis,

[82] Specifically, Buonanno et al. 2020, combining official statistics, retrospective data and original data stemming inter al. by obituaries and death notices, suggest that the reported mortality rate attributable to COVID19 accounts only for 26.6% of the observed excess mortality rate between March 202 and March 2019.

make sense of data and interact with them. This will help policy makers and citizens to understand the impact of containment policies: interactive visualization is instrumental in making evaluation of policy impact more effective. A survey of the visualizations provided by the aggregators is available in the appendix.

6 **Consider carefully the sources of uncertainty in the model.** As the other simulation models, also the ones used to tackle the COVID-19 pandemics suffer from several sources of uncertainty. Such uncertainty could be merely statistically related (e.g. confidence intervals), related to parameters in the model that are difficult to estimate (e.g. the rate of transmission), concerning the data used (e.g. data on fatality rate might be not precisely measured), or of a more conceptual level (e.g. assuming a representative agent).

7 **Tailor the model to specific questions you are trying to address.** Specific modelling strategies (and level of complexity) should be used to address specific research questions. The simplest structure of predictive simulation is given by the aforementioned SIR models, which use few data inputs and can be useful to assess the epidemic outbreak in the short term. Such models cannot be used to depict uncertainty, complexity and behavioural change. Another class of models is given by forecasting models, which use existing data to project conclusions over the medium term. Finally, strategic models that encompass multiple scenarios assessing the impact of different interventions are able to capture some uncertainty underlying the epidemic outbreak and the behaviour of the population and are the foundation for policy making activity.

8 **Use models properly**. Models are not a commodity that provide a number which the policy makers use to take decisions. There needs to be a full understanding of the subtleties involved, the levels of uncertainty, the risk factors. In other words, you need in-house data and model literacy embedded in the policy making process, in house. You can’t outsource that. Indeed, a recent report for the US highlighted the limitations of a process that involved experts on an ad hoc, on demand basis, leaving much arbitrariness to the process: “Expert surge capacity exists in academia but leveraging those resources during times of crisis relies primarily on personal relationships rather than a formal mechanism.” On a similar token, in the UK, a recent article pointed out that experts involved in the SAGE were too "narrowly drawn as scientists from a few institutions". By the same token, there was insufficient in house capacity to manage this input: In the US, “there is currently limited formal capacity within the federal government”, while in the UK, “the criticism levelled at the prime minister may be that, rather than ignoring the advice of his scientific advisers, he failed to question their assumptions”.

1.5 APPENDIX – Aggregators and Data Sources

Table 5 – List of main Aggregators and Data Sources

AGGREGATOR	DATA SOURCES	DATA FOR DOWNLOAD	SCOPE
Columbia University	• The 2020 Centers for Medicare & Medicaid Services (CMS), Health Care Information System (HCRIS) Data File, Sub-System Hospital Cost Report (CMS-2552-96 and CMS-2552-10), Section S-3, Part 1, Column 2 • The 2018 American Hospital Association (AHA) Annual Survey • The 2020 US DHHS Health Resources and Services Administration, Area Health Resources Files (AHRF) • The 2017-2019 CMS Medicare Provider of Services file, Medicare Cost Report, Hospital Compare Files	Yes at this link	Global
European Center for Disease Prevention and Control (ECDC)	Key sources: • Regular updates from EU/EEA countries through the Early Warning and Response System (EWRS), The European Surveillance System (TESSy), the World Health Organization (WHO) and email exchanges with other international stakeholders • Screening of sources from 196 countries: ○ Websites of ministries of health ○ Websites of public health institutes ○ Websites from other national authorities (e.g. ministries of social services and governments) ○ Websites on health statistics and official response team ○ WHO websites and WHO situation reports ○ Official dashboards and interactive maps from national and international institutions • Screening of social media accounts maintained by national authorities	Yes,at this link	European/Global
European Data Portal	• ECDC for data on the epidemics • EUROSTAT Geographics for data on administrative units	Yes at this link	European/Global
Johns Hopkins University's Center for Systems Science and Engineering (CSSE)	• World Health Organization (WHO) • DXY.cn. Pneumonia. 2020. • BNO News • National Health Commission of the People's Republic of China (NHC) • China Centers for Disease Control and Prevention (CCDC)	Yes at this link	Global

	• Hong Kong Department of Health • Macau Government • Taiwan Centers for Disease Control and Prevention • U.S. Centers for Disease Control and Prevention (CDC) • Government of Canada • Australia Government Department of Health • European Centre for Disease Prevention and Control (ECDC) • Ministry of Health Singapore (MOH) • Italian Ministry of Health and Civil Protection • 1Point3Arces • Worldometers		
Our World in Data (Global Change Data Lab, and University of Oxford)	• European Center for Disease Prevention and Control (ECDC).	Yes at this link	Global
World Health Organization (WHO)	• World Health Organisation based on Government agencies and health ministries and other IHR States Parties under the International Health Regulations • For EU/EEA countries and UK the European Center for Disease Prevention and Control (ECDC)	No	Global
Worldometers	• Crowdsourcing: individuals can provide data about cases • Government agencies from all over the world, such as U.S. Centers for Disease Control and Prevention (CDC) • World Health Organization (WHO)	No	Global
SAS Coronavirus Report	• World Health Organization (WHO) • Government agencies from all over the world, such as U.S. Centers for Disease Control and Prevention (CDC) • European Center for Disease Prevention and Control (ECDC) • National Health Council	Yes at this link	Global
Official COVID19 Dashboard public information	• Austrian district administrative authorities and provincial health directorates, the health ministry, as well as the Agency for Health and Food Safety (AGES)	Yes at this link	National Level (Austria)
COVID - 19: Overview of the current situation in the Czech Republic	• National Health Information System, Regional Hygiene Stations, Ministry of Health of the Czech Republic	Yes at this link	National Level (Czech Republic)

Danish Health Authority COVID-19 statistics and charts	• Sundhedsstyrelsen (National board of Health)	No	National Level (Denmark)
Koroonakaart	• Health and Welfare Information Systems Center (TEHIK)	Yes at this link	National Level (Estonia)
Robert Koch-Institut: COVID-19-Dashboard	• Data collected are transmitted to the Robert Koch Institute (RKI) by the responsible health authority at county level in accordance with the Infection Protection Act • There is also a centralized intensive care register	Yes at this link	National Level (Germany)
Italian Department for Civil Protection	• Italian Ministry of Health collects data from all the hospitals	Yes at this link	National Level (Italy)
Population and business statistics related to COVID-19	• Lithuanian Ministry of Health (SAM) • National Center for Public Health (NVSC) • Government of the Republic of Lithuania (LRV) • Information published by municipalities	No	National Level (Lithuania)
COVID-19 Dashboard - Malta	• Ministry for Health	Yes at this link	National Level (Malta)
Development of COVID-19 in the Netherlands	• Ministry of Health, Welfare and Sport	Yes at this link	National Level (Netherlands)
Slovenian COVID-19 Data Tracker	• Daily reports and monitor the announcements of all hospitals for COVID-19 (UKC Ljubljana, UKC Maribor, UK Golnik, SB Celje)	Yes at this link	National Level (Slovenia)
Coronavirus (COVID-19) in the UK	• Lab-confirmed case counts for England and subnational areas are provided by Public Health England • All data on deaths and data for the rest of the UK are provided by the Department of Health and Social Care based on data from NHS England and the devolved administrations	Yes at this link	National Level (United Kingdom)
The COVID Tracking Project	• State/district/territory public health authorities—or, occasionally • Trusted news reporting, official press conferences • Tweets or Facebook updates from state public health authorities or governors.	Yes at this link	National Level (United States)

2 CASE STUDY: NAWM II - THE EUROPEAN CENTRAL BANK NEW AREA-WIDE MODEL II

2.1 Introduction

The European Central Bank New Area-Wide Model (NAWM) was first developed in 2008 at the European Central Bank. NAWM, a micro-founded open-economy model of the euro area, was designed for use in the (Broad) Macroeconomic Projection Exercises regularly undertaken by ECB/Eurosystem staff and for policy analysis[83]. A new version of the model has been developed in 2018[84], called New Area-Wide Model II, in the view to incorporate a financial sector with the following objectives: (i) accounting for the role of financial frictions in the propagation of economic shocks and policies and for the presence of shocks originating in the financial sector itself, (ii) capturing the prominent role of bank lending rates and the gradual interest-rate pass-through in the transmission of monetary policy in the euro area, and (iii) providing a structural framework that can be used for assessing the macroeconomic impact of the ECB's large-scale asset purchases conducted in recent years.

2.2 Rationale

In the last decade, the standard monetary policy carried out by the European Central Bank has been complemented by several non-standard measures (NSMs) aimed at addressing malfunctioning financial markets with the objective to mitigate the impact of the financial crisis on the economy as well as to ensure the transmission of standard monetary policy. These measures have included lowering the deposit facility rate, longer-term refinancing operations and an expanded asset purchase programme targeting a variety of investment-grade private and public sector securities. In this regard, the response in the price of assets has led to the suggestion that these NSMs had the effect of boosting economic growth, however the quantitative impact on other macroeconomic variables remains uncertain. Therefore, it is necessary to analyse the quantitative effects of NSMs by developing a coherent structural macroeconomic modelling framework, going beyond the standard DSGE models which cannot be used to study the transmission channels of NSMs. As highlighted by the informant, the new area-wide model with the most recent vintage is the main aggregated macro-model that is used for the policy preparation process at ECB for the time being. The project started in 2005 and the first vintage was integrated into the policy process as of the end of 2008 and the prime objective was to use it in the context of the macroeconomic projection exercise at the ECB. But then also primarily for analysing the different types of policy scenarios so as an input to the policy preparation process at ECB at large.

2.3 Main actors and stakeholders

The main actors for what concern the case are obviously the European Central Bank, and in particular its staff. Other important stakeholders that take into account the model and its results in taking their policy decisions are the EURO Area central banks, as well as other international organizations such as OECD and International Monetary Fund.

2.4 Historical development of the model

The model, as already mentioned, represents an extension of the NAWM, developed at the European Central Bank in 2008. Specifically, the first version of the model contained only stylised financial frictions (exogenous risk premium shocks), rather than endogenous financial propagation mechanisms. On the contrary, NAWM II includes a fully-fledged financial sector building on funding-constrained "wholesale banks" which engage in maturity transformation and originate long-term loans, as well as on "retail banks" which distribute these loans to the non-financial private sector. Moreover, in NAWM II the holdings of domestic and foreign long-term government bonds by the financial and the non-financial private sector are ruled by a set of no-

83 https://www.ecb.europa.eu/pub/pdf/scpwps/ecbwp944.pdf
84 https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2200.en.pdf

arbitrage and optimality conditions, leading to an explicit exchange-rate channel of private and public-sector asset purchases. Finally, the original NAWM itself is a small-open-economy extension of the Smets-Wouters model (2003, 2007).

2.5 Models

NAWM II is a Dynamic Stochastic General Equilibria economy-wide model. A DSGE is a particular class of econometric, quantitative models of business cycles, proposed by Kydland and Prescott[85] and Long and Plosser[86]. DSGE models are dynamic, in the sense that they study how the economy evolves over time; stochastic, as they measure how the economy reacts to random shocks; general, as they represent the whole economy (referring to the entire economy); and subscribing to the Walrasian general equilibrium theory).

The model is composed of the following building blocks:

- Agents such as households, firms producing intermediate and final goods, the central banking system and fiscal authorities;
- Real and nominal frictions: sticky prices and wages, limited exchange-rate pass-through, habit formation, adjustment costs;
- Financial frictions such as the exogenous domestic and external risk premia;
- Rest-of-the-world block.

The building blocks are estimated on 18 macro time series employing Bayesian inference methods (more on the estimated variables below). The households face loan-in-advance constraint, in the sense that each household accumulates physical capital, the services of which it rents out to firms, while the capital investments by a household have to be financed by new bank loans. Further, financial intermediaries (banks) engage in maturity transformation, meaning that banks provide long-term loans to the private sector to finance investment projects and hold bonds, funding these assets with short-term household deposits and with their equity/net worth.

In the model there are a series of agents:

- The households, which consume, accumulate physical capital, supply differentiated labour services, set wages in monopolistically competitive markets, and trade in domestic and foreign bonds;
- The firms, which are engaged in the production of tradable intermediate and non-tradable final goods. There are three distinct typologies of firms:
  - The domestic intermediate-good firms setting prices in producer currency in monopolistically competitive markets at home and abroad;
  - The foreign intermediate-good firms, setting prices in local currency in monopolistically competitive markets;
  - Final-good firms, combining domestic and foreign intermediate goods into three non-tradable goods, namely a private consumption good, a private investment good, and a public consumption good;
- The central bank system, that sets the short-term nominal interest rate;
- The fiscal authority, which purchases public consumption goods, issues bonds, and levies progressive as well as lump-sum taxes.

The model features a relatively large number of shocks: foreign, demand, technology, markup, and monetary policy. The model displays also a number of frictions: such as external habit formation in consumption, a generalised adjustment cost in investment, imports and exports, sticky prices and wages à la Calvo, fixed cost in intermediate-good production, monopolistic competition in intermediate-good and labour markets, non-state contingent bonds, and domestic and external financial intermediation costs.

85 https://ideas.repec.org/a/ecm/emetrp/v50y1982i6p1345-70.html
86 https://www.jstor.org/stable/1840430

The model is developed in building blocks, and as reported by the informant code from the previous vintage of the EU area-wide models was made available on request as well as within modelling groups, for instance belonging to the European system of central banks and important policy institutions. Given that the model is quite complex, it can be run only with some technical advice provided by the ECB to other central banks and other institutions through the secondment of personnel. Some earlier versions have also been used more widely by several academics who could use then analysis that are focused on fiscal policy mostly, and clearly the ECB has also made the code available following the request of one journal where academic papers on the model model have been published.

The development of the model gained from discussion and input from a wide range of stakeholders. In fact, as reported by the informant, the ECB had initially support by external consultants which were mostly colleagues from other central banks from EU Member States, as well as from the New York Fed and the Sveriges Riksbank, which at the time were quite advanced in developing this type of DSGE models. After having acquired all this expertise, the ECB started to provide advice to other modeling teams that were also trying to build up their own capacities. In fact, the ECB has been quite active in supporting other institutions, other central banks, primarily in building up their modelling capacities, by directly advising on certain modelling projects, but also within the EU system of central banks which includes not only the ECB but also the national central banks. There are modelling working groups which meet several times a year, where the ECB makes available its experience and part of the applications with its models as a mean of transferring knowledge and expertise working with the respective communities. Of course there has also been a lot og exchange with the European Commission, in terms of joint projects and papers.

Therefore, the model has been co-created in collaboration with all the central banking community. Further, when building the model, the ECB reached out regularly to academia by producing also academically oriented papers with the model, which have been published in several journals. This was also the chance to receive feedback and to get peer reviews of the ECB modeling work, also in light to establish a reputation of the modeling function at ECB more generally within the academic community.

Further, the informant reports that the ECB has put a lot of emphasis on model evaluation, as reflected in the working papers which document the NAWM vintages. Specifically, the ECB elaborated based on the literature a number of criteria against which to assess the performance of the model. Moreover, as the models are estimated using Bayesian techniques, there are various statistics and criteria that allow the authors to judge how good the model fits the data. Further, there are a lot of economic checks by looking at transmission mechanisms on the basis of impulse response functions as well as forecast evaluations to judge how good the model performs in terms of forecasting macro aggregates. All these checks are documented in the papers presenting the model, but also in some additional academic papers, as a good practice to establish the credibility of the model and by assuring that it performs reasonably well compared to some standard benchmarks that are used in the literature.

According to the informant, it also has to be taken into account that the projections at ECB are expert-based forecasts so they are not mechanically based on any model. In fact, models are used to inform the whole process and to quantify the impact of changes and assumptions and data. But ultimately the forecasts are very much judgmental, so based on the opinion of experts who consult the models, which are used to promote a narrative at aggregate level for the projection baseline and conduct also scenarios and risk analysis around this baseline. Also, it has to be taken into account that all the macro-models developed are not granular enough to produce also forecasts taking into account the many important aspects of actual economic development. An example is given by the current Covid-19 crises: the models are not equipped to deal properly with the ramification that derives from the current crisis.

2.6 Data sources

For the estimation of the original version of the model, the research team has made use of time series for 18 macroeconomic variables:

- Real GDP;
- Private consumption
- Total investment;
- Government consumption;
- Euro area exports and imports;
- GDP deflator;
- Consumption deflator;
- Extra-euro area import deflator;
- Total employment and nominal wages;
- Short-term nominal interest rate (i.e. the 3-month EURIBOR);
- Nominal effective exchange rate of the euro;
- Foreign demand, prices, and short-term interest rate;
- Competitors' export prices;
- The price of oil.

The time series, apart from the extra-euro area trade variables, are extracted from the 17th update of the Area Wide Model database, which is built on publicly available data from Eurostat and/or reported in the ECB Statistical Data Warehouse (SDW) complemented by aggregating available country data.

The historical data are based on the aggregation of available country information when the original AWM database was compiled. The main source for the country information is Eurostat, complemented by the OECD National Accounts, the OECD Main economic indicators, the BIS and the AMECO databases. The data are originally provided by the National Statistical Institutes following the Statistical Data and Metadata Exchange (SDMX) standard. The data are exchanged electronically through API. As reported by the informant, one of the primary uses of the models is in the context of the macroeconomic projection exercises of the ECB, so this means the model then covers also the main macroeconomic aggregates that play a key role in the projection exercises, which are primarily national accounts data.

As reported by the informant there are internal routines available for data aggregation. More specifically, the ECB macroeconomic projections following a bottom-up approach, according to which projections are produced at country level and there are aggregated according to routines and weights (GDP weights for the most part), allowing them to aggregate the outcomes of the country projections so as to obtain aggregate numbers for the EU area, which are then used to analyze the forecasts with the EU area-wide aggregated models.

More specifically[87], once the individual euro area country figures are agreed upon, the euro area projection is obtained by aggregating the individual country projections. The aggregation of GDP and its expenditure components is performed at chainlinked volumes. Chain-linking of quarterly data uses the annual overlap technique adopted by Eurostat. The GDP deflator and its demand components are derived as the ratio of the variables in nominal terms (obtained by a simple sum in terms of euro) divided by the corresponding variables at chain-linked volumes. The Harmonised Index of Consumer Prices (HICP) aggregation is calculated using Eurostat's methodology, i.e. an annual chain index with changing country weights. The weight of a country is the share of its private final domestic consumption expenditure to the euro area private final domestic consumption expenditure. For the projection period, the latest available set of weights is used. Further, a trade consistency exercise (TCE) is carried out to ensure that individual country projections of trade volume and price variables are consistent with each other and with the assumptions made about the international environment (i.e. world trade, foreign prices and nominal exchange rates). As for trade consistency, it includes the cross-trade consistency of the trade projections at any

87 https://www.ecb.europa.eu/pub/pdf/other/staffprojectionsguide201607.en.pdf

given point in time, which checks that each country's export projection is consistent with the import projections of its trading partners in both volume and price terms. On the other hand, it also includes the ex ante/ex post trade consistency ensures that for each country, external demand and competitors' export prices are updated as the projection exercise progresses, in line with changes in the import and export prices of other euro area countries.

For the estimation of the second version of the model six additional time series are used:

- 10-year government bond yields;
- Composite long-term lending rate;
- Long-term inflation expectations;
- Foreign 10-year government bond yield;
- Long-term growth expectations;
- Output gap.

The sources of the financial data are the Deutsche Bundesbank database, the ECB SDW, and the FRED database of the Federal Reserve Bank of St. Louis. Data are open and available for reuse, and results are shared and published on a regular basis. As reported by the informant, the most recent extension which has a focus on the financial sector includes variables that are an important element of the transmission mechanism of monetary policy in the EU area, giving the importance of the banking sector at large, as well as the long term government bond yields, which also play an important role in the calibration, then also the ECB monetary policy measures, notably asset purchases, which are of course also to be covered by the model in the conduct of policy scenario.

As for the extra EU area trade there are several external sources, given that these are not standard data so there are then some assumptions which are made to construct this extra EU area data series, imports, exports which are not regularly provided by Eurostat, which in turns focus on total trade of the member states but not on extra trade.

Publications of the results are available at least every quarter, and as regards available of data as reported by the informant the final database used for running the model is not available, given that this is confidential to the extent that projection data are also partly used, while older data has been made available. Specifically, the area-wide model database has been actually made available via the EU area business cycle network on an annual basis. A certain degree of transformation is necessary to run the models, and a data description in the model documentation is provided, so that informed users may be able to construct all the necessary data, including projections which are kept confidential.

In the future, it is possible that a more advanced version of the model will be available, even though this is not really a priority in this period of crisis, and also taking into account that opening a model means also being ready to provide documentation and support in order to have the model used properly, otherwise it may be detrimental if one makes available code and he/she is not willing then to support potential users.

2.7 Tools

The code used of the estimation is YADA (Yet Another Dsge Application), which is a Matlab program for Bayesian estimation and evaluation of Dynamic Stochastic General Equilibrium and vector autoregressive models.[88] The estimation of the model does not require the use of very powerful machines, even though the estimation methodology is very advanced. Specifically, as reported by the informant at least for estimation purposes some parallel computing routines to speed up large scale simulations are

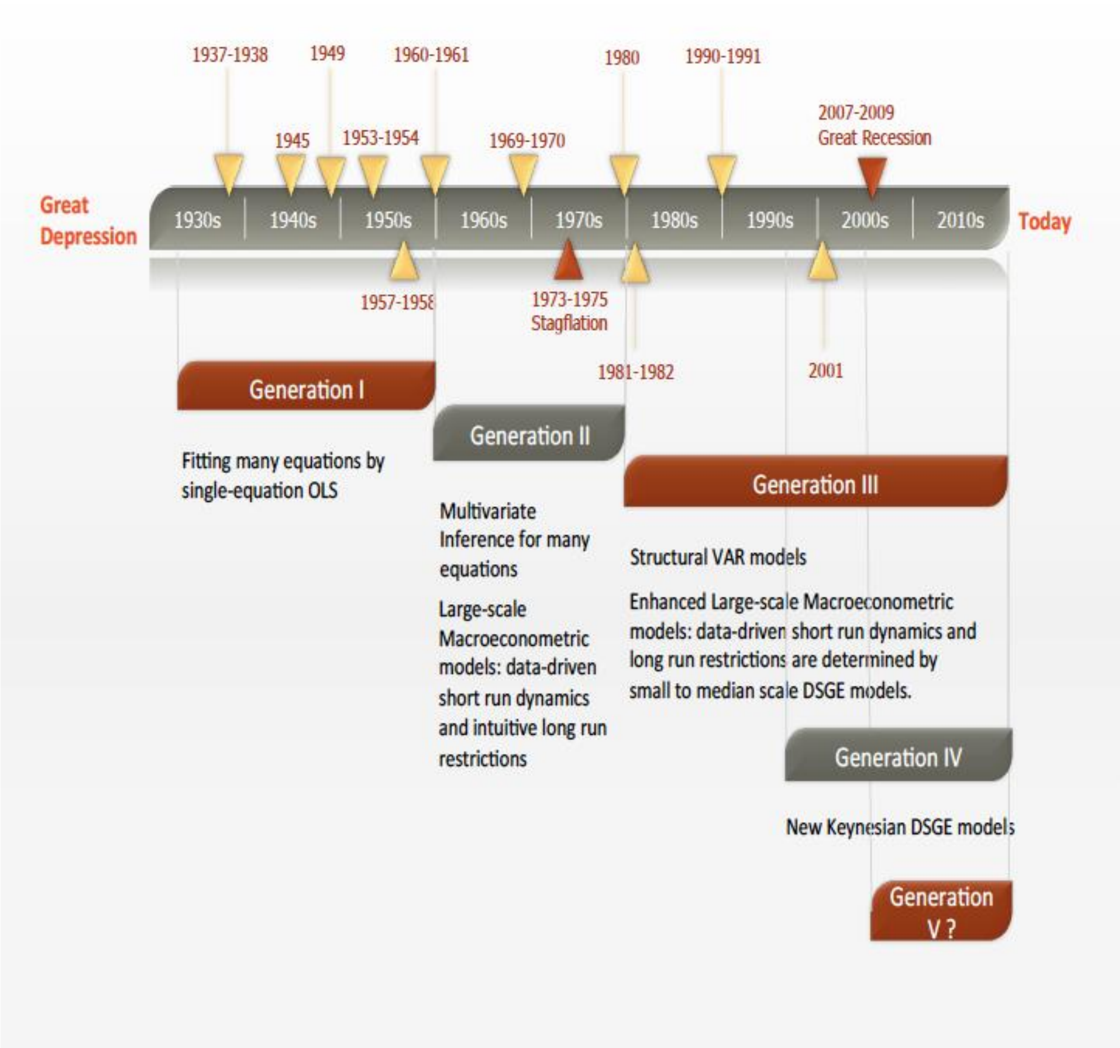
88 https://www.texlips.net/download/yada.pdf

conducted. Therefore, the estimation is not run with a supercomputer but instead parallel computing is used.

2.8 Degree of maturity and implementation phases

The NAWM II is regularly used for policy making by the European Central Bank, and its results are adopted by members of the Euro Area as well as from Member States. As already mentioned, the current model is an extension of the NAWM by Christoffel et al.[89], which in turn itself is a small-open-economy extension of the Schorfheide[90] and Smets-Wouters model[91][92]. As reported by Dou et al.[93] Figure 33 displays the generations of models at major central banks.

Figure 33 – Generations of models at major central banks



Source: https://www.imfs-frankfurt.de/fileadmin/user_upload/Events_2017/MMCI_Conference/Presentations/Dou_presentation.pdf

The first generation of models consisted in fitting multiple equations by single-equation ordinary least squares (OLS). The second generation included multivariate inference for multiple equations, as well as large scale macro-economic models, i.e. data-driven short run dynamics and intuitive long run restrictions. Further, the third generation included structural vector autoregressive models, as well as by enhanced large scale macro econometric models in which data driven short run dynamics and long run

89 https://www.ecb.europa.eu/pub/pdf/scpwps/ecbwp944.pdf
90 https://econpapers.repec.org/article/jaejapmet/v_3a15_3ay_3a2000_3ai_3a6_3ap_3a645-670.htm
91 https://www.ecb.europa.eu/pub/pdf/scpwps/ecbwp171.pdf
92 https://www.aeaweb.org/articles?id=10.1257/aer.97.3.586
93 https://www.imfs-frankfurt.de/fileadmin/user_upload/Events_2017/MMCI_Conference/Presentations/Dou_presentation.pdf

restriction s are determined by small to median scale DSGE models. Finally, the fourth generation is given by the New Keynesian DSGE models, while the fifth generation is yet to come.

2.9 Drivers and challenges

As reported by Dou et al.[94] the main drivers for the adoption of DSGE models are the following:

- DSGE models are less subject to the Lucas critique due to their explicit account for the role of expectations and their identification of deep structural parameters, making them more suitable for policy analysis and counterfactual experiments;
- DSGE models are able to identify and decompose economic and policy structural shocks on the quantitative level by the mean of an impulse-response analysis. In this regard, the identification of structural shocks greatly improves the reliability of policy analysis and counterfactual experiments, and mitigates the Sims critique;
- DSGE models are able to discover deep structural parameters thanks to their capability to link model implications to time-series and cross-sectional data.

On the other hand, the financial crisis of 2007-2009 has given new urgency in extending the power and reach of DSGE models. In the same way as the Great Depression inspired Tinbergen and Klein, and the recession and stagnation of the 1970s inspired Lucas, Kydland, and Prescott, the current macroeconomic situation has prepared the way for a major shift in macroeconomic modelling for policy. Specifically, DSGE models need to take to take risk into account by incorporating individual, institutional, and regulatory responses to changing risks. Further, DSGE models need to incorporate the financial sector and its intricacies. Finally, DSGE models should departure from the assumption of optimizing agents following rational expectations, and allow for certain predictable irrationalities in their behaviour. These agents would still adapt to the economic circumstance, therefore rejecting the Lucas critique, but not in an instantaneous and fully optimal way.

2.10 Role of beneficiaries and technological providers

As reported by the informant, the policy makers provide input and feedback continuously on the application of the model. Further, when the model was elaborated, a wide range of stakeholders from the central banks, academia and institution was engaged in discussions. Clearly there is a regular feedback and validation from the staff within the Euro system given that the model is used to prepare input into the policy process by conducting scenarios, risk analysis, by assessing the impact of policy measures. In fact, the main objective is of course to serve the needs of the policy makers, by using these models to help them to pursue their tasks of conducting policies for the EU area.

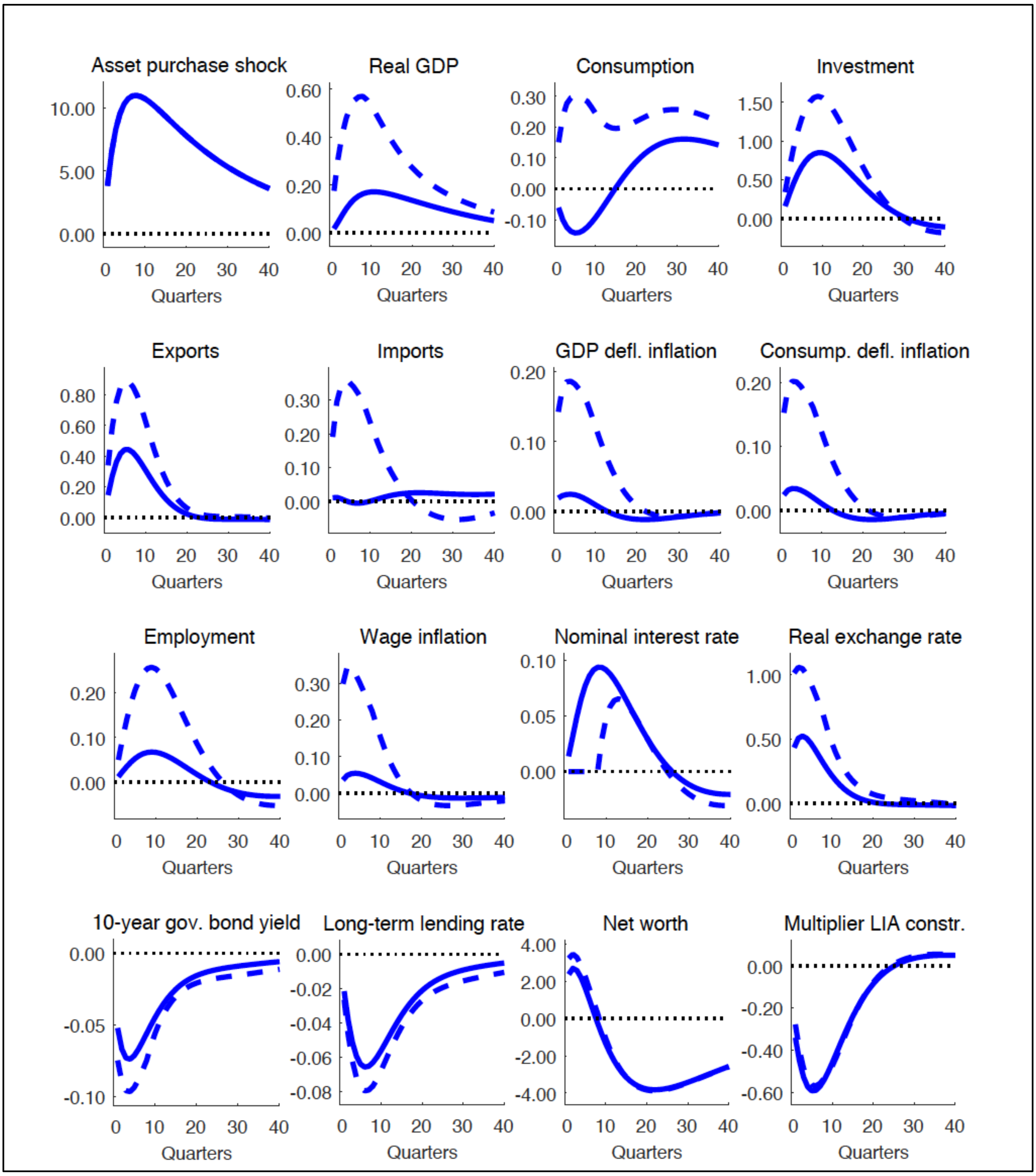
2.11 Social and economic output, outcomes and impacts

There a series of key benefits of global macroeconomic models for forecasting and what-if exercises. First, they provide a framework for understanding how economies work and interact. Secondly, they are a tool for thinking about possible identifiable risks, policy responses and wider consequences. Moreover, multiple applications are allowed, so there is no need to reinvent the wheel each time. Further, they incorporate key magnitudes and impose consistency, and finally they Improve over time in reaction to new ideas and events. Specifically, the NAWM II model allows to carry out economic projections contributing to the elaboration of the projection baseline for the largest euro area countries and to forecasting with judgment and model-based projection narratives. Further, the model allows for risk analysis and policy analysis, the latter related to the impact study of monetary policy options as well of strategic

94 https://www.imfs-frankfurt.de/fileadmin/user_upload/Events_2017/MMCI_Conference/Presentations/Dou_presentation.pdf

issues related to Monetary-fiscal-financial policy mix in the euro area. Coenen et al.[95] report two specific applications of the model: in the first the model is used to assess the macroeconomic impact of large-scale central bank asset purchases under the promise to keep the policy rate unchanged over a number of quarters; and the second in which the mode is used to analyse the adverse impact of a possible de-anchoring of longer-term inflation expectations on the macro economy in an environment where the lower bound on the short-term interest rate is binding. In short, Figure 34 shows that the expanded asset purchase programme has the impact to improve credit conditions and therefore the whole economy. Specifically, the blue solid lines represent the benchmark simulation set-up with an endogenous short-term nominal interest rate reaction, while the blue dashed lines present the benchmark set-up with the nominal interest rate being kept unchanged for eight quarters and with imperfect credibility of the central bank's announcement thereof.

Figure 34 - Effects of asset purchases by the central bank

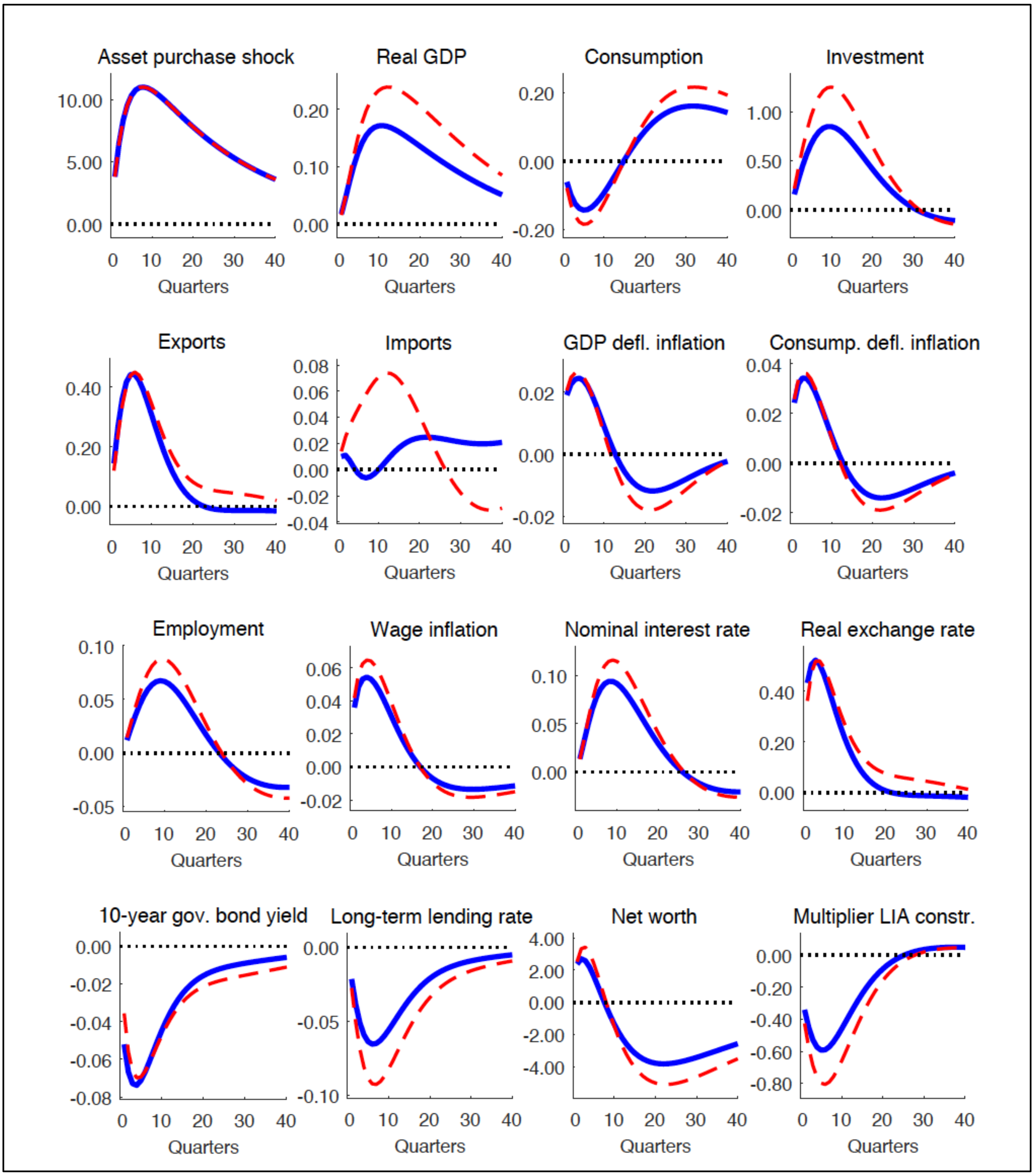


Source: https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2200.en.pdf

95 https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2200.en.pdf

By the same token, Figure 35 displays the same shock with an alternative simulation set-up with a higher riskiness of the long-term investment bonds (i.e. the red dashed lines).

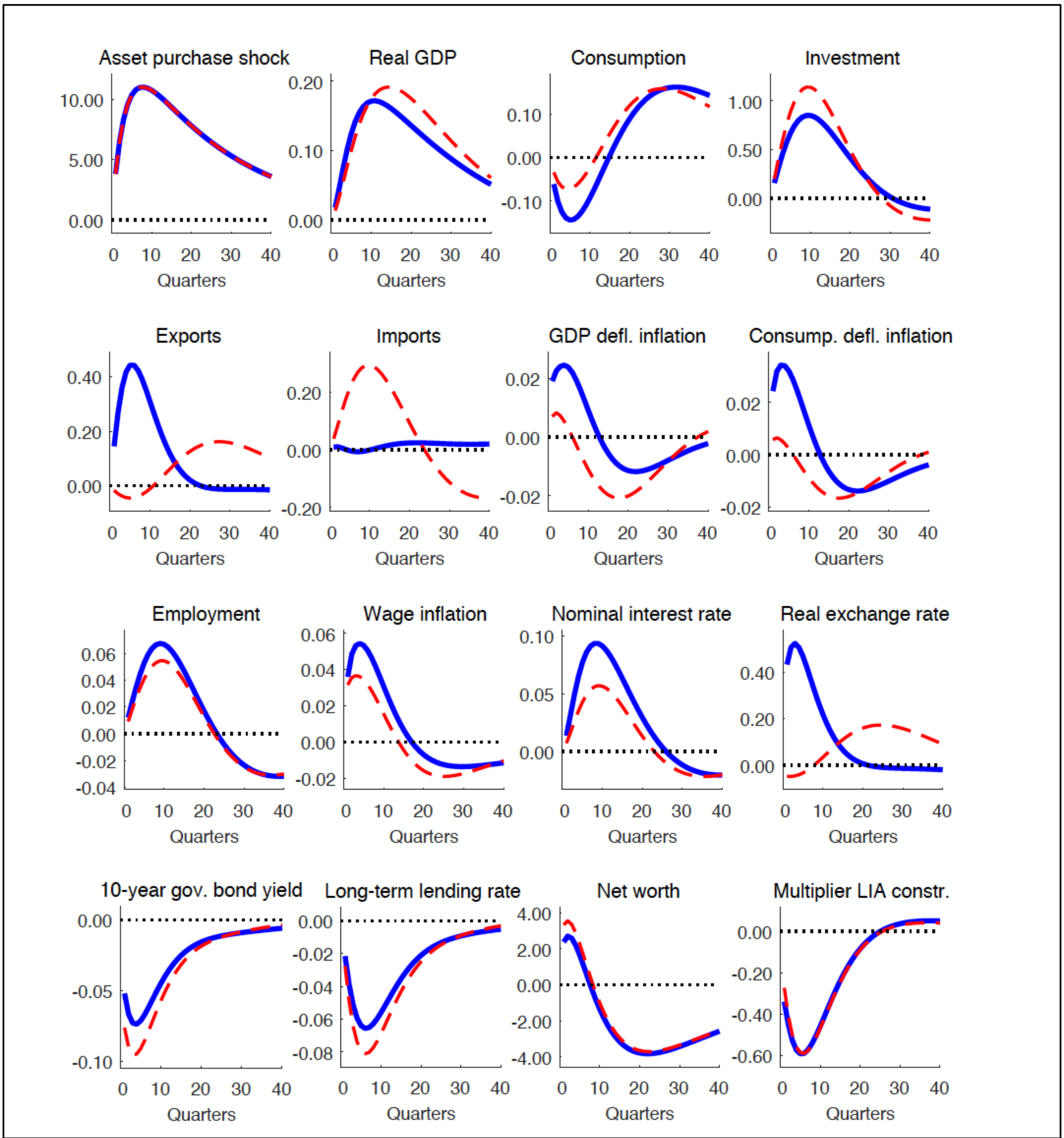
Figure 35 - The role of the riskiness of assets in an asset purchases situation



Source: https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2200.en.pdf

Further, Figure 36 represents the same shock in the standard version of the NAWM II with a no-arbitrage condition for long-term government bonds determining the exchange-rate response (blue solid lines), as well as for a version of the model in which this no-arbitrage condition is replaced by the standard uncovered interest parity condition (red dashed lines).

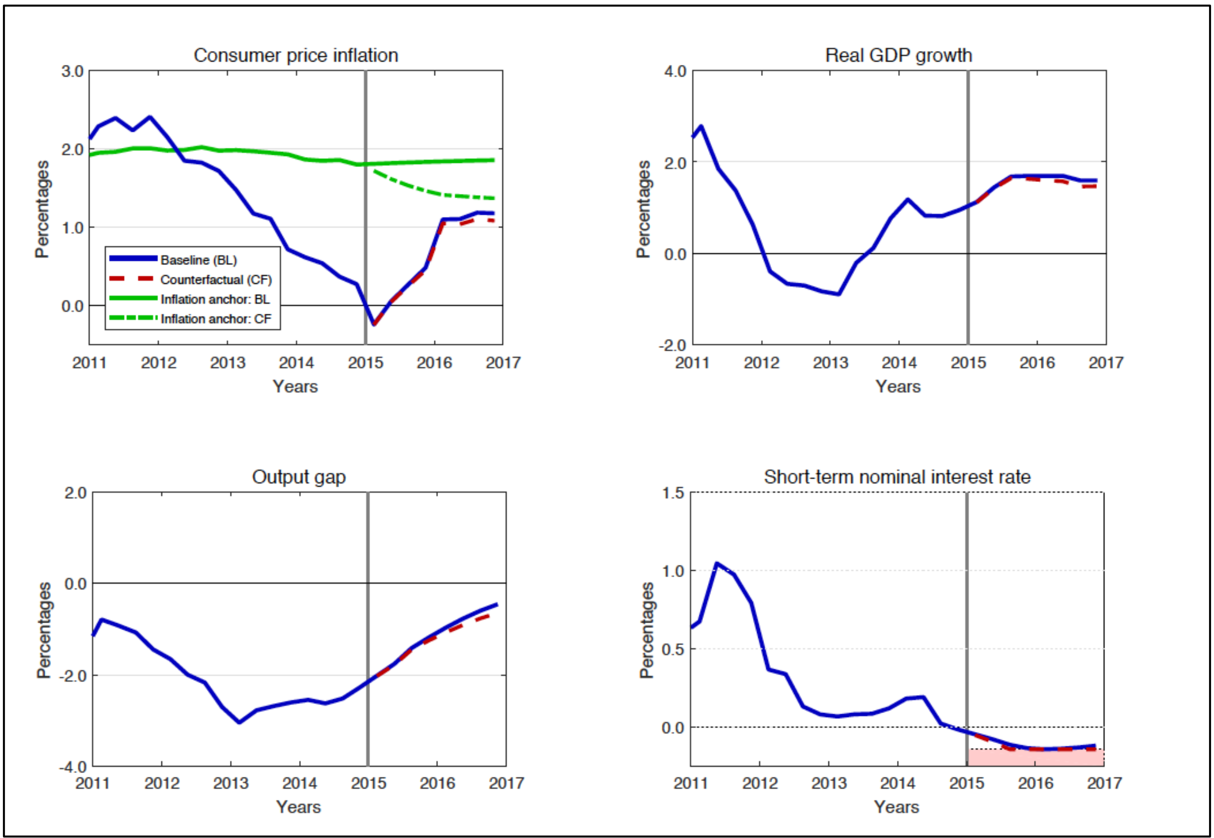
Figure 36 - The role of the exchange-rate channel in an asset purchases situation



Source: https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2200.en.pdf

Finally, in Figure 37 it is shown the use of the model to carry out a counterfactual simulation with the aim of illustrating the fact that persistently low inflation outcomes over the simulation horizon lead to a sizeable additional downward shift in longer-term inflation expectations, and in turn to a GDP growth lower than the baseline.

Figure 37 - Consequences of a de-anchoring of longer-term inflation expectations



Source: https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2200.en.pdf

2.12 Scalability, replicability and transferability considerations

In principle the model can be scaled, as it deals with the estimates of the policy impact in the EURO Area. Therefore, the model can be adapted with including a bigger number of countries by re-estimating the parameters for calibration. The model can in principle also be transferable to another monetary area, again by re-estimating the parameters for calibration, and can be downsized to a smaller level, for instance at regional level (see the derived model EAGLE[96]). However, this is a typical macro-economic model, and therefore the transferability to other domains (e.g. energy) and/or the application to other policy questions is somehow limited, and in any case the adaptation of the model to a multi-country setting, or to other jurisdictions in general would be demanding a quite huge amount of effort.

2.13 Conclusions

The NAWM II is a very successful model in terms of adoption and take up for policy. In principle it is very difficult to assess to what extent the model has improved the policy making activity in the member states, but according to the informant the model has been very impactful as demonstrated by the number of policy makers that have been referring to it in public over the years. Another testimony is provided by the number of citations and applications that the model has fostered on the academic side. As for take out for institutions willing to develop (or further develop) their modelling capabilities, the first would be to build their own capacity through exchange with expert practitioners (such as the ECB) and academics. Further, an important step is to build their models collaboratively and transparently, in order to ensure that the underlying assumptions are robust enough and that the best input available has been used. To this extent, it is also important to make available as much as possible data and code from the model, in order to ensure knowledge exchange and replicability of

[96] https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1786417

results, as well as possibility of integration across models. Las but not least, it is important to follow internationally recognised modelling validation and evaluation frameworks and methodologies, and to systematically take into account input from users in general and policy makers in particular.

2.14 APPENDIX - Database for the Estimation and sources

VARIABLE	DESCRIPTION
CAN_YEN	Current Account Balance as a Share of GDP. Calculated as the ratio of the sum of balance of trade (exports minus imports) and net factor income from abroad, and nominal GDP [CAN_YEN = (Balance of Trade + NFN_YEN * YEN) / YEN]
COMPR	Commodity Prices, US dollars. Calculated as the weighted sum of oil prices and non-oil commodity prices
EEN	Nominal Effective Exchange Rate (NEER), Euro area-19 countries vis-a-vis the NEER-38 group of main trading partners, Base year 1999 (1999Q1 = 1)
EXR	Euro-per-USD Exchange Rate. GCD General Government Final Consumption Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real general government consumption expenditure.
GCR	General Government Final Consumption Expenditure, Millions of euros, Chain linked volume, Calendar and seasonally adjusted data, Reference year 1995
GON	Gross Operating Surplus. Calculated as the residual term of the difference between nominal GDP and the sum of compensation of employees and taxes on production and imports net of subsidies (GON = YEN - WIN - TIN)
HEG HICP	Energy, Index, neither seasonally nor working day adjusted data, Index base year 1996 (1996 = 100)
HEGSYA HICP	Energy, Index, seasonally and working day adjusted data, Index base year 2015 (2015 = 100)
HEGWEI	Weight of the HICP Energy on Overall HICP, Parts per 1000, HICP total = 1000
HEX HICP	All Items Excluding Energy, Index, neither seasonally nor working day adjusted data, Index base year 1996 (1996 = 100)
HEXSYA HICP	All Items Excluding Energy, Index, Working day and seasonally adjusted data, Index base year 2015 (2015 = 100)
HICP HICP	Overall Index, Index, neither seasonally nor working day adjusted data, Index base year 1996 (1996 = 100)
HICPSYA HICP	Overall Index, Index, Working day and seasonally adjusted data, Index base year 2015 (2015 = 100)
ITD	Gross Fixed Capital Formation Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real gross fixed capital formation
ITR	Gross Fixed Capital Formation, Millions of euros, Chain linked volume, Calendar and seasonally adjusted data, Reference year 1995
LEN	Employees, Thousands of persons, Calendar and seasonally adjusted data

LFN	Labour Force, Thousands of persons. Implied from total employment and the employment rate [LFN = LNN / (1 - URX)]
LNN	Total Employment, Thousands of persons, Calendar and seasonally adjusted data
LPROD	Labour Productivity. Calculated as the ratio of real GDP, and total employment (LPROD = YER / LNN)
LTN	Nominal Long-Term Interest Rate, Euro area 10-year Government Benchmark bond yield, Percent per annum
MTD	Imports of Goods and Services Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real imports of goods and services. Based on the gross concept, i.e. both extra- and intra- area trade flows are accounted for
MTR	Imports of Goods and Services, Millions of euros, Chain linked volume, Calendar and seasonally adjusted data, Reference year 1995. Based on the gross concept, i.e. both extra- and intra- area trade flows are accounted for
NFN_YEN	Net Factor Income from Abroad as a Share of GDP. Calculated as the ratio of the sum of primary-income balance (Balance of Payments and International Investment Position), secondary-income balance (Balance of Payments and International Investment Position) and the capital-account balance, and nominal GDP [NFN_YEN = (Primary-income Balance + Secondary-income Balance + Capital-account Balance) / YEN]
PCD	Individual Consumption Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real individual consumption expenditure
PCOMU	Non-oil Commodity Prices, ECB commodity price index US dollar denominated, Import weighted, Total non-energy commodity, Neither seasonally nor working day adjusted data
PCR	Individual Consumption Expenditure, Millions of euros, Chain linked volume, Calendar and seasonally adjusted data, Reference year 1995
POILU	Oil Prices, United Kingdom, Petroleum: UK Brent, US dollars per barrel. SAX Gross Household Saving Rate, Percentage, Calendar and seasonally adjusted data. Defined as the ratio (multiplied by 100) of gross saving, and gross disposable income adjusted for the change in the net equity of households in pension funds reserves [SAX = (Gross Saving / (Gross Disposable Income + Net Equity of Households in Pension Funds Reserves)) * 100]
STN	Nominal Short-Term Interest Rate, Euribor 3-month, Percent per annum, Last trade price
TIN	Taxes on Production and Imports Less Subsidies, Millions of euros, Current prices, Calendar and seasonally adjusted data
ULC	Unit Labour Costs. Calculated as the ratio of compensation of employees, and real GDP (ULC = WIN / YER)
UNN	Number of Unemployed, Thousands of persons, Total (all ages), Total (male and female), Seasonally adjusted but not working day adjusted data
URX	Unemployment Rate, Percentage of civilian workforce, Total (all ages), Total (male and female), Seasonally adjusted, but not working day adjusted data. WIN Compensation of Employees, Millions of euros, Current prices, Calendar and seasonally adjusted data
WRN	Wage per Head. Calculated as the ratio of compensation of employees, and total employment (WRN = WIN / LNN)
XTD	Exports of Goods and Services Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real exports of goods and services. Based on the gross concept, i.e. both extra- and intra- area trade flows are accounted for

XTR	Exports of Goods and Services, Millions of euros, Chain linked volume, Calendar and seasonally adjusted data, Reference year 1995. Based on the gross concept, i.e. both extra- and intra- area trade flows are accounted for
YED	GDP Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real gross domestic product (GDP)
YER	Gross Domestic Product (GDP) at market prices, Million Euro, Chain linked volume, Calendar and seasonally adjusted data, Reference year 1995
YFD	GDP at Factor Costs Deflator, Index. Defined as the ratio of nominal, and real GDP at factor costs
YFN	GDP at Factor Costs. Calculated as the sum of compensation to employees and gross operating surplus (YFN = WIN + GON)
YIN	GDP, Income Side. Calculated as the sum of GDP at factor costs and taxes on production and imports less subsidies (YIN = YFN + TIN)
YWD	"World" GDP Deflator, Index, Index base year 1995 (1995 = 1). Defined as the ratio of nominal, and real "world" GDP
YWDX	"World" Demand Deflator, Composite Indicator. Calculated as the weighted sum of "world" GDP deflator expressed in euros and the euro area export deflator [log(YWDX) = w(YWD * EEN) * log(YWD * EEN) + w(XTD) * log(XTD)]
YWR	"World" GDP, Millions of US dollars. Calculated as the weighted sum of the GDP of the main trading partners of the Euro Area at the time of the creation of the model. These countries are the US, the UK, Japan and Switzerland [log(YWR) = w(US) * log(GDP(US)) + w(UK) * log(GDP(UK)) + w(JP) * log(GDP(JP)) + w(CH) * log(GDP(CH)), where w(US) + w(UK) + w(JP) + w(CH) = 1]
YWRX	"World" Demand, Composite Indicator. Calculated as the weighted sum of "world" GDP and domestic demand net of exports for the euro area.[log(YWRX) = w(YWR) * log(YWR) + w(FDD-XTR) * log(FDD-XTR), where w(YWR) + w(FDD-XTR) = 1]

Sources:

- https://econpapers.repec.org/article/jaejapmet/v_3a15_3ay_3a2000_3ai_3a6_3ap_3a645-670.htm
- https://ideas.repec.org/a/ecm/emetrp/v50y1982i6p1345-70.html
- https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1786417
- https://www.aeaweb.org/articles?id=10.1257/aer.97.3.586
- https://www.ecb.europa.eu/pub/pdf/other/staffprojectionsguide201607.en.pdf https://www.texlips.net/download/yada.pdf
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- https://www.imfs-frankfurt.de/fileadmin/user_upload/Events_2017/MMCI_Conference/Presentations/Dou_presentation.pdf
- https://www.jstor.org/stable/1840430

3 CASE STUDY: WEM - WORLD ENERGY MODEL

3.1 Introduction

Energy is a key driver of the modern global economy, therefore modeling and simulation of energy systems receives a lot of attention from policy makers and researchers. The International Energy Agency (IEA) has provided medium- to long-term energy projections using the World Energy Model (WEM) since 1993. The WEM is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the IEA's World Energy Outlook (WEO) scenarios. The WEO is a leading source of strategic insight on the future of energy and energy-related emissions, providing detailed scenarios that map out the consequences of different energy policy and investment choices. The IEA has become one of the most important inputs into government decision-making about energy, and its annual WEO report has a significant effect on the political and economic decisions of administrations and stakeholders regarding both conventional and renewable energy. Developed over many years and updated annually, the WEM consists of three main modules: final energy consumption (covering residential, services, agriculture, industry, transport and non-energy use); energy transformation including power generation and heat, refinery and other transformation; and energy supply. Outputs from the model include projections of energy flows by fuel, investment needs and costs, CO2 emissions and end-user pricing. The current version of WEM covers energy developments up to 2040 in 25 regions.

3.2 Rationale

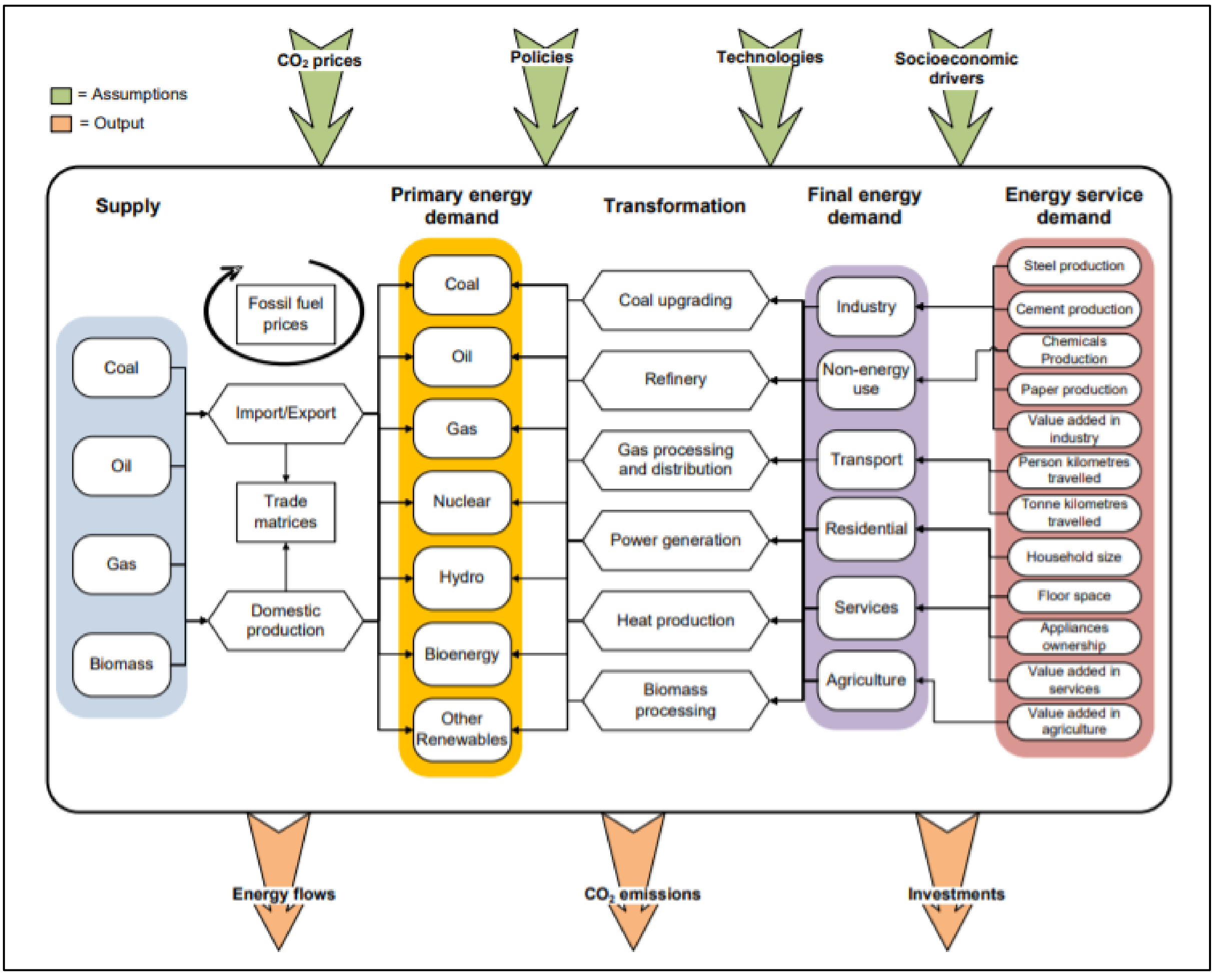
The energy sector is prime contributor to environmental concerns such as climate change, air pollution and water pollution. Data on final energy consumption help governments and stakeholders to estimate the environmental impacts of energy use. The type and extent of energy-related pressures on the environment depend both on the sources of energy (and how they are used) and on the total amount of energy consumed. Reductions in energy-related pressures on the environment could stem from reducing the energy consumption for energy-related activities, or by using energy in a more efficient way (thereby using less energy per unit of demand), or from a combination of the two. Energy policy formulation and the fostering of technology improvements can decelerate the growth of greenhouse-gas emissions from energy use. The trends in final energy consumption by sector provide a broad indication of progress made in reducing energy consumption and associated environmental impacts. The IEA's WEO report, based on WEM projections, presents plausible scenarios of energy developments. It helps to assess achievability of policy targets related to energy consumption and energy efficiency. It can also be used to identify appropriate policy response options for making the energy sector more sustainable, combat climate change and reduce water and air pollution. The main concerns of national, regional and local governments are to provide energy at affordable cost for consumers, in a reliable and safe way, and without supply interruptions. For energy companies, sector models can help to anticipate long-term and short-term energy needs and account for market liquidity problems due to bottlenecks in supply and storage capacity. Energy expansion projects are multibillion-dollar propositions and should be backed up with robust modelling projections to ensure that investment risks are reduced. The OECD has been using economic models and quantitative assessments for decades to inform policy makers of the costs, benefits and potential trade-offs of environmental policies and climate change mitigation scenarios. The World Energy Model is a large-scale simulation model covering energy supply, energy transformation and energy demand. Outputs from the model include projections of energy flows by fuel, investment needs and costs, CO2 emissions and end-user pricing. The IEA's annual World Energy Outlook report relies on the WEM to develop scenarios regarding projected future energy trends. For the World Energy Outlook 2019 (WEO-2019), detailed projections for three scenarios were modelled and presented: the Stated Policies Scenario, the Current Policies Scenario and the Sustainable Development Scenario. The WEO uses a scenario-based approach to highlight the key choices, consequences and contingencies that lie ahead, and to illustrate how the course of the energy system might be affected by changing some of the key variables, chief among them the energy policies adopted by governments around the world. The WEM-based scenarios enable the IEA to evaluate the impact of specific policies and measures on energy demand, production, trade, investment needs, supply costs and emissions.

3.3 Main actors and stakeholders

The International Energy Agency has a significant impact on both political and economic decisions of governments and stakeholders regarding energy. The annual WEO report is used by all OECD member nations as well as many non-member countries and other entities to inform their energy and climate policies. The IEA's mandate has been broadened to focus on three areas of energy policy: energy security, economic development, and environmental protection, in particular mitigating climate change. The IEA has a broad role in promoting alternate energy sources, including renewable energy; rational energy policies; and multinational cooperation in energy technology. The IEA’s annual World Energy Outlook report relies on the WEM to develop scenarios regarding projected future energy trends. For the World Energy Outlook 2019 (WEO-2019), detailed projections for three scenarios were modelled and presented: the Stated Policies Scenario, the Sustainable Development Scenario and the Current Policies Scenario. The scenarios differ with respect to what is assumed about future government policies related to the energy sector. The WEO uses a scenario-based approach to highlight the key choices, consequences and contingencies that lie ahead, and to illustrate how the course of the energy system might be affected by changing some of the key variables, chief among them the energy policies adopted by governments around the world. The WEM scenarios enable the IEA to evaluate the impact of specific policies and measures on energy demand, production, trade, investment needs, supply costs and emissions. The analysis is supported by a database of policies and measures, which details policies addressing renewable energy, energy efficiency and climate change.[97] An overview of the model structure is depicted in Figure 38.

[97] This database is available at: http://www.iea.org/policiesandmeasures/.

Figure 38 – World Energy Model Overview



Source: https://iea.blob.core.windows.net/assets/d496ff6a-d4ca-4f6a-9471-220adddf0efd/WEM_Documentation_WEO2019.pdf

3.4 Historical development of the model

The World Energy Model has been developed over many years and is updated annually. Since 1993, the IEA has used the WEM to provide medium- to long-term energy projections. The WEM consists of three main modules: final energy consumption; energy transformation; and energy supply. Outputs from the model include projections of energy flows by fuel, investment needs and costs, CO2 emissions and end-user pricing. The current version of WEM covers energy developments up to 2040 in 25 regions. The majority of the end-use sectors use stock models to characterise the energy infrastructure. In addition, energy-related CO2 emissions and investments related to energy developments are specified. Though the general model is built up as a simulation model, specific costs play an important role in determining the share of technologies in satisfying an energy service demand. The model is recalibrated each year to the latest available data point (for WEO-2019, this is typically 2017 although 2018 data is included where available). The World Energy Outlook provides critical analysis and insights on trends in energy demand and supply, and what they mean for energy security, environmental protection and economic development. The detailed projections are generated by the World Energy Model, a large-scale simulation tool, developed at the IEA over a period of more than 20 years that is designed to replicate how energy markets function. It covers the whole energy system, allowing for a range of analytical perspectives from global aggregates to elements of detail, such as the prospects for a particular technology or the outlook for end-user prices in a specific country or region.

The WEO uses a scenario-based approach to highlight the key choices, consequences and contingencies that lie ahead, and to illustrate how the course of the energy system might be affected by changing some of the key variables, chief among them the energy policies adopted by governments around the world.[98]

Data sources

Consistent, accurate and timely energy data and statistics are fundamental to developing effective and efficient national energy policies, as well as a key element in longer-term planning for investment in the energy sector. To this end, the IEA Energy Data Centre provides the world's most authoritative and comprehensive source of global energy data. The development and running of the WEM requires access to huge quantities of historical data on economic and energy variables. Most of the data are obtained from the IEA's own databases of energy and economics statistics. A significant amount of additional data from a wide range of external sources are also used. The parameters of the demand-side modules' equations are estimated econometrically. To take into account expected changes in structure, policy or technology, adjustments to these parameters are sometimes made over the Outlook period, using econometric and other modelling techniques. Simulations are carried out on an annual basis. Demand modules can be isolated and simulations run separately. This is particularly useful in the adjustment process and in sensitivity analyses of specific factors. The analysis is supported by a database of policies and measures, which details policies addressing renewable energy, energy efficiency and climate change.[99]

The IEA Energy Data Centre provides the world's most authoritative and comprehensive source of global energy data. The IEA collects, assesses and disseminates energy statistics on supply and demand, compiled into energy balances. In addition, the Energy Data Centre has developed a number of other key energy-related indicators, including energy prices, public RD&D and measures of energy efficiency, with other measures in development. The time series stretches back to 1971, and currently covers up to 95% of global energy supply and over 150 countries. The focus is on quality, comparability, and alignment with internationally agreed definitions and methodologies, and close collaboration with national offices responsible for energy statistics and other relevant stakeholders.[100]

This emphasis on sound data provides a unique platform for modelling work and tracking both short-term shifts and long-term trends in countries' energy transitions, particularly for clean energy. Furthermore, the IEA Energy Data Centre has established close cooperation with national and regional organisations on training and capacity building activities. As well as allowing for expanded coverage, this further ensures the quality of the Centre's data products.[101]

3.5 Data availability

There is a huge amount of data and publications available, and an entire website dedicated to the model.[102] Economic growth assumptions for the short to medium term are based largely on those prepared by the OECD, IMF and World Bank. Over the long term, growth in each WEM region is assumed to converge to an annual long-term rate. This is dependent on demographic and productivity trends, macroeconomic conditions and the pace of technological change. The IEA generates monthly statistics with timely and consistent oil, oil price, natural gas and electricity data for all OECD member countries back to 2000. A major challenge is ensuring the reliability of the energy data as the IEA relies on national administrations to maintain the quality of their own statistics. Breaks in time series and missing data could compromise the completeness of IEA statistics and affect any type of analysis, including modelling.

[98] More info available at https://www.iea.org/topics/world-energy-outlook
[99] This database is available at: http://www.iea.org/policiesandmeasures/.
[100] Have a look at the World Energy Model Documentation available at https://iea.blob.core.windows.net/assets/d496ff6a-d4ca-4f6a-9471-220adddf0efd/WEM_Documentation_WEO2019.pdf
[101] https://www.iea.org/areas-of-work/data-and-statistics
[102] Available at https://www.iea.org/reports/world-energy-model/documentation#abstract

3.6 Models

The IEA's annual World Energy Outlook report relies on the WEM to develop scenarios regarding projected future energy trends. For the World Energy Outlook 2019 (WEO-2019), detailed projections for three scenarios were modelled and presented: the Stated Policies Scenario, the Current Policies Scenario and the Sustainable Development Scenario. The scenarios differ with respect to what is assumed about future government policies related to the energy sector.

The WEO uses a scenario-based approach to highlight the key choices, consequences and contingencies that the future holds, and to illustrate how the course of the energy system might be affected by changing some of the key variables, chief among them the energy policies adopted by governments around the world. The WEM scenarios enable the IEA to evaluate the impact of specific policies and measures on energy demand, production, trade, investment needs, supply costs and emissions. The analysis is supported by a database of policies and measures, which details initiatives addressing renewable energy, energy efficiency and climate change.

The WEM consists of three main modules: final energy consumption (covering residential, services, agriculture, industry, transport and non-energy use); energy transformation, including power generation and heat, refinery and other transformation; and energy supply. The demand modules can be isolated and simulations run separately. In different parts of the model, Logit and Weibull functions are used to determine the share of technologies based upon their specific costs. This includes investment costs, operating and maintenance costs, fuel costs and in some cases costs for emitting CO2.

Total final energy demand (consumption) is the sum of energy consumption in each final demand sector. In each sub-sector or end-use, at least six types of energy are shown: coal, oil, gas, electricity, heat and renewables. However, this aggregation conceals more detail. For example, the different oil products are modeled separately for the transport sector, and renewables are split into "biomass and waste" and "other renewables".

The current version of WEM covers energy developments up to 2040 in 25 regions. For the Sustainable Development Scenario, key results are published until 2050. Depending on the specific module of the WEM, individual countries are also modelled: 12 in demand; 101 in oil and gas supply; and 19 in coal supply. The Africa Special Focus carried out for the WEO-2019 edition covers the individual modelling of 10 additional countries in sub-Saharan Africa.

The WEM is designed to analyse:

- Global and regional energy prospects: These include trends in demand, supply availability and constraints, international trade and energy balances by sector and by fuel in the projection horizon;
- Environmental impact of energy use: CO2 emissions from fuel combustion are derived from the projections of energy consumption. Greenhouse gases and local pollutants are also estimated linking WEM with other models;
- Effects of policy actions and technological changes: Alternative scenarios analyse the impact of policy actions and technological developments on energy demand, supply, trade, investments and emissions.
- Investment in the energy sector: The model evaluates investment requirements in the fuel supply chain needed to satisfy projected energy demand in the projection horizon. It also evaluates demand-side investment requirements, including energy efficiency, electric vehicles and industrial carbon capture and storage;
- Modern energy access prospects: These include trends in access to electricity and clean cooking facilities. It also evaluates additional energy demand, investments and CO2 emissions due to increased energy access.

The main exogenous assumptions concern economic growth, demographics and technological developments. Electricity consumption and electricity prices dynamically link the final energy demand and transformation sector. Consumption of the main oil products is modelled individually in each end-use sector and the refinery model links the demand for individual products to the different types of oil. Demand for primary energy serves as input for the supply modules. Complete energy balances are compiled at a regional level and the CO_2 emissions of each region are then calculated using derived CO_2 factors.

3.7 Tools

The WEM is implemented in the simulation software Vensim (www.vensim.com), but makes use of a wide range of software, including specific database-management tools, econometric software and simulation programmes. Logit and Weibull functions are used in different parts of the model to determine the share of technologies based upon their specific costs, including investment costs, operating and maintenance costs, fuel costs and in some cases costs for emitting CO_2.

3.8 Degree of maturity and implementation phases

The IEA and its WEO report have grown to have a significant impact on energy-related economic and political decision-making by governments and stakeholders. The annual WEO projections, which are based on the WEM, are used by all OECD member nations as well as many non-member countries and other entities to inform their energy and climate policies. The WEM is continually reviewed and updated to ensure its completeness and relevancy. The development of the WEM benefits from expert review within the IEA and beyond and the IEA works closely with colleagues in the modelling community, for example, by participating in the annual International Energy Workshop.[103] The following changes were made to WEM for World Energy Outlook 2019 (WEO-2019) as depicted below.

Temporal horizon and granularity:

- For the first time, WEO-2019 published key results of the Sustainable Development Scenario extending to 2050. The extended timeframe allows for improved insight into compatibility of the Sustainability Development Scenario with targets set out in the Paris climate agreement.
- WEO-2019 saw the update of the hourly electricity demand and supply modelling tools to output the hourly variability in electricity supply CO_2 emissions and calculate the average CO_2 emissions associated with electricity use for each end-use. This enhancement enables calculation of the emissions savings, price changes, and changes to flexibility needs, associated with enhanced energy efficiency and enhanced demand-side response by end-use.

Regional scope:

- WEO-2019 Africa Special Focus covers the individual modelling, for all sectors, of 10 additional countries in sub-Saharan Africa (alongside South Africa): Angola, Côte d’Ivoire, DR Congo, Ethiopia, Ghana, Kenya, Mozambique, Nigeria, Senegal and Tanzania that represent three-quarters of primary energy demand and GDP of the region.
- The regional split has been slightly revised in Eastern Europe (Lithuania and Latvia). The new split allows for easier grouping by OECD versus non-OECD.

Energy carriers:

- End-use sectors modelling of bioenergy was improved to model separately three forms of bioenergy: solid, liquid and gas (biogas and biomethane) and related technologies. Biogas technology costs reflect both the cost of installing a biodigester to produce biogas, and the end-use technology used to convert biogas into useful energy. WEO-2019 saw the development a new and detailed global assessment of the sustainable technical potential and costs of biogas and biomethane supply, and how this might evolve in the future.
- End-use sectors and power sector now integrates the blending shares of biomethane and hydrogen into gas networks. Biomethane is reported under bioenergy while hydrogen is reported under hydrogen use in the energy balances. Different production routes for hydrogen are modelled separately, including production from fossil fuels with CCUS.

103 http://internationalenergyworkshop.org

- Improvements of hydrogen vehicles projections have been made, taking into account the recent car market developments and policy announcements. The use of hydrogen in industrial processes such as chemicals production and steel-making is included as well.

Buildings module:

- Historical energy demand for space cooling and historical Cooling Degree Day (CDD) data is combined to normalise projections of space cooling energy demand, removing the impact of year on year volatility in space cooling needs. Projections of space cooling energy demand remain linked to projected changes in CDDs by region under each scenario's temperature pathway.
- Industry module:
- Assumptions of material demand were updated so as to account for finding of a recent IEA report on material efficiency (IEA, 2019a) and to fully reflect the decarbonisation potential that comes with strategies to reduce consumption of industrial goods along the entire product lifetime e.g. design, fabrication, use and end-of-life.
- Steel projections of demand and production were overhauled in preparation for the IEA Steel Roadmap 2020. The new methodology explicitly models steel demand based on a per-capita approach reflecting saturation levels of demand. It then derives production of steel on a per-country basis.

Transport module:

- The resolution of passenger car vehicle types has been enhanced, covering four additional car categories depending on their size (small, medium, large and SUVs). For this development, in-house and commercial databases have been used (i.e. GFEI report, Mobility Model e.tc.). This new feature improved the granularity of the model for assessing a spectrum of scenarios with different levels of heavier and bigger cars' penetration and evaluating also the impact of SUVs on future oil demand.
- For the purpose of electric cars projections, a thorough review on electromobility targets for the top 20 global automakers has been conducted. This analysis permits us to assess if the automakers commitments for launching new electrified car models are falling behind the necessary EVs rollout for meeting fuel economy goals and Zero Emission Vehicles mandates.

Power generation:

- The modelling of offshore wind power generation was significantly enhanced for the special focus on wind offshore in WEO-2019. In collaboration with Imperial College London, a detailed geospatial analysis was undertaken to assess the technical potential for offshore wind worldwide.
- Investment and financing:
- Investment data across all energy supply sectors now reflect estimates of ongoing capital spending based on estimated lead times. Previously, investment was counted as if all capital expenditures were made on an overnight basis.
- Dedicated investment tables are now included in an annex. The tables consolidate supply and demand at the global level, as well as regional-level investment projections for power and fuel supply.
- A high-level framework for analysing financial flows in energy investment was included for the first time, after more detailed assessment of the sources of finance and financing costs associated with investments was carried out in some sectors and regions. Within WEO-2019, and WEO Special Reports, more detailed financing cost analysis was performed for offshore wind projects, coal mining companies, LNG projects, renewable power projects in India and independent power producer projects in Southeast Asia.

3.9 Technical aspects and key assumptions

The World Energy Model is based on annual data, and has three main model blocks: 1) energy supply, 2) conversion/transformation, and 3) energy demand. The most important exogenous assumptions relate to plans and measures for energy and climate policies, costs of CO2 emissions, technological progress by industry and region, and assumptions for macroeconomic developments. Reflecting this broad set of assumptions, final demand from different sectors in each country is a result of economic activity in these sectors. Final demand is directed at a range of conversion processes, and primary demand is determined by the energy required for these processes. Production, trade, and price formation for energy commodities like coal, oil, and natural gas, natural gas and biomass is then determined by the interaction with primary energy demand in different industries and regions. WEM divides the world in 25 regions, 12 of which are countries, and the remaining 13 are groups of countries. The horizon of projections is typically 25-30 years, and exogenous assumptions include forecasts for economic growth, population growth, technological progress, and policy developments. Technically speaking, crude-oil and natural-gas prices are also exogenous, while end-user prices for a range of energy products are determined by the model. Output from the model typically includes projections on supply and demand for different energy products, costs and investments, end-user prices and energy-related greenhouse-gas emissions. Demand side drivers, such as steel production in industry or household size in dwellings, are estimated econometrically based on historical data and on socioeconomic drivers. All end-use sector modules base their projections on the existing stock of energy infrastructure. This includes the number of vehicles in transport, production capacity in industry, and floor space area in buildings. The various energy service demands are specifically modelled, in the residential sector e.g. into space heating, water heating, cooking, lighting, appliances, space cooling. To take into account expected changes in structure, policy or technology, a wide range of technologies are integrated in the model that can satisfy each specific energy service. The same macroeconomic and demographic assumptions are used in all the scenarios. The projections are based on the average retail prices of each fuel used in final uses, power generation and other transformation sectors. These end-use prices are derived from projected international prices of fossil fuels and subsidy/tax levels. As with all attempts to describe future trends, the WEM-based energy projections presented in the WEO are subject to a wide range of uncertainties. The reliability of WEM projections depends on how well the model represents reality and on the validity of the assumptions it works under.

3.10 Drivers and challenges

The IEA's World Energy Model is a comprehensive and detailed system of models, drawing on insights from geology, technology, economics and political science. A common argument against the methodology and models of the WEM is that the flexibility of economic behaviour is effectively contained, and that the relations of the modelling system are not sufficiently responsive to shifts and shocks in technology, preferences, policies and prices, Klaus Mohn at the University of Stavanger Business School said in a September 2017 conference paper.[104] Critics also argue that the IEA's World Energy Outlook, which uses the WEM, is largely a product of historical trends and developments, "combined with a rich set of exogenous assumptions and coefficients for the evolution of technology, prices and policies," according to Mohn., which lead to "a status quo bias in favour of fossil fuels." Mohn also says that "any sort of feedback effects from energy policies, technological change and energy back on economic activity (growth) is neglected in the main scenarios. This is clearly a shortcoming of the modelling approach," he says. Mohn also notes a "general suspicion that IEA's methodology and modelling strategy puts too little emphasis on the flexibility in economic behaviour."

Hoekstra et al in a 2017 paper make a similar contention: that the WEM and other models "underestimate the potential of technologies that diverge from the status quo." The paper focuses on WEM's photovoltaic predictions in the World Energy Outlook, saying "stagnation of the solar industry is predicted over and over again." Further, "The IEA acknowledges that PV has grown exponentially with – on average – 43.3% per year over the last 26 years," it says. Nonetheless, the model "predicts linear growth from 228 GW in 2015 to 1800 GW in 2050," according to the Hoekstra paper.

104 Klaus Mohn at the University of Stavanger Business School said in a September 2017 conference paper. https://www.researchgate.net/publication/322951643_Undressing_the_emperor_A_review_of_IEA's_WEO

"This disconnection from reality could be due to, for example, sponsor requirements or mental biases like confirmation bias, status quo bias, or system justification bias, but the way the model works could also be a factor," the authors conclude. They argue that "most of the energy transition management model requirements that we deduce from the literature are implemented partially or not at all. The result is a model that is unable to envision and leverage the exponential developments in solar energy," they said, adding that: "Since the WEM is a proprietary model, it's hard to pinpoint the cause of the problem."

Richard G. Newell, Stuart Iler and Daniel Raimi also urge greater transparency, but with a broader argument – to improve the comparability of the projections produced by different organizations. "Outlooks vary in a number of important methodological aspects, and comparing between outlooks is not straightforward," they say in a 2018 paper. "Without a way to clearly compare one outlook to the next, decision-makers may not understand the range of possibilities envisioned by different short-, medium- and long-term projections, or the assumptions that underpin those projections."

Metayer et al found evidence of that WEO projections on wind power as well as solar energy had been "significantly under-estimated," according to a 2015 research paper. "It can be concluded that future projections for renewable-energy generation of WEO reports are structurally too conservative and limited in their relevance. Furthermore, the model of the WEO for RE projections and its foundation on a structurally wrong growth pattern needs to be substantially reworked," the authors said.

The IEA has acknowledged the criticism and defends itself with the argument that the WEO doesn't make forecasts, but provides policy-dependent projections. IEA Executive Director Fatih Birol wrote in the foreword to the 2016 edition of the WEO: "Some colleagues and friends in the renewables industry have at times criticised the projections of future renewables energy supply in our main scenario as too conservative. They may indeed turn out to be too conservative; I sincerely hope that they do. But they rest squarely on the foundation of officially declared policy intentions. More can and should be done, as we demonstrate clearly in our other scenarios that require a more rapid pace of decarbonisation; but the underlying policies will have to change to make it happen. A clear-headed, rigorous assessment of what today's policy intentions can deliver, in my view, is the best way to encourage the necessary changes."

In 2017, the WEO introduced the Sustainable Development Scenario, which is focused on climate issues. And Fereidoon Sioshansi, president of California-based consultancy Menlo Energy Economics, praised the 2018 edition of the WEO for expanding the agency's focus beyond oil and other fossil fuels. The WEO-2018 focused on the growing role of electricity as the fuel of choice among end-users, he noted. The "IEA's new focus on electricity as the future fuel of choice has shifted attention to related issues such as how to balance supply and demand in a future dominated by increasing amounts of renewable energy resources – such as the need for supply diversity and flexibility," he wrote.

The IEA also has addressed some transparency issues. In the latest edition, WEO-2019, the IEA says: "We have made all the key policy assumptions available for all scenarios, along with all the underlying assumptions on population, economic growth and energy resources (which are held constant across the scenarios) and information on prices and technology costs (which vary by scenario depending on the market and policy context)."

3.11 Dimension/Scalability

The World Energy Model is used both at global and at national/regional level. The current version of WEM covers energy developments up to 2040 (2050 for the Sustainable Development Scenario) in 25 regions. Depending on the specific module of the WEM, individual countries are also modelled: 12 in demand; 101 in oil and gas supply; and 19 in coal supply. Demand modules can be isolated and simulations run separately.

3.12 Use in policy making / social and economic output, outcomes and impacts; monitoring system

The International Energy Agency has a significant impact on both political and economic decisions of governments and stakeholders around the world regarding energy. The WEO report published every year estimates for the coming decades how total primary energy demand and generation will evolve. The WEO is used by all OECD member nations as well as many non-member countries to inform energy and climate policies. The IEA has a broad role in promoting alternate energy sources, including renewable energy; rational energy policies; and multinational cooperation in energy technology. Policy-makers and stakeholders are continually trying to address the need to achieve a balance of environmental sustainability, energy security, and energy equity (access and affordability), and so putting forward different policy options. Each policy option under consideration has some cost associated with it. The cost of one scenario versus the other must not only be considered in terms of necessary capital investments and the impact on economic growth; the overall environmental impact and climate-change adaptation costs also need to be taken into account.

A core application of the WEM-based WEO is also on the Paris Climate Agreement, as well as to the Sustainable Development Goals. Other policy areas where it has been used include:

- Implement energy strategies for sustainable development, including diversified energy sources using cleaner technologies
- Increasing the share of renewable sources to meet climate objectives
- Diversifying energy supplies, including via new infrastructure
- Reducing energy consumption through improved energy efficiency
- Introduce energy-conservation technologies
- Promoting carbon capture and storage
- Greater support of research and development for environment, energy and transport
- Supporting the deployment of clean technologies
- Strengthening the EU Emissions Trading Scheme
- Infrastructure investment in transport, energy and environment
- Improve integration of energy efficiency and environment into energy policies

3.13 Conclusions

The World Energy Model is a powerful and data-rich tool for providing projections on key areas of policy-making. It is important for governments, companies and researchers of energy systems to be able to develop energy strategies based on state-of-the-art modelling approaches. But it's also important to continually question and validate the underlying assumptions. In this regard, models should maintain a high level of transparency.

Lessons learnt

- Projections, not forecasts: The IEA defends itself with the argument that the WEO doesn't make forecasts, but provides policy-dependent projections. "Some colleagues and friends in the renewables industry have at times criticised the projections of future renewables energy supply in our main scenario as too conservative. … But they rest squarely on the foundation of officially declared policy intentions." -- IEA Executive Director Birol;

- New technologies: the WEO in 2017 introduced the Sustainable Development Scenario, which is focused on climate issues. Consultancy Menlo Energy Economics praised the 2018 edition of the WEO for expanding the focus beyond oil and other fossil fuels, and including the growing role of electricity as the fuel of choice among end-users;
- Transparency: in the latest edition of the WEO, the IEA says: "We have made all the key policy assumptions available for all scenarios, along with all the underlying assumptions on population, economic growth and energy resources (which are held constant across the scenarios) and information on prices and

technology costs (which vary by scenario depending on the market and policy context)."

Takeout for the European Commission

- Incorporating feedback from stakeholders in the process is essential to success. Openness to new potential scenarios is key.

3.14 APPENDIX - Sources

- World Energy Model Documentation, 2019 version – International Energy Agency https://iea.blob.core.windows.net/assets/d496ff6a-d4ca-4f6a-9471-220adddf0efd/WEM_Documentation_WEO2019.pdf
- International Energy Agency – Energy Data Collection and Statistics https://www.iea.org/areas-of-work/data-and-statistics
- European Environmental Agency – Final energy consumption - outlook from IEA
  Last updated February 2017 https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-outlook-from-iea
- Hoekstra et al -- Creating Agent-Based Energy Transition Management Models That Can Uncover Profitable Pathways to Climate Change Mitigation Volume 2017 |Article ID 1967645 -- https://doi.org/10.1155/2017/1967645
- World Energy Outlook https://www.iea.org/topics/world-energy-outlook
- Mohn, Klaus. (2017). Undressing the emperor: A review of IEA's WEO. https://www.researchgate.net/publication/322951643_Undressing_the_emperor_A_review_of_IEA's_WEO
- Metayer et al in a 2015 research paper: The projections for the future and quality in the past of the World Energy Outlook for PV and other renewable energy technologies http://energywatchgroup.org/wp-content/uploads/2018/01/EWG_WEO-Study_2015.pdfs_.pdf
- Fabien Roques et al – March 2009, Integrated Modelling of Economic-Energy-Environment Scenarios
  C.I.R.E.D. -- Centre international de recherches sur l'environnement et le développement
  http://www2.centre-cired.fr/IMG/pdf/CIREDWP-200915.pdf
- Ruud Weijermars et al. review of models http://www.alboran.com/files/2013/07/ES-9.pdf
- Global Energy Outlooks -- Comparison Methods -- 2018 Update RFF -- Richard G. Newell, Stuart Iler, and Daniel Raimi https://www.ief.org/_resources/files/events/the-eight-iea-ief-opec-symposium-on-energy-outlooks/rff-global-energy-outlook-comparison-methods.pdf
- The IEA's World Energy Outlook and its Coal Bias -- 20 February 2018 https://www.greenpeace.org.au/blog/ieas-world-energy-outlook-coal-bias/
- IEA: Future is electric and increasingly renewable – Dec. 14, 2018 -- by Fereidoon Sioshansi https://energypost.eu/iea-future-is-electric-and-increasingly-renewable/
  Fereidoon Sioshansi, president of Menlo Energy Economics, a consultancy based in San Francisco, CA and editor/publisher of Energy Informer

4 CASE STUDY: PRIMES - PRICE-INDUCED MARKET EQUILIBRIUM SYSTEM

4.1 Introduction

The PRIMES (Price-Induced Market Equilibrium System) is a large scale applied energy system model that provides detailed projections of energy demand, supply, prices and investment. It covers the entire energy system including emissions for each individual European country and for Europe-wide trade of energy commodities. PRIMES focuses on prices as a means of balancing demand and supply simultaneously in several markets for energy and emissions. The model produces projections up to 2070 in five-year intervals.

The distinctive feature of PRIMES is the combination of behavioural modelling (following a micro-economic foundation) with engineering and system aspects and technology progress, covering all energy sectors and markets. The model focuses on simulation of structural changes and long-term system transitions, rather than short-term forecasting. It handles multiple policy objectives, such as GHG emissions reductions, energy efficiency and renewable energy targets; it also provides pan-European simulation of internal markets for electricity and gas.

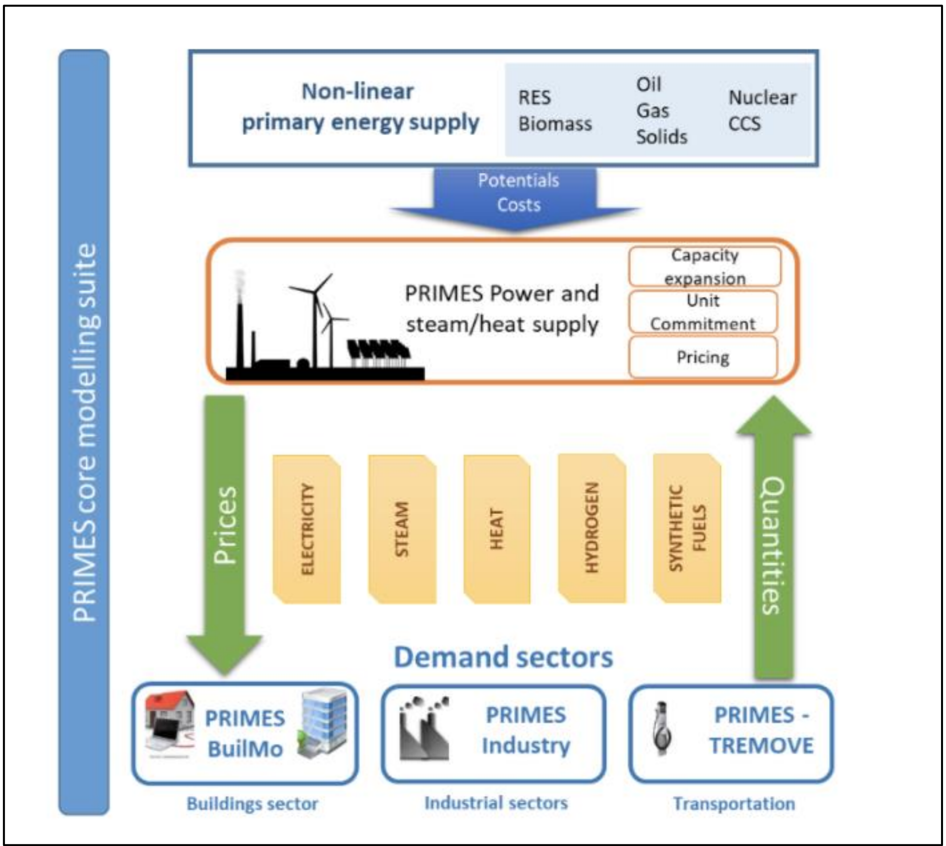
Developed by the Energy-Economy-Environment Modelling Laboratory (E3M Lab) at National Technical University of Athens, the PRIMES model covers individual projections for the EU28 Member States, as well as other European countries. The model simulates a multi-market equilibrium solution for energy supply and demand and for ETS and other potential markets by explicitly calculating prices which balance supply and demand. PRIMES is designed to analyse complex interactions within the energy system; its modular design aims to represent agent behaviours and their interactions in multiple markets.

PRIMES captures technology and engineering detail together with micro and macro interactions and dynamics. Because the PRIMES model follows a structural modelling approach, it integrates technology/engineering details and constraints in economic modelling of behaviours. The modelling of decisions draws on economics, but the constraints and possibilities reflect engineering feasibility and restrictions.

The model thus combines economics with engineering, ensuring consistency in terms of engineering feasibility, being transparent in terms of system operation and being able to capture features of individual technologies and policies influencing their development. Nevertheless, PRIMES is more aggregated than engineering models, but far more disaggregated than econometric models.

PRIMES is designed to provide long-term energy system projections and system restructuring up to 2050, both in demand and supply sides. The model can support impact assessment of specific energy and environment policies and measures, applied at Member State or EU level, including price signals, such as taxation, subsidies, ETS, technology promoting policies, RES supporting policies, efficiency promoting policies, environmental policies and technology standards. PRIMES is sufficiently detailed to represent concrete policy measures in various sectors, including market design options for the EU internal electricity and gas markets. Policy analysis is based on comparing results of scenarios against a reference projection. The linked model system PRIMES, GEM-E3 and IIASA's GAINS (for non-CO2 gases and air quality). The linked model system PRIMES, GEM-E3 and IIASA's GAINS (for non-CO2 gases and air quality) perform energy-economy-environment policy analysis in a closed-loop. The PRIMES core modelling suite is available at Figure 39.

Figure 39 - PRIMES core modelling suite



Source: https://e3modelling.com/modelling-tools/primes/

4.2 Rationale

PRIMES model design is suitable for medium- and long-term energy system projections and system restructuring up to 2070, in both demand and supply sides. The model can support impact assessment of specific energy and environment policies and measures, applied at Member State or EU level, including price signals, such as taxation, subsidies, ETS, technology promoting policies, RES supporting policies, efficiency promoting policies, environmental policies and technology standards.

Designed to analyse complex interactions within the energy system in a framework of multiple agents and multiple markets, PRIMES is sufficiently detailed to represent concrete policy measures in various sectors, including market-design options for the EU internal electricity and gas markets. The model is well placed to simulate long-term transformations in markets and includes non-linear formulation of potentials by type (resources, sites, acceptability, etc.) and technological development. Policy analysis draws on comparing results of scenarios against a reference projection. The model's use in the European Commission packages Clean Planet for All and Clean Energy for All Europeans stand out in the mind of Georgios Zazias, Project Manager and Modelling Coordinator with E3-Modelling in Athens and informant in the case study.

The linked models PRIMES, GEM-E3 and IIASA's GAINS (for non-CO2 gases and air quality) perform energy-economy-environment policy analysis in a closed loop. The PRIMES sub-models (modules) can be used in a stand-alone fashion or can be coupled with the rest of the PRIMES energy systems model. In the latter case, the integration with the PRIMES model enhances the dynamic character of the model, since the interaction of the different energy sectors is taken into account in an iterative way.

The PRIMES model offers the possibility of handling market distortions, barriers to rational decisions, behaviours and market-coordination issues, as well as investment on infrastructure. The model goes up to 2070 in five-year intervals and includes all EU member states individually, and has also provided detailed outlooks for Switzerland, Norway, Turkey, Albania, Bosnia, Montenegro, Serbia, FYROM and Kosovo.

4.3 Main actors and stakeholders

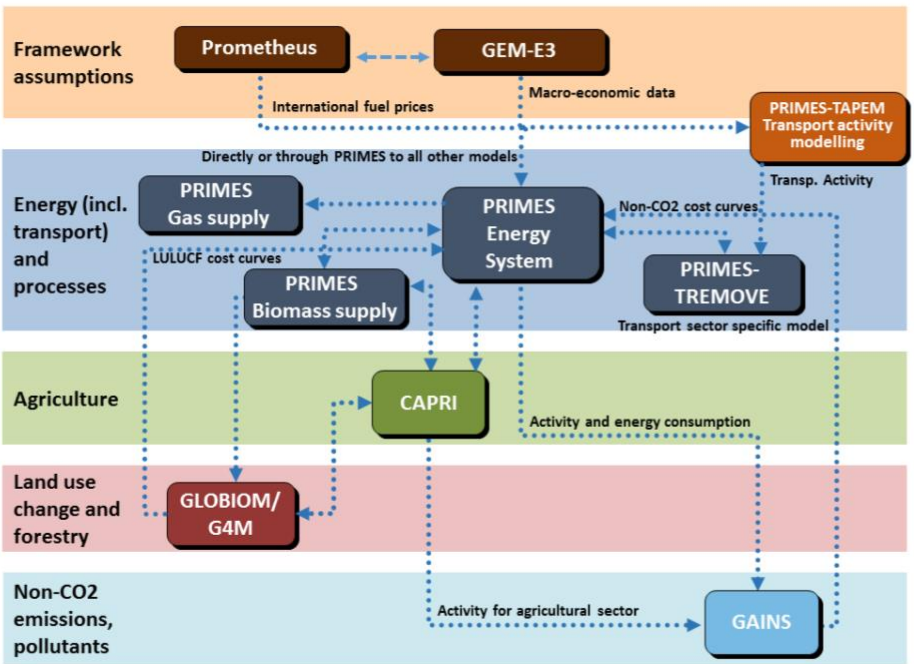
The PRIMES model has served various European Commission DGs over the years, including being used in the Energy Roadmap to 2050. PRIMES has supported analysis for major energy policy and market issues, including electricity market, gas supply, renewable energy development, energy efficiency in demand sectors and numerous technology specific analysis. The model also has quantified energy outlook scenarios and has been used in impact-assessment studies by the EU. PRIMES also has supported national projections for governments, companies and other institutions, including for EURELECTRIC and EUROGAS.

The model includes all European Union member states individually and also has provided detailed outlooks for Switzerland, Norway, Turkey, Albania, Bosnia, Montenegro, Serbia, FYROM and Kosovo. Numerous third-party studies have used projections produced using PRIMES; the majority of these studies focused on medium- and long-term restructuring of the EU energy system, aiming at reducing carbon emissions.

On co-creation, the informant at E3-Modelling in Athens says that although the PRIMES model is proprietary there has been input from the European Commission from the beginning and it continues to this day. "Some people at the European Commission, they were quite insightful," the informant said. "They really helped, not by writing code, for example, but by providing the specifications of what they need exactly. The model has been developed according to the needs to the European Commission," he said. The informant points to the inclusion of climate-neutral scenarios in the model for the "Clean Planet for All" communication. "It was the first time we were asked to model climate-neutrality scenarios," he said. "So because of this need, we added several technologies, regarding sectorial integration or negative-emissions technologies that we didn't have in the past," he said.

The EU uses PRIMES in a system that links it with other models. The models are linked with each other in formally-defined ways to ensure consistency in the building of scenarios. The model inter-linkages are available at Figure 40.

Figure 40 - Model inter-linkages



Source: https://e3modelling.com/modelling-tools/primes/

According to the European Commission, the model suite has a successful record of use in the Commission's climate policy impact assessments. As a suite, the models cover all GHG emissions and removals:

- Emissions: CO2 emissions from energy and processes (PRIMES), CH4, N2O, fluorinated greenhouse gases (GAINS), CO2 emissions from LULUCF

(GLOBIOM-G4M), air pollution SO2, NOx, PM2.5-PM10, ground level ozone, VOC, NH3 (GAINS);

- Emission reduction and removals: structural changes and technologies in the energy system and industrial processes (PRIMES), technological non-CO2 emission reduction measures (GAINS), changes in land use (GLOBIOM-G4M-CAPRI);
- Geography: individually all EU Member States, EU candidate countries and, where relevant Norway, Switzerland and Bosnia and Herzegovina;
- Impacts: on energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification, eutrophication), macro-economy with multiple sectors, employment and social welfare[105].

4.4 Historical development of the model

The PRIMES energy-system model was developed by the Energy-Economy-Environment Modelling Laboratory at National Technical University of Athens in the context of a series of research programmes co-financed by the European Commission. From the beginning, in 1993-1994, the PRIMES model was designed to focus on market-related mechanisms and explicitly project prices influencing the evolution of energy demand and supply, as well as technological progress.

PRIMES has a modular structure. The modules differ by sector in an aim to represent agent behaviours and their interactions within multiple markets as close as possible to reality. The model design combines microeconomic foundation of behaviours with engineering and technology details. The mathematical specification focuses on simulation of structural changes and long-term system transitions, rather than short-term forecasting.

The model is regularly extended and updated. Numerous studies have been performed using PRIMES, and numerous third-party studies have used projections produced using PRIMES. The majority of these studies focused on medium- and long-term restructuring of the EU energy system, aiming at reducing carbon emissions. PRIMES supported analysis for major energy policy and market issues, including electricity market, gas supply, renewable energy development, energy efficiency in demand sectors and numerous technology specific analysis. The PRIMES model has quantified energy outlook scenarios and been used in impact-assessment studies by the EU. PRIMES also has supported national projections for governments, companies and other institutions, including for EURELECTRIC and EUROGAS.

In addition to PRIMES, E3MLab has developed another major energy model -- GEM-E3 (general equilibrium macro-economic model), which is applied to world regions and EU specific countries. E3MLab also has developed and maintains a stochastic world energy/technology model, PROMETHEUS, and a large-scale energy demand and supply model, MENA-EDS.

4.5 Models

The PRIMES model comprises several sub-models (modules), each one representing the behaviour of a specific (or representative) agent, a demander and/or a supplier of energy. The sub-models link with each other through a model integration algorithm, which determines equilibrium prices in multiple markets and equilibrium volumes meets balancing and overall constraints.

Within the modular structure, the modules differ by sector in an aim to represent agent behaviours and their interactions within the markets as close as possible to reality. The model design combines microeconomic foundation of behaviours with engineering and technology details. The mathematical specification focuses on simulation of structural changes and long-term system transitions, rather than short-term forecasting.

105 More info available at https://ec.europa.eu/clima/policies/strategies/analysis/models_en

The PRIMES model simulates an energy market equilibrium in the EU and each of its Member States. This includes consistent EU carbon-price trajectories. Decision-making behaviour is forward looking and grounded in micro-economic theory. The model also represents in an explicit and detailed way energy demand, supply and emission abatement technologies, and includes technology vintages.

The full suite comprises the following models[106]:

- PRIMES-TREMOVE transport model: Because of its importance, PRIMES devotes particular focus on transport and includes very detailed modelling which covers the energy and mobility nexus and also can handle a large variety of policy measures addressing the transport sector. This model projects the evolution of demand for passengers and freight transport. It is essentially a dynamic system of multi-agent choices under several constraints, which are not necessarily binding simultaneously. The model consists of two main modules, the transport demand allocation module and the technology choice and equipment operation module. The two modules interact with each other and are solved simultaneously. When coupled with the rest of the PRIMES energy system model, interaction of the different energy sectors is taken into account in an iterative way. The model was recently enhanced to include linkage to synthetic fuels and hydrogen and to detailed spatial projections of transport activity and route assignment by the forthcoming TRIMODE model. The model can either be used as a stand-alone model or may be coupled with the rest of the PRIMES energy systems model. In the latter case, the integration with the PRIMES model enhances the dynamic character of the model, since the interaction of the different energy sectors is taken into account in an iterative way;
- PRIMES BuiMo residential and services model: new model with high resolution representation of the housing and office building stock embedded in an economic-engineering model of multi-agent choice of building renovation, heating system and equipment/appliances by energy use;
- PRIMES-Industry model: recently enhanced version of the very detailed industrial model that includes a high-resolution split of industrial consumption by sector and type of industrial process and now includes possibility of using hydrogen and synthetic fuels directly, extended possibilities of electrification and the possible emergence of non-fossil hydrocarbon feedstock in the chemicals;
- PRIMES Biomass supply model: detailed biomass supply model that includes land use constraints, many types of biomass and waste feedstock, sustainability regulation and endogenous learning and industrial maturity of a large number of potential biomass to biofuels conversion technologies; recently enhanced in the linkage with the IIASA models that handle LULUCF and forestry, as well as linkage with the agricultural model CAPRI. This model can be either solved as a satellite model through a closed-loop process or as a stand-alone model. It is an economic supply model that computes the optimal use of biomass/waste resources and investment in secondary and final transformation, so as to meet a given demand of final biomass/waste energy products, projected to the future by the rest of the PRIMES model. The biomass supply model determines the consumer prices of the final biomass/waste products used for energy purposes and also the consumption of other energy products in the production, transportation and processing of the biomass/waste products. It can work as a standalone model provided that the demand for bio-energy commodities is given exogenously, but is more often used together with the PRIMES Energy System Model as a closed loop system;
- PRIMES Electricity and Heat/Steam supply and market model: fully new model version which includes the hourly unit commitment model -with pan-European market simulation over the grid constraints and detailed technical operation restrictions, the long-term power system expansion model, the costing and

106 Source: https://e3modelling.com/modelling-tools/primes/

pricing electricity and grid model, the integration of heat supply and industrial steam supply with synchronised hourly operation;
- PRIMES Gas Supply and Market model: a stand-alone model representing in detail the gas infrastructure in the Eurasian and Middle-East area and the internal European market of gas within an oligopoly model embedding engineering gas flow modelling;
- PRIMES new Fuels and storage model covering Hydrogen, Synthetic fuels, Power-to-X, CO2 capture from the air and biogenic, CCS/CCU and process-emissions modelling to enhance and perform sectoral integration aiming at simulating a zero-CO2 system;
- PRIMES IEM model: a simulation tool for the internal energy market; it aims to simulate in detail the sequence of operation of the European electricity markets, namely the day-ahead market, the intraday and balancing markets and finally the reserve and ancillary services market or procurement.

4.6 Data sources

Eurostat is the primary data source. The PRIMES model is calibrated to Eurostat statistics wherever possible. Eurostat data is complemented by other statistical sources as needed.

Here is a breakdown:

- EUROSTAT: Energy balance sheets; energy prices (complemented by other sources, such IEA); macroeconomic and sectoral activity data; population data and projections; physical activity data (complemented by other sources); CHP surveys; CO2 emission factors; and EU ETS registry for allocating emissions between ETS and non-ETS;
- TECHNOLOGY DATABASES: MURE, ICARUS, ODYSEE – demand sectors, VGB (power technology costs), TECHPOL – supply sector technologies, NEMS model database, IPPC BAT Technologies IPTS;
- OTHER DATABASES: District heating surveys, buildings and houses statistics and surveys (various sources), IDEES, BSO, BPIE;
- POWER PLANT INVENTORY: ESAP SA and PLATTS;
- RES POTENTIAL: ECN, DLR and EURObserver;
- NETWORK INFRASTRUCTURE: ENTSOE, ENTSOG, GIE, TEN-T (transport infrastructure).

Data are open and available for reuse, and results are shared and published on a regular basis. But E3-Modelling's full database is not accessible because it includes much proprietary data, the informant explained.

4.7 Typical Inputs and Outputs of PRIMES

Inputs:

- GDP and economic growth per sector (many sectors);
- World energy supply outlook – world prices of fossil fuels;
- Taxes and subsidies;
- Interest rates, risk premiums, etc.;
- Environmental policies and constraints;
- Technical and economic characteristics of future energy technologies;
- Energy consumption habits, parameters about comfort, rational use of energy and savings, energy efficiency potential;
- Parameters of supply curves for primary energy, potential of sites for new plants especially regarding power generation sites, renewables potential per source type, etc.

Outputs:

- Detailed energy balances (EUROSTAT format);
- Detailed demand projections by sector including end-use services, equipment and energy savings;

- Detailed balance for electricity and steam/heat, including generation by power plants, storage and system operation;
- Production of fuels (conventional and new, including biomass feedstock);
- Investment in all sectors, demand and supply, technology developments, vintages;
- Transport activity, modes/means and vehicles;
- Association of energy use and activities;
- Energy costs, prices and investment expenses per sector and overall;
- CO2 Emissions from energy combustion and industrial processes;
- Emissions of atmospheric pollutants;
- Policy Assessment Indicators (e.g. import dependence ratio, RES ratios, CHP ratios, efficiency indices, etc.).

4.8 Tools

E3-Modelling uses three clusters of computers in Athens to run PRIMES. "It is like a small network of high computing-power machines that we use to run PRIMES," The informant said. To run an iteration of the full PRIMES model for the whole EU takes about 10 hours, he said. The software used to code PRIMES is mainly GAMS, a mathematical language used to write and solve optimization problems. "We write 95% of our models in GAMS. PRIMES is entirely in that," The informant said.

4.9 Degree of maturity and implementation phases

The PRIMES model has been continuously extended and updated from its start in the mid-1990s. The model is used regularly by the European Commission and has supported analysis for major energy policy and market issues, including electricity market, gas supply, renewable energy development, energy efficiency in demand sectors and numerous technology specific analyses. PRIMES also has supported national projections for governments, companies and other institutions, including for EURELECTRIC and EUROGAS. Numerous third-party studies have used projections produced using PRIMES; the majority of these studies focused on medium- and long-term restructuring of the EU energy system. The model was successfully peer-reviewed in the framework of the European Commission's work in 1997 and in 2012. The technological and economic parameters of the PRIMES model were reviewed by a broad range of stakeholders within a July 2018 ASSET project study.

4.10 Drivers and challenges

The main driver for the use of the PRIMES model is the need for medium- and long-term energy system projections, in both demand and supply sides, in particular projecting prices influencing the evolution of energy supply and demand, as well as technological progress, that cover the entire energy system including emissions.

Matthias Duwe of the Ecologic Institute and Lola Vallejo of IDDRI in an October 2018 paper on the EU's climate ambitions said: "The PRIMES model currently used by the Commission is frequently criticized for its lack of transparency on modelling inputs and assumptions, which reduces confidence in its results."

But they went on to say that: "This criticism is potentially an expression of a larger concern over the lack of transparency in decision-making on long-term policy. A shared disaggregated structure describing the key indicators of the transition and an engagement process spanning more than a few months are needed to elaborate meaningful dialogue and narratives. This needs to also include additional dimensions (e.g. social and cultural) that are of key interest for stakeholders but often go beyond the capacities of 6 modelling tools," according to the paper.

The European Federation for Transport and Environment, in an August 2018 report, included a lack of transparency among "technical limitations" of the PRIMES model in the transport sector. Among other things, the environmental campaign group urged the European Commission to:

- Improve the transparency of the process and include more active stakeholder involvement;
- Give a stronger focus on the potential of zero-emissions technologies to achieve full decarbonization in the transport sector;

- Include all transport emissions, particularly in the aviation and maritime sectors;
- Better account for the societal cost of greenhouse gas emissions, including an analysis of the impact of non-action.

Eurelectric said in a 2012 report on the Energy Roadmap 2050 that stakeholders needed better access to elements of PRIMES. "Stakeholders are not able to access the country-specific output from the PRIMES model used to develop the different scenarios. Without this national breakdown of information (to allow comparison, for example, with national studies on 2050 pathways) it is difficult to provide detailed comments on the validity of the assumptions and output from the PRIMES 2050 pathway analysis. This national breakdown should be made available to all stakeholders," Eurelectric said. On infrastructure, Eurelectric said "further clarity would be needed to understand how cross-country transmission capacities, as well as national distribution capacities, are considered in the PRIMES approach," according to the paper.

The European Commission undertook a project in 2018 to ensure robustness and representativeness of the technology assumptions in the PRIMES model by reaching out to relevant experts, industry representatives and stakeholders, who are in possession of the most recent data in the different sectors.

The informant said the consultation work on technology assumptions "was quite positively received by the stakeholders and the Commission itself" and likely will become more routine. "I think it's going to become a thing and we will do it quite often from now on," he said. "It's going to be expanded maybe in the future to other domains" and to other assumptions.

The informant said efforts are being made to address other issues as well. "An effort is being made, which started with this consultation on technology costs, to open up parts of the model that we can open, unlike other parts like the proprietary databases," he said. "This is a part of the effort to be more transparent and alleviate such concerns by some stakeholders."

"Another effort is the fact that we now prepare some tools, like the compact version of PRIMES, that we deliver these versions to clients," The informant said. "We develop these tools and they reflect the PRIMES way of thinking and the PRIMES methodology, and we deliver it to clients."

"We hope to intensify this effort in the future," he said." We don't have concrete plans, but I think also the European Commission in their scenarios they want to be more transparent, and I think this is something that will continue in the future."

4.11 Dimension/scalabilty

The PRIMES sub-models (modules) can be used in a stand-alone fashion or can be coupled with the rest of the PRIMES energy systems model. In the latter case, the integration with the PRIMES model enhances the dynamic character of the model, since the interaction of the different energy sectors is taken into account in an iterative way. PRIMES can be used in linked fashion with GEM-E3 and IIASA's GAINS to perform energy-economy-environment policy analysis in a closed loop. The PRIMES model is mostly used at maximum level. PRIMES is designed to represent agent behaviours and their interactions in multiple markets. The model has combined microeconomic foundation with engineering representations aiming at simulating structural changes and long-term transitions. The PRIMES model has served to quantify energy outlook scenarios for DG TREN and DG ENER, impact assessment studies for DG ENV, DG MOVE, DG CLIMA and DG ENER and others, including Energy Roadmap to 2050 and Policies to 2030 on climate. PRIMES also has been used at national level for governments, companies and other institutions.

Theoretically, the supply module could be run separately from the demand module, the informant said. But "because the strong point of PRIMES is the fact that it models the equilibrium of markets," it is more productive to run them together. "It balances the supply and demand of energy through prices," he said.

E3-Modelling has developed a simplified version of PRIMES that does not contain the full set of equations of the full PRIMES. The simplified, or compact, version of PRIMES was developed to be used on a country-by-country basis. When running the model for a stand-alone country, it doesn't have to model the whole network of Europe in order to model only one country. "So the stand-alone model of Turkey excludes the network equations that have to balance the whole network across Europe," the informant said.

4.12 Use in policy making / social and economic output, outcomes and impacts; monitoring system

PRIMES includes a rich representation of policy instruments and measures. Based on long experience with using PRIMES in major policy-analysis and impact-assessment studies of the European Commission, national governments and industrial institutions, detailed mechanisms have been built in the model to represent a large variety of policy measures and regulations. Scenario construction assumptions about the inclusion of policies can be made in close collaboration with the authority getting the modelling service because the modelling detail is high allowing for mirroring policies close to reality.

The model can support policy analysis in the following fields:

- Standard energy policy issues: security of supply, strategy, costs (includes all costs), etc.;
- Environmental issues;
- Pricing policy and taxation, standards on technologies;
- New technologies and renewable sources;
- Energy efficiency in the demand-side;
- Alternative fuels;
- Conversion to decentralisation and electricity-market liberalization;
- Policy issues regarding electricity generation, gas distribution, and new energy forms.

PRIMES is organised by an energy production subsystem for supply consisting of oil products, natural gas, coal, electricity and heat production, biomass supply, and others, and by end-use sectors for demand consisting of residential, commercial, transport, and nine industrial sectors. Some demanders may also be suppliers, as for example industrial co-generators of electricity and steam. PRIMES has been used to create energy outlooks for the EU, to develop a climate-change and renewable-energy policy package for the EU and also, to analyse a number of different policies to reduce GHG. The model also has been used by several EU governments as well as private companies.

The policy instruments classified in groups are as follows.

Targets:

- Targets can be directly included in the model at various levels, by sector, by country, and EU-wide; they may concern emissions, renewables, energy efficiency, security of supply, fossil fuel independence, and others. Performance against targets derives from projection data. The PRIMES reporting facility includes calculation of indicators according to regulations.

Price or cost driving policies:

- Taxation is exogenous and follows the level of detail of regulations, being specific for fuels, sectors and countries. The data draw from the EU taxation directives. Additional information determine values for subsidies and other forms of state supports;
- Cap-and-trade mechanisms and tradable certificate systems, including the Emission Trading Scheme, green and white certificates; the model represents a variety of regimes and regulations, including grandfathering and auctioning with different regulations by sector, and can handle floor and cap prices as well as various assumptions about allowances and their composition. Trade of certificates or allowances can be handled over the EU or by country (or other grouping of countries) and also over time including consideration of influence of foresight and risk-related behaviours;

- Feed-in tariffs and other renewable support schemes: treated in great detail in PRIMES including historical data and projection of consequences over time; inclusion of possible budget constraints and modelling of individual project developments on RES based on project-based financing depending on support schemes totally or partially and the eventual involvement of the RES project in the market;
- Institutional mechanisms and regulations that may induce lower interest rates and lower perception of risks by individual investors; largely applied for modelling energy efficiency policies and other policies addressed to numerous individuals;
- Contract for differences and purchasing agreements backed by the state aiming at securing return on investment;
- Regulations and policies that address market failures and/or enable tapping on positive externalities (e.g. technology progress) which induce reduction of cost elements (technology costs) and improve perception by consumers leading to lower subjective cost components.

Regulations on standards and command-and-control measures -- they are explicit in the model and depending on specification they are showing to eliminate certain technologies or options in the menu in technology choices in various sectors modelled:

- Eco-design standards in detail;
- Best Available Technology regulations
- Emission standards or efficiency standards on vehicles and other transport means;
- Large combustion plant directives;
- Emission performance standards;
- Energy performance standards;
- Reliability and reserve standards (power and gas sectors);
- Policies regarding permitting power plant technologies at national level, for example regarding nuclear, CCS etc., including constraints applicable to new site development or expansion in existing sites. Also, policies regarding possibility of extension of lifetime of power plants (e.g. nuclear) and retrofitting (e.g. to comply with emission regulation).

Infrastructure policies and development plans in various sectors can vary in scenario assumptions and influence possibilities of technology deployment and system costs. Coverage for infrastructure:

- Power interconnectors among countries, including expansion to remote areas for RES development purposes, and different options about management and allocation of capacities
- Power grids and smart systems within countries, which are not spatially represented but only through reduced-form cost-possibility curves in which parameters mirror development plans with influences on future technology development (for RES, highly distributed generation, metering, demand response, etc.);
- Gas transport, LNG, storage and liquefaction infrastructure;
- Refuelling and recharging infrastructure in all transport modes;
- CO2 transport and storage infrastructure;
- Transport infrastructure parameters influence mobility and modal shifts but modelling does not include spatial information (limited to urban, semi-urban and inter-urban);
- Hydrogen transport and distribution infrastructure (reduced form spatial modelling);
- Heat-steam district heating infrastructure (no spatial modelling).

ETS market simulation is explicit in PRIMES. However, the projections based on PRIMES are compatible with the five-year time resolution of the model and the model algorithm only approximates the arbitration of allowances holders over time. Nonetheless, PRIMES can handle multi-target analysis, for example, simultaneously for ETS, non-ETS, RES and energy efficiency, where the aim is to determine optimal distribution of achievements (targets) by sector and by country. PRIMES has successfully provided results for that purpose in the preparation of the 2020 Energy and Climate Policy Package (2007-2008) and recently for the 2030 Policy Analysis (2013).

Detailed reporting and ex-post calculations: to support impact assessment studies PRIMES provides detailed reports of scenario projections. The reports calculate cost indicators (with various levels of detail distinguishing between cost components and sectors), as well as for numerous other policy-relevant indicators. Topics covered include environment, security of supply and externalities (e.g. noise and accidents in transport). Thus, the model provide elements and projections to support cost-benefit analysis studies, which are the essential components of impact assessments. When PRIMES links with the macroeconomic model GEM-E3, the coverage of projection data for the purposes of cost-benefit evaluations is more complete and comprehensive. Similarly, linkages with GAINS (from IIASA) provide wider coverage of cost-benefit projections regarding atmospheric pollution, health effects, etc.

The PRIMES-TREMOVE Transport model includes a large variety of policy measures which can be mirrored in scenarios. Policy targets, for example on future emissions in transport, can be forced in scenario projections. The model can handle multiple targets simultaneously. Market penetration of technologies is not pre-defined but is a result of the model depending on economics and behaviours. Technology learning is explicitly represented and depends on volume of anticipated sales. Market penetration of alternative technologies and fuels in transport heavily depends on successful market coordination of various agents having different aspirations. At least four types of agents are identified: developers of refuelling/recharging infrastructure aiming at economic viability of investment depending on future use of infrastructure; fuel suppliers who invest upstream in fuel production the economics of which depend on market volume; providers of technologies used in vehicles and transport means who need to anticipate future market volume to invest in technology improvement and massive production lines in order to deliver products at lower costs and higher performance; consumers requiring assurance about refuelling/recharging infrastructure with adequate coverage, and low cost fuels and vehicle technologies in order to make choices enabling market penetration of alternative fuel/technologies. The PRIMES model can be used to explicitly analyse the dynamics of market coordination with individual focus on stylised agents allowing for development of complex scenarios, which may assume different degrees of success in effective market coordination. Thus, projections of market penetration of alternative fuels/technologies are fully transparent and include the entire spectrum of interactions between consumer choices, technology learning, infrastructure economics and fuel supply.

PRIMES-TREMOVE transport model is linked with the entire PRIMES energy systems model and the PRIMES-Biomass Supply model. The linkage calculates lifecycle energy and emissions of fuels and energy carriers used for transportation.

The PRIMES model projects the entire energy balances and thus calculates primary energy requirements which correspond to the final energy amounts by fuel consumed in transport. Thus, policy analysis and targets focusing on primary energy or energy imports can be handled. PRIMES also projects greenhouse gas emissions related to energy covering the entire chain of energy transformations. Therefore, it can calculate energy-related lifecycle emissions of transport fuels. Similar lifecycle calculations can be handled for air pollution. More enhanced air pollution calculations can be carried out using PRIMES model suite linked with GAINS model (IIASA).

The PRIMES biomass supply model covers the entire lifecycle of bio-fuels and calculates greenhouse gas and air pollution for the entire chain of transformations, including cultivation, imports, pre-treatment, transport and conversion of biomass feedstock into biofuels. So, calculations of sustainability indices can be performed for all types of fuels used in transport, including mineral oil and bio-fuels (of various types and based on feedstock of various technology generations). The entire PRIMES model suite is able to perform calculations of energy requirements and emissions and also to handle policy targets, standards or taxation associated to such lifecycle indices.

The PRIMES suite is also designed to simulate emission trading markets (e.g. ETS) which can include parts or the entire transport sector. Actually, aviation is included in the EU ETS; effects from that inclusion on costs, prices and efficiency improvement are fully captured in the model and obviously depend on ETS carbon prices.

4.13 What PRIMES cannot do

PRIMES gives scenario projections not forecasts. PRIMES is not an econometric model. It cannot perform closed-loop energy-economy equilibrium analysis, unless linked with a macroeconomic model such as GEM-E3. PRIMES has more limited resolution than engineering electricity, refinery and gas models dedicated to simulating system operation in detail. Although rich in sectoral disaggregation, PRIMES is limited by the concept of representative consumer per sector, not fully capturing differences due to heterogeneity of consumer types and sizes. PRIMES lacks spatial information and representation (at a level below that of countries) and so it does not fully capture issues about retail infrastructure for fuels and electricity distribution, except for electricity and gas flows over a country-to-country based grid infrastructure, which is well represented in the model. PRIMES is an empirical numerical model with emphasis on sectoral and country specific detail; it has a very large size and so some compromises were necessary to limit computer time at reasonable levels. PRIMES differs from overall optimization energy models, qualified by some as bottom-up approaches, for example MARKAL, TIMES, EFOM. Such models formulate a single, overall mathematical programming problem, do not include explicit energy price formation and have no or simple aggregate representation of energy demand as well as energy supply. PRIMES formulates separate objective functions per energy agent, simulates in detail the formation of energy prices and represents in detail energy demand, as well as energy supply. PRIMES differ from econometric-type energy models, such as POLES, MIDAS and the IEA's World Energy Model. These models use reduced-form equations that relate in a direct way explanatory variables (such as prices, GDP etc.) on energy demand and supply. These models have weak representations of useful energy demand formation. They are usually poor in representing in detail capital vintages and technology deployment in energy supply sectors and lack engineering evidence, as for example the operation of interconnected grids and detailed dispatching.

4.14 Conclusions

There are several lessons learnt extrapolated from the model.

Transparency:

- E3M undertakes a `total revamp of all the assumptions' in PRIMES with European Commission every 4-5 years;
- E3M has opened technology assumptions to broader public.

Stakeholder access:

- E3M has started regular consultations with stakeholders on various issues, including a `validation workshop' in 2018 on technology costs;
- Plan is to have consultations and workshops regularly.

Emissions:

- E3M added negative-emissions technologies to PRIMES in order to model for 'climate neutral' to support the analysis in the European Commission's Clean Planet for All Europeans.

Takeout for the European Commission

- Stakeholder involvement and buy-in are key to successful strategy. Transparency of process and flexibility in development are essential.

4.15 APPENDIX - Sources

- https://e3modelling.com/modelling-tools/primes/
- https://e3modelling.com/wp-content/uploads/2018/10/The-PRIMES-MODEL-2018.pdf
- https://ec.europa.eu/energy/en/studies/review-technology-assumptions-decarbonisation-scenarios

- https://www.transportenvironment.org/sites/te/files/2018_07_2050_model_paper_final.pdf
- https://ec.europa.eu/clima/policies/strategies/analysis/models_en
- https://www.eurelectric.org/media/1698/roadmap_2050_response_paper_final-2012-100-0003-01-e.pdf
- Think 2050, Act 2020: Bringing European ambition and policies in line with the Paris Agreement. By: Matthias Duwe (Ecologic Institute) and Lola Vallejo (IDDRI)
- https://ieep.eu/uploads/articles/attachments/7fe71a36-8480-4e6a-aa12-83d217782b1b/Think%202030%20Bringing%20European%20ambition%20and%20policies%20in%20line%20with%20the%20Paris%20Agreement.pdf?v=63730596552
- https://www.euroheat.org/wp-content/uploads/2016/04/Heat-Roadmap-Europe-I-2012.pdf
- https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

5 Case Study: GAINS - Greenhouse gas - Air pollution Interactions and Synergies

5.1 Introduction

The **International Institute for Applied Systems Analysis** (**IIASA**) funds several research programs. One of these is the **Air Quality and Greenhouse Gases** (**AIR**). AIR's system aim is to develop new policies, in order to maximise co-benefits between climate and air quality strategies, and development, economic and social policy objectives. The maximisation of these potential co-benefits poses a host of complex challenges to decision-makers. AIR supports those developing innovative methodologies, which collect relevant insights from researches on geophysical, economic and social aspects of pollution control. In particular, these researches mainly concern: a global perspective on air pollution; air quality-climate interactions; mitigation options for non-CO2 greenhouse gases; the nitrogen cycle; local pollution management with global benefits.

These research topics are addressed through specific projects, usually in close collaboration with partners, which are part of a large international and multi-disciplinary scientific network. AIR projects provide tools that explore cost-effective emission control strategies in several global countries, policy reports, key findings that are relevant for decision-makers, scientific publications and access to global databases on emissions and air pollution.

To support AIR program, IIASA developed **The Greenhouse gas Air pollution Interactions and Synergies** (**GAINS**) model. GAINS provides an authoritative framework for assessing strategies that reduce emissions of multiple air pollutants and greenhouse gases, minimising costs and their negative effects on human health, ecosystems and climate change. In particular, it collects together information on **future economic, energy and agricultural development, potential reduction of emissions and its costs, atmospheric dispersion and environmental sensitivities towards air pollution**.

5.2 Rationale

GAINS was launched in 2006 as an extension to the **Regional Air Pollution Information and Simulation** (**RAINS**) model. The RAINS model has been developed by IIASA as a tool for the integrated assessment of alternative strategies to reduce acid deposition in Europe and Asia. GAINS is an extension of the RAINS model that includes major greenhouse gases (e.g. CO_2, CH_4, N_2O and the F-gases). This allows to simultaneously analyse the effects of mitigation of greenhouse gases emissions and air pollution. In this way, the most important interactions and synergies between the mitigation of climate-relevant gases and air pollution can be studied. Non-CO_2 greenhouse gases (GHGs) in the GAINS model include methane (CH), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), which are all addressed in the Kyoto protocol[107]. GAINS model has been used on several occasions to estimate current and future emissions of non-CO_2 GHGs in the European Union in support of the EU climate strategy. The Baseline emissions of greenhouse gases in the EU and policy scenarios for mitigation are estimated by the **PRIMES, CAPRI, GAINS** and **GLOBIOM** models. All models use economic forecasts from the European Commission (DG-ECFIN) as a starting point for model scenarios. While CO_2 emissions are modelled within the PRIMES energy systems model, emissions of non-CO_2 GHGs and air pollutants consistent with the estimated CO_2 emissions, are modelled using the GAINS model. The consistency between the models is maintained in GAINS, through the use of energy activity, for instance, fuel production and consumption from the PRIMES model, and agricultural activity data as the livestock numbers and fertiliser application from the CAPRI model. **The GAINS model and its predecessor, the RAINS model, assist key policy negotiations on improving air quality in Europe.** In particular, these include:

[107] Kyoto protocol; https://unfccc.int/resource/docs/convkp/kpeng.pdf

1. **Under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution:**
    - the Second Sulfur Protocol in 1994[108];
    - the Gothenburg Multi-pollutant/multi-effect Protocol of the UNECE Convention on long-range Transboundary Air Pollution in 1999[109];
    - the review[110] (2008) and revision[111] of the Gothenburg protocol (2012).
2. **For the European Union:**
    - the Acidification Strategy of the European Union in 1995[112];
    - the National Emission Ceilings Directive of the European Union in 2001[113];
    - the Clean Air for Europe (CAFE) program developing the EU Thematic Strategy on air Pollution in 2005[114];
    - the revision of the National Emission Ceilings Directive (2006-2009)[115];
    - the Climate and Energy Package (2008-2009)[116];
    - the Communication of the European Commission on Options to move beyond 20% greenhouse gas emission reductions (2010)[117];
    - the EU Roadmap for moving to a low-carbon economy in 2050 (2011)[118];
    - the review of EU air quality legislation (2011 - 2015)[119];
    - the EU Climate and Energy Strategy for 2030[120].
    - The GAINS model has also been implemented in China and in India, where air quality is a really serious problem that must be faced

5.3 Main actors and stakeholders

The main actor is the **International Institute for Applied Systems Analysis** (**IIASA**). The IIASA is a scientific research institute, founded in 1972. IIASA conducts policy-oriented research into problems of a global nature that are too large or too complex to be solved by a single country or academic discipline. It is sponsored by its National Member Organisations in Africa, the Americas, Asia, and Europe, and it is governed by a Council, composed by one representative of each member country. GAINS model was developed by IIASA and lunched in 2006.

GAINS is actually implemented in Europe, including **43 European countries** and part of Russia, and in Asia, including **31 provinces in China** and **15 states in India**.

108 Protocol on further reduction of sulphur emissions: http://www.unece.org/env/lrtap/fsulf_h1.html
109 Protocol to abate acidification, eutrophication and ground-level ozone; https://www.unece.org/env/lrtap/multi_h1.html
110 Review of the gothenburg protocol; https://www.emep.int/publ/other/TFIAM_ReviewGothenburgProtocol.pdf
111Revision of the gothenburg protocol; https://iiasa.ac.at/web/home/research/researchPrograms/air/policy/Gothenburg-revised_2012.en.html
112 The acidification strategy of the european union; https://ec.europa.eu/commission/presscorner/detail/en/IP_97_205
113 The national emission ceilings directive of the European union in 2001; https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:309:0022:0030:EN:PDF
114 The clean air for Europe program (CAFE); https://iiasa.ac.at/web/home/research/researchPrograms/air/policy/CAFE---Clean-Air-For-Europe.en.html
115 The revision of the national emission ceilings directive; https://www.eea.europa.eu/themes/air/air-pollution-sources-1/national-emission-ceilings
116 The climate and energy package; https://ec.europa.eu/clima/policies/strategies/2020_en
117 The communication of the European Commission on options to move beyond 20% greenhouse gas emission reductions; https://ec.europa.eu/clima/news/articles/news_2012013002_en
118 The EU roadmap for moving to a low-carbon economy in 2050; https://ec.europa.eu/clima/sites/clima/files/2050_roadmap_en.pdf
119 The review of eu air quality legislation; https://ec.europa.eu/environment/air/clean_air/review.htm
120 The EU climate and energy strategy for 2030; https://www.consilium.europa.eu/en/policies/climate-change/2030-climate-and-energy-framework/

GAINS is used for policy analyses by **United Nations Economic Commission for Europe** (**UNECE**) under the **Convention on Long-range Transboundary Air Pollution** (**CLRTAP**)[121], for instance, it has been used for the revision of the **Gothenburg Protocol**[122]. GAINS has also been used by the **European Union** for the **EU Thematic Strategy on Air Pollution and the air policy**[123] review.

Scientists in many nations use GAINS as a tool to assess emission reduction potentials in their regions. For the negotiations under the **United Nations Framework Convention on Climate Change** (**UNFCCC**[124]), a special version of GAINS has been developed to compare greenhouse gas mitigation efforts among the involved countries.

5.4 Historical development of the model

The GAINS model, as already mentioned, represents an extension of the **RAINS model**, developed by IIASA in the late **1980s**. It combines information on expected trends in anthropogenic activities causing transboundary air pollution with data on the options available for reducing emissions from these activities and their costs. After calculating how air pollutants are transported over Europe and how they influence air quality, RAINS estimates the impacts on human health and ecosystems. These expected impacts can then be compared with environmental targets, highlighting areas where the assumed measures fail to meet the environmental policy objectives. A unique feature of RAINS is its ability to investigate the optimal distribution of further reduction efforts across the whole of Europe (from Norway to Italy and from Spain to the Urals) to meet air quality objectives. For this, the current RAINS model balances controls for SO_2 , NO_x , NH_3, VOC and particulate (PM) emissions to reduce impacts on human health, acidification and eutrophication.

The **GAINS model**, first launched in **2006**, addresses emission control strategies that simultaneously address air pollutants and greenhouse gases in order to maximise benefits at all scales. GAINS is an extension of the RAINS model that includes major greenhouse gases, as CO_2, CH_4, N_2O and the F-gases. GAINS estimates historical emissions of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics, emission inventories and on data supplied by countries themselves. It assesses emissions on a medium-term time horizon, with projections specified in five-year intervals through the year 2050.

5.5 Data sources

The GAINS model holds relevant data for European and no European countries, employing international energy and agricultural statistics and appropriate emission factors.

GAINS **energy database** includes three major components of the energy system:

1. Electricity and district heat generation in the power and district heating sector (PP);
2. energy use for primary fuel production, conversion of primary to secondary energy other than conversion to electricity and heat in the power and district heating plants, and for delivery of energy to final consumers (CON);
3. final energy use in industry (IN), domestic sector (DOM), transport (TRA), and non-energy use of fuels (NONEN). The domestic sector covers residential and commercial sector, as well as agriculture, forestry, fishing and services.

Historical data have been **extracted from energy statistics**. GAINS contains alternative pathways of energy use up to 2050 derived from national and international energy projections (e.g., scenarios developed for Europe by the PRIMES model,

[121] UNECE Convention on Long-range Transboundary Air Pollution; http://www.unece.org/fileadmin//DAM/env/lrtap/full%20text/1979.CLRTAP.e.pdf

[122] Gothenburg protocol, https://www.unece.org/environmental-policy/conventions/envlrtapwelcome/guidance-documents/gothenburg-protocol.html

[123] EU Thematic Strategy on Air Pollution; https://eur-lex.europa.eu/legal-content/EN/ALL/;ELX_SESSIONID=RRCpJ2dLQ9Q2mVqDdlWHl9DLp4Ln7Zd8LkdpL15wdxxvkGkFpkZH%21405769600?uri=CELEX:52005DC0446

[124] UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC); https://unfccc.int/

projections of the International Energy Agency, scenarios based on national studies). While these data are stored in the GAINS database, they are exogenous input to GAINS. Format of energy data in GAINS is convenient for calculating emissions of air pollutants and greenhouse gases. Energy tables show fuels that are actually used in combustion processes in various economic sectors. Fuel production figures, like coal mining or oil and gas extraction, are reported in the process data tables only if they are relevant for emissions calculations.

Total energy consumption in a given country can be derived by summing up the fuel used in the **conversion sector** (CON), **power sector** (PP) and **final demand sectors** (e.g., IN, DOM, TRA, and NONEN). Although this total is a sum of primary and secondary energy, it is equal to the total primary energy demand at a country level. Conversion of fuel consumption from natural units (tons, m3) should be made using net (or lower) calorific value of fuels.

In detail, the GAINS database includes data from the following sectors:

1. Aggregation of energy carriers

GAINS includes a rather detailed specification of energy carriers. This is because mission factors for air pollutants and greenhouse gases heavily depend on the type and quality of fuel used. Consumption of fuel in a given economic sector determines the level of energy-related activity used in emissions calculations.

For brown coal/lignite and hard coal, different grades are distinguished. In this way, differences in fuel quality (calorific value, sulphur and ash content, sulphur retention in ash) can be taken into account. It is up to the user to decide how many grades of coal need to be distinguished. In addition, biomass and waste fuels are sub-divided into more detailed categories to include differences in emission factors. Again, detailed disaggregation of biomass fuels is country-specific. Some fuels (e.g., dung) are very important in Southeast Asia but are not in use in Europe. In order to consider the effects of switching to clean energy sources, GAINS also stores information on energy carriers that do not emit air pollutants (e.g., electricity, heat, renewables other than biomass).

2. Power plant sector (PP)

Power and district heating plants (PP_TOTAL) are the overarching sector that is subdivided into existing plants with wet bottom boilers (PP_EX_WB), other existing plants (PP_EX_OTH), IGCC plants (PP_IGCC), and other new plants (PP_NEW). Industrial power and CHP plants, as well as public district heating plants, are included.

The power plant sector covers fuel inputs to- and gross electricity and heat output from power and district heating plants. It contains public power and district heating plants, power plants of auto producers, as well as public and industrial combined heat and power (CHP) plants.

3. Energy production and conversion/transformation sector (CON)

The definition of the "conversion sector" (CON) in GAINS follows the "energy transformation sector" as defined in the energy balances of the International Energy Agency[125]. However, fuel input to- and (gross) electricity and heat output from the power and district heating plants is reported in the power sector. CON sector includes on-site consumption of fuel and energy in coal mines, refineries, coke and briquette plants, gasification plants etc. It also includes own use of electricity and heat in the power and district heating sector, as well as transmission and distribution losses for electricity, heat, and gas. Sector CON is further divided into fuel used in combustion processes (CON_COMB) and own use and losses that occur without combustion (CON_LOSS). This distinction is necessary to account for different emission factors in combustion and non-combustion part.

[125] International Energy Agency; https://www.iea.org/

GAINS treats fuel combustion separately in boilers and in furnaces. This is because operating conditions, emission factors, and emission control technologies for these two types of combustors are different.

Sector CON_COMB covers fuel combustion in furnaces used in the energy sector. Examples are combustion in crude oil distillation furnaces and catalytic cracking installations in oil refineries, or coking gas use for heating coke batteries in coke plants. Fuel combusted in heat only boilers (in oil refineries, coke plants, coalmines, coal gasification plants etc.) should be reported in the sector called "Combustion in industrial boilers" (IN_BO)5. If it is not possible to distinguish between combustion in boilers and combustion in furnaces, please report all fuel combustion in energy industries belonging to the CON sector under CON_COMB.

4. Industry

Energy consumption in industry is divided into the combustion in (heat only) boilers (IN_BO), other industrial combustion (IN_OCTOT), and non-energy use (NONEN). Boiler fuel consumption is divided into consumption in the conversion sector (IN_CON_BO), chemical industry (IN_CHEM_BO), pulp and paper industry (IN_PAP_BO) and in other industries (IN_OTH_BO). If detailed split by subsectors is not known for a given energy pathway, total boiler fuel consumption should be reported under "IN_OTH_BO".

Others industrial combustion (IN_OC_TOT) are divided into iron and steel (IN_ISTE_OC), chemical (IN_CHEM_OC), non-ferrous metals (IN_NFME_OC), non-metallic minerals (IN_NMMI_OC), paper, pulp, and printing (IN_PAP_OC) and other manufacturing industries (IN_OTH_OC). If detailed split by sub-sectors is not known for a given energy pathway, total fuel consumption should be reported under "IN_OTH_OC". Fuel use in the energy sector's CHP plants needs to be reported in the power plant (PP) sector. In case a division of fuel consumption between boilers and other combustion is not known, total fuel consumption can be reported under "other industrial combustion".

For "other industrial combustion", GAINS calculates emissions based on activity data reported under "IN_OC". This column is internally calculated by the GAINS model during data initialization by subtracting energy use reported for cement and lime production from the total energy use in industry (IN_OCTOT). Thereby, the model takes into account the high retention of the sulphur during cement and lime production and calculates emissions from these activities under "industrial process emissions". These measures are taken to avoid double counting of emission.

5. Domestic sector

Domestic sector in GAINS (DOM) includes the following sub-sectors:

- residential (DOM_RES);
- commercial and public services (DOM_COM);
- other services, agriculture, forestry, fishing, and non-specified sub-sectors (DOM_OTH).

Fuel consumption by mobile sources in agriculture and fishing should be included in the transport sector energy demand. Since energy statistics incorporate these categories in the domestic (DOM) sector, appropriate corrections to statistical data need to be made.

If the detailed split of domestic energy consumption is not known, total sector consumption can be reported under DOM_OTH.

6. Transport and other mobile sources

Transport and other mobile source sectors (TRA) are divided into transportation by road (TRA_RD), other non-road mobile sources (TRA_OT), and sources from the so-called national sea traffic (TRA_OTS). The latter includes seagoing ships and fishing boats operating between the ports in the same country. Each of the major sectors is additionally divided into more detailed vehicle categories.

5.6 Models

GAINS model addresses health and ecosystem impacts of particulate pollution, acidification, eutrophication of ecosystems, and impacts of tropospheric ozone. Simultaneously, GAINS assesses the effects of various scenarios on greenhouse gases mitigation and the resulting co-benefits for air pollution. Historical emissions of air pollutants and GHGs are estimated for each country based on international emission inventories and statistics as well as on inputs from collaborating national expert teams. Emissions are assessed on a medium-term time horizon up to the year 2050 with five-year intervals. Options and costs for controlling emissions are represented by several emission reduction technologies. Atmospheric dispersion processes are often modelled exogenously and integrated into the **GAINS Model framework**. Critical load data and critical level data are often compiled exogenously and incorporated into the GAINS modelling framework. The model can be operated in the **scenario analysis mode**, for instance, following the pathways of the emissions from their sources to their impacts. In this case, the model provides estimates of regional costs and environmental benefits of alternative emission control strategies. The model can also operate in the **optimisation mode,** which identifies where emissions can be reduced most cost-effectively. In this case, the model identifies a balance of concrete measures for different pollutants, sectors, and countries/regions that achieve air quality and greenhouse gas reduction targets at least cost, considering the contributions of different pollutants to different air quality and climate problems. The current version of the model can be used for viewing activity levels and emission control strategies, as well as calculating emissions and control costs for those strategies. All results are immediately calculated, to ensure that the most recent data set is used at all times. The Gains web interface enables users to display and download all the input data and the scenario results.

GAINS model considers about 3500 measures for reducing emissions of SO_2, NOx, VOC, NH_3, PM, CH_4, N_2O and F-gases, as well as 350 options to reduce CO_2 through structural changes. In order to assess emission control costs accurately, it is important to identify the factors leading to variations in costs between countries, economic sectors and pollutants. Diversity is caused by differences in the structural composition of existing emission sources (e.g., fuel use pattern, fleet composition, etc.), the state of technological development, and the extent to which emission control measures are already applied. Assuming no trade barriers in the market for emission control technologies, the same technology is assumed available to all countries at the same investment costs. However, country and sector specific circumstances (e.g., size distributions of plants, plant utilisation, fuel quality, energy and labour costs, etc.) lead to justifiable differences in the actual costs at which a given technology removes pollution at different sources.

For the **estimation of the pollutants**, GAINS has made use of following variables:

- the activity (e.g., number of animals, amounts of fuel or waste);
- the emission factor for the fraction of the activity subject to control by technology;
- the application rate of technology to the activity;
- the no control emission factor for the activity;
- the removal efficiency of technology when applied to the activity.

For each of the 3500 emission control options, GAINS estimates the **costs of local application** considering:

- annualised investments,
- fixed and variable operating costs,
- how the investments and costs depend on technology, country and activity type.

Mitigation costs per unit of activity are calculated in GAINS as the sum of investment costs, labour costs, fuel costs (or cost-savings), and operation and maintenance costs (or cost-savings) unrelated to labour and fuel costs.

5.7 Tools

The GAINS model is implemented as an **interactive web-based software tool** that communicates with an **ORACLE database**[126]. The **GAINS portal**[127] provides access to the on-line implementations of the GAINS model for various groups of countries and parts of the world. The latest browsers installed with **JAVA software** it is recommended. GAINS model is accessible through any **web browser software** (**Mozilla Firefox**, **Opera**, **Microsoft Internet Explorer**), and access is free. The **web interface** of the GAINS model can be accessed from the home page of the **IIASA APD**[128]. The web interface provides interactive access to input data, emission projections and costs implications of alternative emission control scenarios, as well as to the environmental impacts these imply. The current version allows access to emission projections and control costs for air pollutants (SO_2, NOX, VOC, PM, NH_3), emission inventories and emission projections for greenhouse gases (CO_2, CH_4, N_2O and the F-gases), forecasts of underlying activity data, lists of control measures and their costs, display of air quality indicators (ambient concentrations and deposition of air pollutants), computation and display of indicators that assess the impact of air pollution on human health and natural environment and data management.

5.8 Degree of maturity and implementation phases

IIASA has been a pioneer in developing the methodology and tools necessary for assessing atmospheric pollution and the decision support analysis techniques for reducing and controlling it. In the late 1980s, IIASA developed the **Regional Air pollution Information and Simulation** (**RAINS**) model. RAINS is an air pollution emission and impact model that helps in analysis of policy implications of controlling emissions of major air pollutants (SO_2, NOX, VOC, PM, NH_3) at the national and international scales. With some extensions, the multi-pollutant/multi-effect approach of the RAINS model became a useful tool for addressing the positive and negative interactions between climate change and classical air pollution. One of these extensions is the **GAINS** model, first launched in 2006. The GAINS model addresses emission control strategies that simultaneously address air pollutants and greenhouse gases in order to maximise benefits at all scales. It includes major greenhouse gases, like CO_2, CH_4, N_2O and the F-gases. GAINS estimates historical emissions of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics, emission inventories and data supplied by countries themselves. It assesses emissions on a medium-term time horizon, with projections specified in five-year intervals through the year 2050.

Actually, the GAINS model is used successfully as a policy support tool in **Europe** and **Asia**, and aims to support informed decision making that maximises synergy between different measures. The model could also extend to **South Africa**. Indeed, the implementation of the GAINS model would assist South Africa in the development of GHG and air quality polices and would be in line with the overall national development goals. To date, several studies have completed integrated assessments of future air pollution and climate policies in South Africa using GAINS.

5.9 Drivers and challenges

Current and future economic growth will cause serious **air quality problems**, negatively impacting human health and crop production, unless further air pollution control policies are implemented. Increasing levels of greenhouse gases in the atmosphere are causing the planet to warm. **Global warming** is a major component of climate change. It is causing floods and droughts, affecting food supplies and water quality and availability. Infectious disease and insect-borne diseases are also likely to increase, while higher temperatures can also worsen **air pollution**. Much of this air

[126] Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications; https://www.sciencedirect.com/science/article/pii/S1364815211001733

[127] GAINS portal; https://gains.iiasa.ac.at/index.php/home-page/241-on-line-access-to-gains

[128] IIASA APD; http://gains.iiasa.ac.at/index.php/home-page/241-on-line- access-to-gains

pollution is caused by the burning of fossil fuels (primarily coal and oil) to produce energy for homes, industry and transport. The burning of fossil fuels accounts for about 60 per cent of all greenhouse gas emissions, while agriculture, food production and industry account for about 30 per cent of emissions.

Clean air and climate change are key areas of concern for global policy makers, and many countries have set targets for reducing their greenhouse gas emissions. The GAINS model was developed with the intention of facing great challenges, like global warming, reducing air pollution, at the minimum cost.

The GAINS model offers **three ways to assess policy interventions** with multiple benefits:

1. simulation of the costs, health and ecosystem benefits of user-defined packages of emission control measures;
2. cost-effectiveness analysis to identify least-cost packages of measures that achieve user-defined policy targets;
3. cost-benefit assessments that maximise (monetised) net benefits of policy interventions.

Indeed, GAINS provides an authoritative framework for assessing strategies that reduce emissions of multiple air pollutants and greenhouse gases at least costs and minimise their negative effects on human health, ecosystems and climate change.

5.10 Social and economic outcomes

There are a series of key benefits related to the Gain model. In particular, the model can explore cost-effective strategies to reduce emissions of air pollutants to meet specified environmental targets. It also assesses how specific control measures simultaneously influence different pollutants, permitting a combined analysis of air pollution and climate change mitigation strategies, which can reveal important synergies and trade-offs between these policy areas.The GAINS methodology identifies cost-effective portfolios of specific measures that improve local air quality and, at the same time, reduce global climate change. This focus on actions that yield co-benefits at different spatial and temporal scales, provides a fresh perspective to clean air and climate policy development in many countries and world regions. In particular, IIASA is contributing to the following policy processes:

- **European Union Air Quality and Climate policies:** In 1995, the European Union adopted an integrated approach for developing its air quality and climate policy legislation, following the multi-pollutant/multi-effect concept of IIASA's RAINS and GAINS models. Since then, the European Commission derives their quantitative proposals for air and climate policies from cost-effectiveness analyses with IIASA's GAINS and RAINS models that balance emission reduction measures across different pollutants, economic sectors and the Member States.
- **Convention on Long-range Transboundary Air Pollution (LRTAP):** Since the 1980s, methodologies and modelling tools developed by IIASA have been applied as the analytical backbone for the negotiations on a series of protocols under the **LRTAP Convention**. The GAINS model and its predecessor, the RAINS model, provided the negotiators with an integrated perspective of the scientific knowledge that emerged from the scientific working groups and task-forces of the LRTAP Convention.
- **Climate and Clean Air Coalition (CCAC):** In collaboration with **UNEP** (**United Nations Environment Programme**) and **WMO** (**World Meteorological Organisation**), IIASA identified 16 practical measures that would improve human health, secure crop yields and, at the same time, reduce global temperature increase in the near-term by up to 0.5 °C. To initiate a concrete action on these measures, US State Secretary Hillary Clinton launched a "**Climate and Clean Air Coalition to Reduce Short-Lived Climate**

Pollutants" in February 2012. By 2018 the Coalition was joined by more than 60 countries and 60 non-state partners.

- **Arctic Council:** The Arctic Council, a high-level intergovernmental forum to promote cooperation, coordination and interaction among the Arctic States, addresses inter alia critical issues of the Arctic environment and climate change. IIASA is regularly participating in scientific working groups and task forces of the Arctic Council and contributing to their reports.
- **Pollution Management and Environmental Health (PMEH) in Developing Countries:** With the Pollution Management and Environmental Health program of the World Bank, IIASA develops practical tools for air quality management planning in large urban areas in developing countries.
- **UN Convention on Climate Change (UNFCCC):** In the 2009 run-up for the **COP15 Copenhagen Climate conference**, IIASA developed an interactive tool for an impartial scientific assessment of efforts that are implied by various negotiation offers of Parties. While actual negotiations did not reach a state where the comparability of mitigation efforts would become a critical issue, IIASA continued contributing to UNEP (United Nations Environment Programme) analyses of the emission gaps between pledges offered by Parties and the requirements for temperature stabilisation.

In addition, the GAINS model helps identify measures to mitigate local air pollution and thus, global climate change. For instance, worldwide implementation of 17 emission reduction measures targeting black carbon and ozone precursors could reduce future global warming by 0.5°C and could avoid the loss of 1–4% of the global production of maize, rice, soybean and wheat each year.

According to estimations made in the course of the **GAINS-Asia** assessment, application of advanced emission control technologies could reduce health impacts in China by 43% in 2030. GAINS in optimisation mode was also able to identify the most cost-effective portfolio of measures to achieve these health improvements, but at 20% of the costs.

In addition, GAINS would assist **South Africa**, that reports approximately 20,000 premature deaths due to air pollution annually, in the development of GHG and air quality policies.

5.11 Scalability, replicability and transferability considerations

Currently, the GAINS model is implemented at a **global level**, in 165 regions, including 48 European countries and 46 provinces/states in China and India.

The model can be adapted to a **bigger number of countries**. In particular, the GAINS model would be probably used soon in **South Africa**, to face the big challenge of premature deaths due to air pollution.

5.12 Conclusions

The take outs from the model are the following:

- **Synergies and trade-off of mitigation strategies:** many traditional air pollutants and greenhouse gases have common sources. Their emissions also interact in the atmosphere, causing a variety of harmful environmental effects at the local, regional, and global scales. Assessing how specific control measures simultaneously influence different pollutants permits a combined analysis of air pollution and climate change mitigation strategies, which can **reveal important synergies and trade-offs** between these strategies;
- **Reduction of emissions of multiple air pollutants and greenhouse at the minimum cost:** GAINS provides an efficient framework for assessing strategies, which reduce emissions of multiple air pollutants and greenhouse gases at the minimum cost, and, as much as possible, their negative effects on human health, ecosystems and climate change. The model simulates the costs of possible policy interventions, defining the health and ecosystem benefits of

these. This model enables a cost-effectiveness analysis to identify the best least-cost packages of measure that achieve user-defined policy targets;

- **Measures to mitigate local air pollution:** GAINS helps **identify measures to mitigate local air pollution and thus global climate change**. For instance, world-wide implementation of 17 emission reduction measures targeting black carbon and ozone precursors could reduce future global warming by 0.5°C and could avoid the loss of 1–4% of the global production of maize, rice, soybean and wheat each year. According to estimations made in the course of the GAINS-Asia assessment, application of advanced emission control technologies could reduce health impacts in China by 43% in 2030. GAINS in optimization mode was also able to identify the most cost-effective portfolio of measures to achieve these health improvements, but at 20% of the costs;

- **Framework to cover all sectors:** moreover, the GAINS model can be used in conjunction with the energy model **MESSAGE**, the land-use model **GLOBIOM**, the air pollution and GHG model **GAINS**, the aggregated macro-economic model **MACRO** and the simple climate model **MAGICC**, creating a framework that covers all major sectors, including agriculture, forestry, energy, and industrial sources, permitting a concurrent assessment of how to address major sustainability challenges**.**

5.13 APPENDIX - Sources

- The GAINS Model (feb, 2012): https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/gains_en.pdf;
- IIASA Science for global insight – Gains online: Tutorial for advanced users (oct, 2009): https://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS-tutorial.pdf;
- International Institute for Applied Systems Analysis (IIASA) website: https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html;
- Carmen Klausbruckner et al. - Energy Policy, Air Quality, and Climate Mitigation in South Africa: The Case for Integrated Assessment (apr, 2018): https://www.researchgate.net/publication/324366196_Energy_Policy_Air_Quality_and_Climate_Mitigation_in_South_Africa_The_Case_for_Integrated_Assessment.

6 CASE STUDY: MESSAGE - MODEL FOR ENERGY SUPPLY STRATEGY ALTERNATIVES AND THEIR GENERAL ENVIRONMENTAL IMPACT

6.1 Introduction

Energy services are a fundamental human need and are thus indispensable for human well-being. Indeed, inadequate access to safe, clean and affordable energy is closely linked to a range of social concerns, including reduced economic and social opportunities contributing to poverty, poor health, and reduced educational attainment.

The provision of adequate energy services is a precondition for socio-economic development and human well-being, but presenting energy systems faces a number of major challenges, which need to be addressed urgently and simultaneously. These range from the lack of access to of the impoverished parts of the population to environmental problems of climate change and air pollution as well as concerns with respect to security and resilience of present systems. The design of effective and appropriate policies to address these major energy challenges requires a deep understanding of the pathways along which new energy systems can emerge and develop over time.

The **International Institute for Applied System Analysis** (**IIASA**) developed an **Energy Program** (**ENE**)[129] to better understand the nature of alternative future energy transitions, their implications for human well-being and the environment and how they might be shaped and directed by current and future decision-makers. ENE Program is a pioneer in the application of new methodologies in the areas of integrated assessment, spatial and behavioural heterogeneity, multi-criteria analysis, energy technology assessments, and uncertainty and risk analysis. These methodologies are used in systematic and holistic scenario studies to assess the costs and benefits of energy transformation. ENE's research activities combine solution-oriented and policy-relevant research with exploratory and empirical analysis. The main areas of research include integrated assessment and energy transformation pathways, environmental impacts of the energy system, energy access and poverty and energy security analysis.

Since its beginnings, IIASA's Energy Program ENE developed several energy analytics tools, including the **Model for Energy Supply Strategy Alternatives and their General Environmental Impact** (**MESSAGE**). This model has been developed since the 1980s, and it stands at the core of ENE's modelling framework. It provides a flexible framework for the comprehensive assessment of major energy challenges and has been applied extensively for the development of energy scenarios and the identification of socio-economic and technological response strategies to these challenges.

Scenario analysis with MESSAGE is used in two major areas:

1. the description of future uncertainties;
2. the development of robust technology strategies and related investment portfolios to meet a range of user-specified policy objectives.

Typical scenario outputs provide information on the utilisation of domestic resources, energy imports, and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions (traditional indoor and outdoor air pollutants as well as greenhouse gases), and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. MESSAGE is also increasingly used for detailed analysis of energy demand issue, such as for policy analysis of energy access in the residential sector.

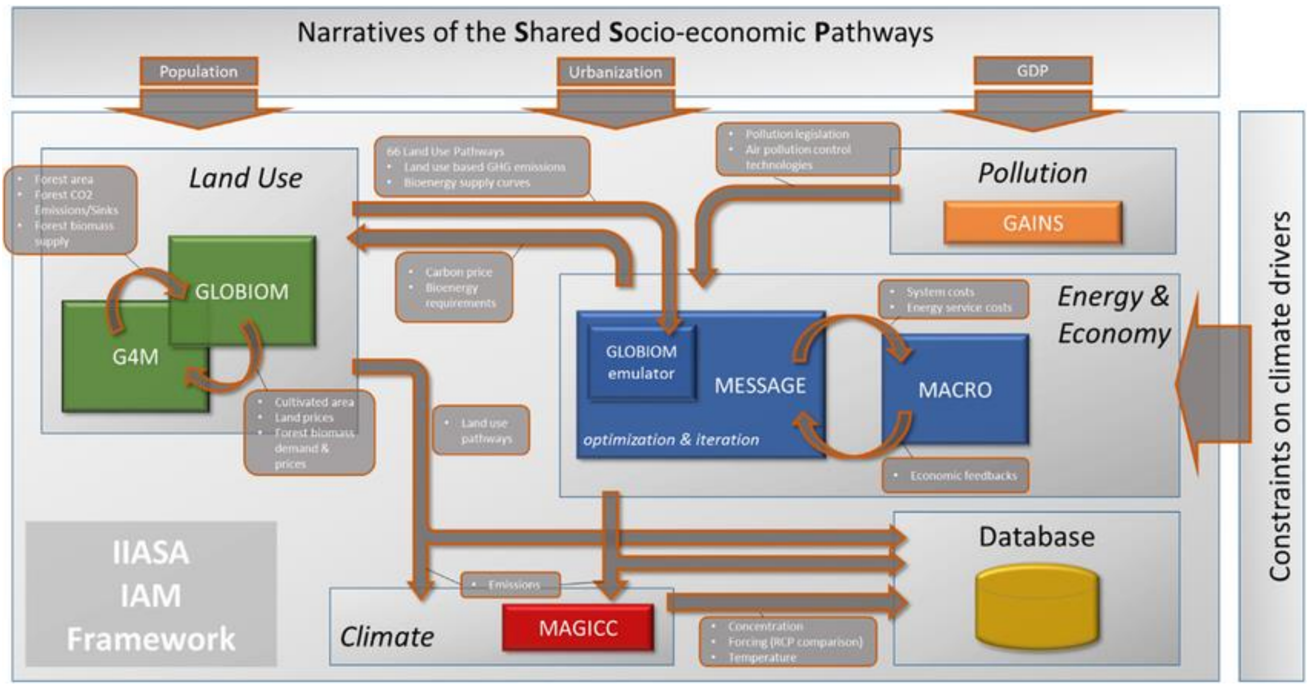
[129] Energy program; https://iiasa.ac.at/web/home/research/researchPrograms/Energy/About-Energy-Program.en.html

6.2 Rationale

The Energy Program develops tools to address complex, interrelated sustainability issues that involve energy systems and their interactions with other major economic sectors. From the collaboration between ENE and other research Programs at IIASA, was developed the **IIASA-IAM framework** that combines a careful blend of rich disciplinary models, operating at different spatial resolutions, which are interlinked and integrated into an overall assessment framework. The framework covers all major sectors, including agriculture, forestry, energy, and industrial sources, and permits the concurrent assessment of how to address major sustainability challenges.

In particular, as depicted in the figure 1, the IIASA-IAM framework consists of a combination of five different models or modules, which complement each other and are specialised in different areas. These models are the energy model **MESSAGE**, the land use model **GLOBIOM**, the air pollution and GHG model **GAINS**, the aggregated macro-economic model **MACRO** and the simple climate model **MAGICC**. All models together build the IIASA IAM framework, also referred to as **MESSAGE-GLOBIOM,** since the energy model MESSAGE and the land-use model GLOBIOM are its central components. The five models provide input to and iterate between each other during a scenario development cycle. An overview of the IIASA IAM framework is available at Figure 41.

Figure 41 - Overview of the IIASA IAM framework



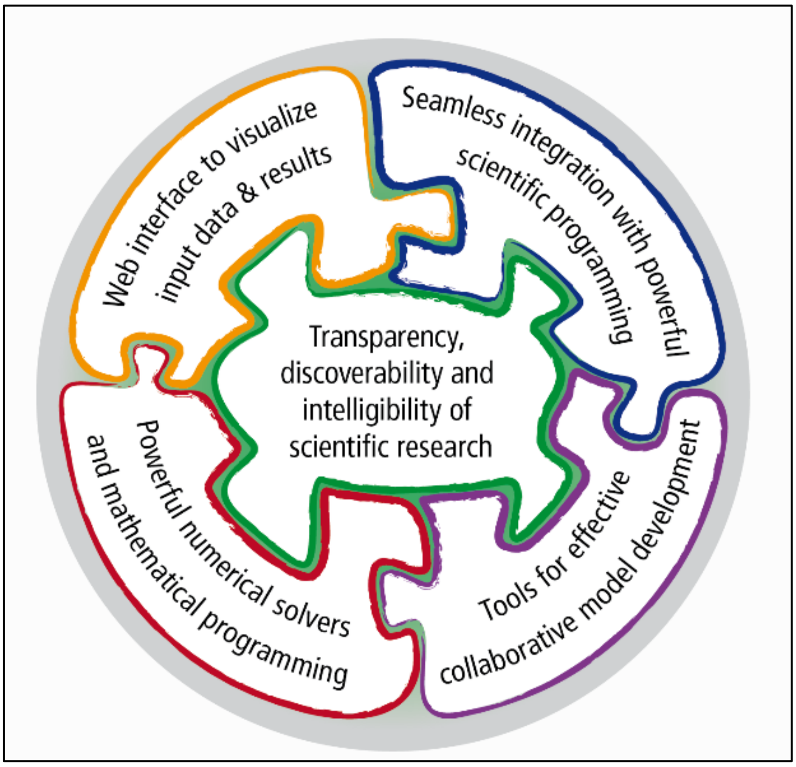
Source: https://message.iiasa.ac.at/_/downloads/global/en/latest/pdf/

MESSAGE represents the core of the IIASA IAM framework, and its main task is to **optimise the energy system to satisfy specified energy demands at the minimum cost.** MESSAGE carries out this optimisation in an iterative setup with MACRO, a single sector macro-economic model, which provides estimates of the macro-economic demand response that results from energy system and services costs computed by MESSAGE. GLOBIOM provides MESSAGE with information on land-use and its implications, including the availability and cost of bioenergy and availability, and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Other Land Use) sector. To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator which provides an approximation of land-use outcomes during the optimisation process. Only once the iteration between MESSAGE and MACRO has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding analysis with the full-fledged GLOBIOM model. This ensures full consistency of the results from MESSAGE and GLOBIOM, and also allows producing a more extensive set of land-use related indicators. Air pollution implications of the energy system are taken into account by MESSAGE applying technology-specific air pollution coefficients derived from the GAINS model. Finally, the combined results for land use, energy, and industrial emissions from MESSAGE and GLOBIOM are merged and fed into MAGICC, a global carbon cycle and climate model, which provides estimates of the climate implications in terms of atmospheric concentrations, radiative forcing, and global-mean temperature increase.

The entire framework is linked to an **online database infrastructure** which allows visualisation, analysis, comparison and dissemination of results. The scientific software underlying the global MESSAGE-GLOBIOM model is called the **MESSAGEix framework**, an open-source, versatile implementation of a linear optimisation problem. It was developed for strategic energy planning and integrated assessment of **energy-engineering-economy-environment** systems (**E4**). The framework can be applied to analyse scenarios of the energy system transformation under technical-engineering constraints and political-societal considerations. The optimization model can be linked to the general-economy **MACRO** model to incorporate feedback between prices and demand levels for energy and commodities. The equations are implemented in the mathematical programming system **GAMS**[130] for numerical solution of a model instance.

The MESSAGEix framework is fully integrated with **IIASA's ix modeling platform** (**ixmp**), a data warehouse for high-powered numerical scenario analysis (Figure 42). The platform supports an efficient workflow between original input data sources, the implementation of the mathematical model formulation, and the analysis of numerical results. The platform can be accessed via a web-based user interface and application programming interfaces (API) to the scientific programming languages **Python** and **R**. The platform also includes a generic data exchange API to GAMS for numerical computation.

Figure 42 - The ix modeling platform



Source: https://message.iiasa.ac.at/en/stable/

130 GAMS; https://www.gams.com/

6.3 Main actors and stakeholders

MESSAGE model has been developed by **IIASA**. IIASA conducts policy-oriented research into problems of global nature that are too large or too complex to be solved by a single country or academic discipline. MESSAGE supports the energy model of several national governments, which are members of the IIASA, involving not only the ministries and the government officials, but researchers as well. It is sponsored by its **National Member Organisations** in **Africa**, the **Americas**, **Asia**, and **Europe** and it is governed by a Council, composed by one representative of each member country.

MESSAGE model provides core inputs for major international assessments and scenarios studies, such as the **Intergovernmental Panel of Climate Change** (**IPCC**), the **World Energy Council** (**WEC**), **the German Advisory Council on Global Change** (**WBGU**), the **European Commission**, and most recently the **Global Energy Assessment** (**GEA**).

In general, IIASA has developed different instances of the MESSAGE model, and the choice of the partners depends on the research request and the scope and the skills of the project. The involved stakeholders work together, for example, in local decision-maker or governance. Having a very detailed stakeholder process allows identifying the initiative questions and data that people want to use at the local level, which determine the structure and the design of the model. Indeed, **depending on the partners' needs and local skills, the model can be differently structured and designed**.

6.4 Historical development of the model

As already mentioned, the model has been developed by IIASA in Austria since the 1980s, and it was the last in a series of Linear Programming (LP) energy models, developed by the Institute.

The most significant differences between MESSAGE and its predecessors are the following:

- the inclusion of an optional number of primary energy resource categories, allowing for the modelling of the nonlinear relation between extraction costs and the available amount of a resource;
- the explicit consideration of demand load curves, to take into account factors, as the the variation of demand for electricity;
- the calculation of residual discharges to the environment;
- increased program flexibility allowing, for instance, easy modular inclusion and removal of technologies.

MESSAGE was previously used to develop global energy transition pathways together with the World Energy Council and GHG emission scenarios for the **Intergovernmental Panel on Climate Change**. In the mid-1990s IIASA developed the robust decision-making version of MESSAGE to test ranges of plausible input data for energy systems. Such modelling approaches provide a better understanding of the uncertainties inherent in medium-term and long-term modelling of the energy system. In 2009, IIASA reported on the incorporation of a variety of risk management techniques into a reduced-form representation of MESSAGE, giving the model an enhanced utility as a risk management model.

The actual **global MESSAGE** model hosts 11 macro-regions https://webarchive.iiasa.ac.at/Research/ENE/model/regions.html - map11and has a time horizon until 2100 that is divided into 10-year steps. It provides information on the utilisation of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy.

6.5 Data sources

Demand data are exogenously given for all the energy forms defined at the secondary, final, or useful level. In general, MESSAGE model was developed over the last four decades, and it is difficult to identify what kind of data is collected and from which data sources. Data collected by MESSAGE concerns emissions, technology for various energy sectors, costs, water and transport demands. There are almost 20-30 different sectors, and for each, there is specific literature of data sources. Not all the data updates of these sectors are regular, depending on the characteristics of the model. Indeed, some of the sectors do not need to be updated every year.

Examples of data in input for the MESSAGE model are:

- energy system structure;
- base-year energy flows and prices;
- energy demand via a link to MACRO[131];
- technology and resource options & their techno-economic performance profiles;
- technical and policy constraints.

The Energy Program (ENE) hosts a growing number of databases for the integrated assesment modelling community, some of which are open to the wider public:

- **IAMC 1.5°C Scenario Explorer:** Hosted by IIASA, this Scenario Explorer presents an ensemble of quantitative, model-based climate change mitigation pathways underpinning the **Special Report on Global Warming of 1.5°C** (**SR15**) by the **Intergovernmental Panel on Climate Change** (**IPCC**). The scenario ensemble contains more than 400 emissions pathways with underlying socio-economic development, energy system transformations and land-use change until the end of the century, submitted by over a dozen research teams from around the world.
- **CD-LINKS Scenario Database:** The **CD-LINKS consortium** has developed a set of consistent national and global low-carbon development pathways that take current national policies and the **Nationally Determined Contributions** (**NDCs**) as an entry point for short-term climate action and then transition to long-term goals of 1.5 and 2°C as defined by the **Paris Agreement**. These climate policy scenarios are also used as a basis to explore synergies and trade-offs between multiple sustainable developments objectives.
- **Low Energy Demand study (LED):** The Low Energy Demand scenario study is a collaborative exploratory research carried out by several IIASA Programs: **Transitions to New Technologies Program** (**TNT**), **Energy Program** (**ENE**), **Air Quality & Greenhouse Gases Program** (**AIR**), and **Ecosystems Services and Management** (**ESM**). The LED scenario explores a pervasive transformation of the demand side of resource systems including food, energy, land, and water, as opposed to the more traditional scenario and modelling analysis, including **Integrated Assessment Models** (**IAMs**), which typically focus on resource provisioning or supply-side transformations.
- **IPCC AR5 Scenarios Database:** The IPCC AR5 scenarios database comprises 31 models and 1184 scenarios. To be included in the database, four criteria had to be met. First, only scenarios published in the peer-reviewed literature could be considered, per IPCC protocol. Second, the scenario must contain a minimum set of required variables and some basic model and scenario documentation (metadata) must be provided. Third, only models with at least full energy system representation were considered. Lastly, the scenario must provide data out to at least 2030.

131 MACRO MODEL; https://iiasa.ac.at/web/home/research/researchPrograms/RISK/MACRO1.html

- **SSP Scenario Database:** The SSP database aims at the documentation of quantitative projections of the so-called **Shared Socioeconomic Pathways** (**SSPs**) and related Integrated Assessment scenarios. The SSPs are part of a framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.
- **LIMITS Scenario Database:** The LIMITS scenario database, operated by IIASA for the **LIMITS consortium**, hosts the results of the LIMITS modelling comparison exercise. The LIMITS project aims at advancing the understanding of the implementation of climate policies consistent with 2°C. The main objective of the project is to provide an assessment of the emissions reductions strategies at global level.
- **AMPERE Scenario database:** The AMPERE database, operated by IIASA for the AMPERE consortium and hosts the model results. The **AMPERE project** was a collaborative effort among 22 institutions in Europe, Asia and North America. The AMPERE results have improved the understanding of possible pathways toward medium and long-term climate targets at the global and European levels and provided insights into the cost implications of policy delay, technology availability and unilateral action in a fragmented international policy landscape.
- **Representative Concentration Pathways Database:** The **Representative Concentration Pathways** (**RCPs**) are a set of five scenarios, developed for the **IPCC Fifth Assessment Report** (**AR5**). The RCP database, which documents the emissions, concentrations, and land-cover change projections based on these four RCPs, is intended to provide input to climate models. They also facilitate and expedite future climate change assessments across the integrated assessment community.
- **Global Energy Assessment Scenario Database:** The Global Energy Assessment scenario database collects results and assumptions of the **Global Energy Assessment** (**GEA**) energy transformation pathways that underpin the GEA. The database serves as a central data repository for the dissemination of GEA scenario information.
- **Greenhouse Gas Initiative Scenario Database (GGI-SD):** The Greenhouse Gas Initiative scenario database documents the results of greenhouse gas emission scenarios created using the **IIASA Integrated Assessment Modelling Framework** (**IAMF**).

6.6 Models

The energy supply model MESSAGE is a **dynamic linear programming** (**DLP**) model which minimises total discounted costs of energy supply over a given time horizon. The **main subject** of the model is the balancing of demand for secondary (or final) energy and supply of primary energy resources via driver technologies. The most important **model constraints** reflect limits on the speed of build-up of technologies, the availabilities of indigenous and imported resources, and technological relationships. Major distinctive features of the model are the consideration of load regions for electricity demand, the disaggregation of resources into cost categories, and the consideration of the environmental impact of energy supply strategies. The **model output** is used to describe scenarios of energy supply. The description comprises the physical flows of energy between primary energy and eventual use as specified by the demand data, shadow prices of supply and demand constraints, and the environmental impact of energy supply paths, expressed as emissions and concentrations of pollutants. The energy flows give a consistent picture of the supply/demand balance, and the shadow prices allow for an assessment of the incremental benefit of additional resources, the incremental benefit of new technologies, and the marginal costs of meeting additional demand. The environmental module may be used to model the influence of emission or concentration standards (upper limits) on the model solution. Another possibility is the inclusion of emissions and/or concentrations of pollutants in the objective function.

MESSAGE model provides a **framework** for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Scenarios are developed by MESSAGE by minimising the total systems costs under the constraints imposed on the energy system. Given this information and other scenario features, such as the demand for energy services, the model configures the evolution of the energy system from the **base year to the end** of the time horizon. It provides the **installed capacities of technologies**, **energy outputs and inputs**, **energy requirements at various stages of the energy system**, **costs**, **emissions**, etc. The degree of technological detail in the representation of an energy system is flexible and depends on the geographical and temporal scope of the problem being analysed. A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a **Reference Energy System** (**RES**) to be included in a given study/analysis that includes all the possible energy chains that the model can make use of. In the course of a model run, MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimising total discounted energy system costs.

The Reference Energy System (RES) is represented in the figure 3 and it defines the **total set of available energy conversion technologies**. In MESSAGE terms, energy conversion technology refers to all types of energy technologies from resource extraction to transformation, transport, distribution of energy carriers, and end-use technologies.

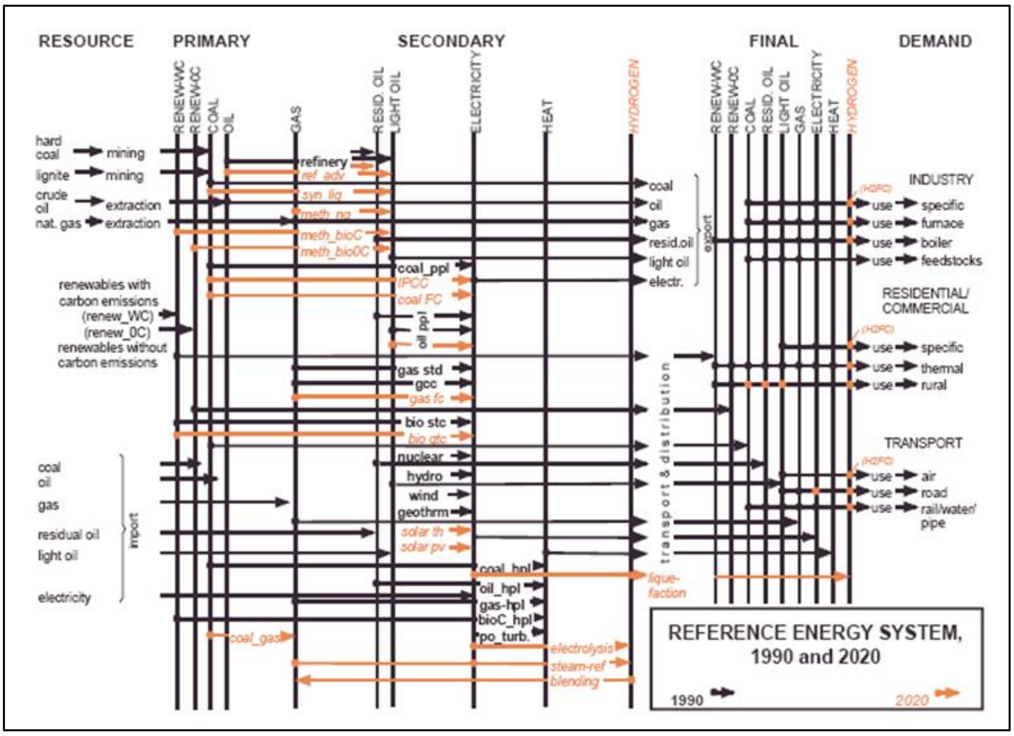
In particular, because few conversion technologies convert resources directly into useful energy, MESSAGE works on five energy levels:

- **Resource**, like coal, oil, natural gas in the ground or biomass on the field.
- **Primary energy**, like the refineries crude oil at the refinery.
- **Secondary energy**, like gasoline or diesel fuel at the refinery, or wind- or solar power at the power plant
- **Final energy**, like diesel fuel in the tank of a car or electricity at the socket.
- **Useful energy that satisfies some demand for energy services**, like heating, lighting or moving people.

Technologies can take in from one level and put out at another level or on the same level. The energy forms defined in each level can be envisioned as a transfer hub, that the various technologies feed into or pump away from. The useful energy demand is given as a time series. Technologies can also vary per time period. The mathematical formulation of MESSAGE ensures that the flows are consistent, matching the demand, equaling inflows and outflows and not exceeding constraints.

An example of a RES is given in Figure 43.

Figure 43 - Schematic diagram of the basic energy system structure in the MESSAGE model



Source: https://webarchive.iiasa.ac.at/Research/ENE/model/res.html

6.7 Technologies

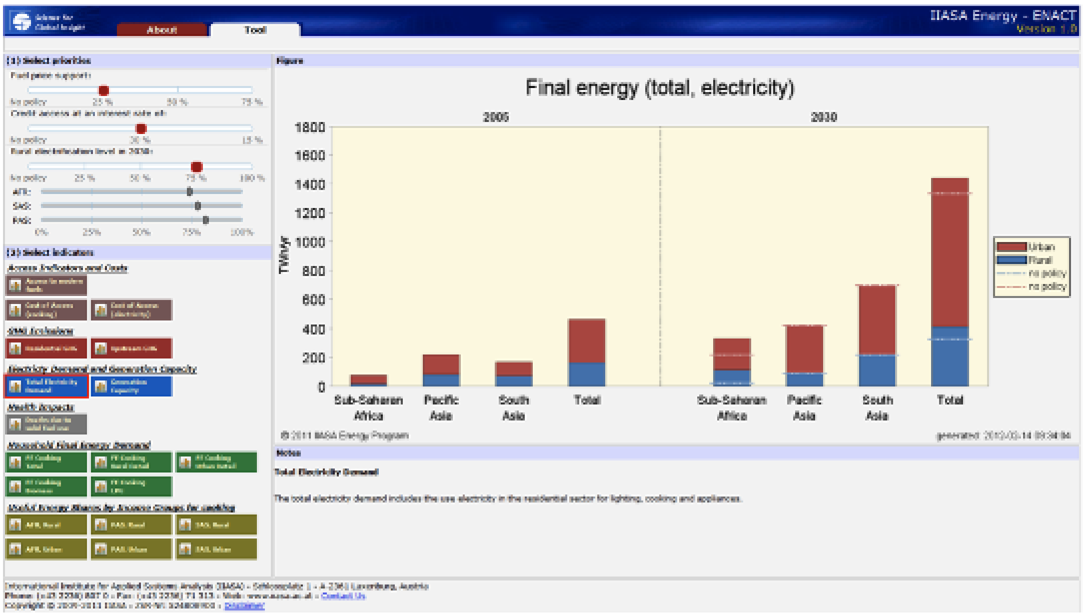
To make the insights from MESSAGE easier to understand, the Energy Program has developed interactive tools that visualise the large volume of raw data from the model:

- **Energy Access Interactive Tool** (**ENACT**)**:** The Energy Access Interactive Tool was developed by IIASA to assist national and regional policymakers and analysts in their strategic policy planning processes, mainly to improve energy access for the rural poor in developing countries. In particular, this tool is used to visualise costs and benefits that each policy or combination of policies could bring. It thus enables analysts and decision-makers to compare a large number of alternate energy access futures within a common framework. This allows them to gain a quick understanding of how alternate policies can shape the future of energy access in different ways. The main information generated by the tool for each policy investigated are funding requirements, potential policy effectiveness, the implications of the policy for energy demand, the policy's effect on greenhouse gas emissions and air pollution and the impacts on health. Through this tool, users can choose from three energy access policies: fuel price support; access to credit at a reduced interest rate; rural electrification target. Decision-makers can use the tool to compare the various synergies and trade-offs involved when one of three energy access policies is preferred over the rest. The possibility to choose different combinations of targets in the tool is particularly useful, as the policies typically compete for scarce funding. The tool allows users to see how alternative worldviews, in other words, different preferences, can lead to qualitatively different futures in terms of energy access. It also permits users to visualise the not always obvious cost and benefits of the different policy choices they are considering.

  The tool is populated with a rich ensemble of 60 energy scenarios, which have been developed using IIASA's **MESSAGE-Access model**, the global household energy access model. The scenarios explore policies and their impacts for achieving universal modern energy access by 2030. For instance, some scenarios include energy access policies such as fuel price support (subsidies) for cooking energy but do not consider any rural electrification policies or targets, while other scenarios have credit access and rural electrification only.

The Energy Access tool allows users to select their policies for universal modern energy access by moving the interactive slider bars shown on the tool interface (upper left), as shown in Figure 44.

Figure 44 – Energy Access Interactive Tool Interface



Source: https://iiasa.ac.at/web/home/research/researchPrograms/Energy/ENACT.en.html

Once users have selected the policies for energy access, they can visualise the impacts of these policies by selecting one of the various indicator tabs on the tool interface. Among the indicators included are access indicators and costs, GHG emissions, electricity demand and generation capacity, health impacts, household final energy demand and useful energy shares by income groups for cooking.

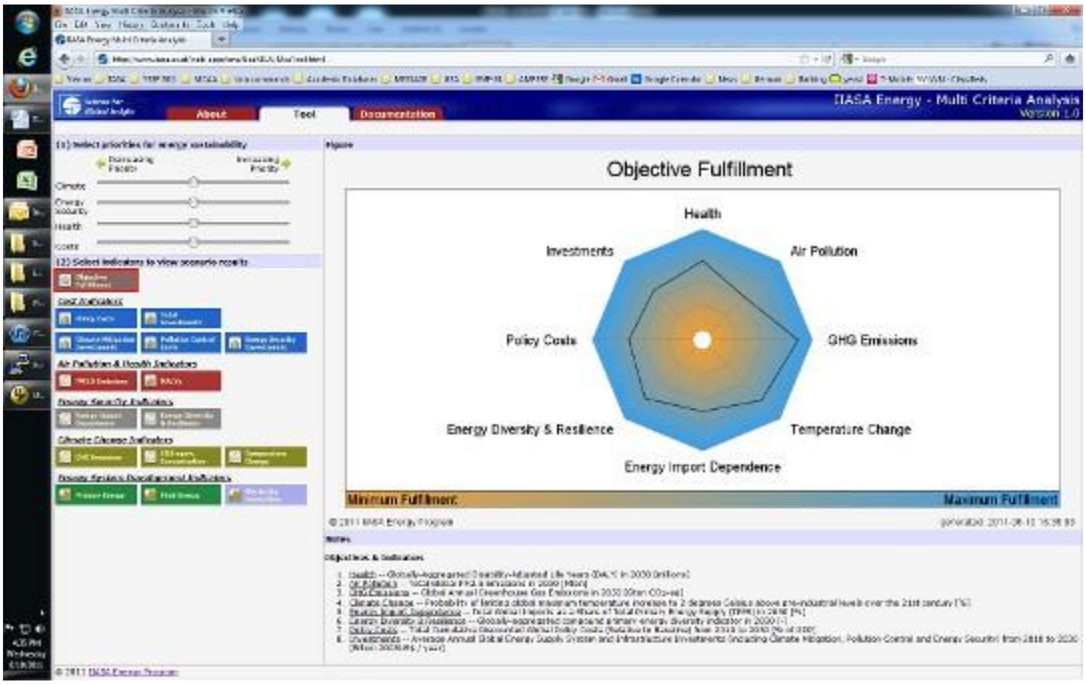
- **Energy Multi-Criteria Analysis Tool** (**MCA**)**:** The Energy Multi-Criteria Analysis tool by IIASA, to allow energy decision-makers to conduct a comprehensive and integrated assessment of the major energy challenges, to make the best choices through sustainable energy development pathways. The tool was populated with more than 600 ensembles of energy futures, each of which meets the different objectives for energy sustainability in a unique way. These energy futures were generated using IIASA's **MESSAGE Integrated Assessment Modeling Framework**.

  The tool provides a comprehensive and interactive overview to allow decision-makers to compare the various synergies and trade-offs involved, when each of the four main energy sustainability objectives (climate, energy security, health, and costs) is prioritised over the rest. The possibility to personalise the priorities in the tool is particularly useful, as not all objectives are given the same priority by different policymakers. The tool allows users to see how alternative worldviews can lead to qualitatively different energy system futures. It also permits users to visualise the complex synergies and trade-offs of the different policy choices.

  The Energy Multi-Criteria Analysis interactive tool allows users select their priorities for energy sustainability by moving the interactive slider bars shown on the tool interface (upper left), and to assign a relative importance to each, as shown in

  Figure 45.

Figure 45 - Schematic diagram of the basic energy system structure in the MESSAGE model



Source: https://webarchive.iiasa.ac.at/Research/ENE/model/res.html

6.8 Degree of maturity and implementation phases

The MESSAGE framework is mature and consolidated, and its results provide core inputs for major international assessments and scenarios studies, such as:

- the **Intergovernmental Panel of Climate Change (IPCC)**[132], the leading international body for the assessment of climate change;
- the **World Energy Council (WEC)**[133], a global and inclusive forum for thought-leadership and tangible engagement;
- the **German Advisory Council on Global Change (WBGU)**[134] an independent, scientific advisory body**;**
- the **European Commission**;
- the **Global Energy Assessment (GEA)**[135], the first *global* and interdisciplinary *assessment* of *energy* challenges and solutions.

6.9 Extent of adoption, drivers and challenges

Great work is currently being undertaken at IIASA to extend MESSAGE. The extensions are the result of modelling the energy chain up to useful energy, of running the model for a longer period, and of modelling countries for which detailed data are available.

MESSAGE could be used in conjunction with other models. In particular:

1. **MESSAGE-Access** describes a residential energy and technology choice model, which interacts with the global energy system model (MESSAGE). It is used to assess pathways to achieve universal access to modern energy by 2030, by accelerating the transition to clean cooking fuels and electrification in the regions of South Asia, Pacific Asia, Central America, and sub-Saharan

132 The intergovernmental panel of climate change (IPCC); https://www.ipcc.ch/
133 The world energy council (WEC); https://www.worldenergy.org/
134 The German advisory council on global change (WBGU); https://www.wbgu.de/en/
135 The global energy assessment; https://iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Home-GEA.en.html

Africa. MESSAGE-Access provides a strong modelling framework to analyse effective policy choices, improving the penetration of modern cooking fuels among the poor and electrifying rural areas. It is the first model to explicitly account for heterogeneous economic conditions and the preferred energy choices of poor populations living in rural and urban settings. The MESSAGE-Access Model is based on data from nationally representative consumer surveys. This data is used to calibrate the model in the base year to represent the existing patterns of energy use in households distinguished by their place of residence and income level.

2. **MESSAGE-MACRO** results from the linking of the detailed energy supply model (MESSAGE) with a macroeconomic model (MACRO). The reason for linking the two models is to consistently reflect the influence of energy supply costs, as calculated by MESSAGE, in the mix of production factors considered in MACRO, and the effect of changes in energy demand on energy costs. The combined MESSAGE-MACRO model can generate a consistent economic response to changes in energy prices. In practice, the MACRO model receives prices related to the total and marginal costs of energy supply from the MESSAGE model; from these, it supplies the quadratic demand functions for MACRO so that the overall energy demand can be adjusted. MESSAGE is then rerun with these adjusted demands to give adjusted prices. This cycle is repeated until prices and energy demands are stabilised.
3. **MESSAGE-MAGIC** results from the linking of the energy model MESSAGE with the climate model MAGICC allows the integrated analysis of (probabilistic) climate. The MESSAGE-MAGIC framework is used for the development of internally consistent energy-economic greenhouse gas mitigation scenarios. MAGICC receives inputs from the MESSAGE model with respect to anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur dioxide (SO_2), reactive gases (CO, NOx, VOCs), and halocarbons. MAGICC then relates GHG emissions and their outputs (physical and chemical sink processes) to changes in the atmospheric carbon concentration. From these inputs, the MAGICC model estimates net carbon flows and atmospheric CO_2 concentration, as well as changes in radiative forcing, temperature, and sea level. If desired, MAGICC can also estimate a range of temperature change or probability of staying within a given warming target (e.g., the 2°C global warming target).
4. **MESSAGE-GLOBIOM** results from the linking of the energy model MESSAGE and the IIASA's Global Biosphere Management Model (GLOBIOM)[136]. GLOBIOM is used to analyse the competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors. As such, the model can provide scientists and policymakers with the means to assess, on a global basis, the rational production of food, forest fibre, and bioenergy, all of which contribute to human welfare. MESSAGE-GLOBIOM 1.0 was developed for the quantification of the so-called Shared Socioeconomic Pathways (SSPs), which are the first application of the IAM framework. To date, GLOBIOM provides MESSAGE with information on land use and its implications. To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator that provides an approximation of land-use outcomes during the optimisation process. Only once the iteration between MESSAGE and MACRO has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding analysis with the full-fledged GLOBIOM model. This ensures full consistency of the results from MESSAGE and GLOBIOM, and also allows producing a more extensive set of land-use related indicators.

The combined MESSAGE-GLOBIOM framework has global coverage and divides the world into 11 regions which are also the native regions of the MESSAGE model. GLOBIOM natively operates at the level of 30 regions which in the linkage to MESSAGE are aggregated to the 11 regions (listed in the table in annex):

[136] GLOBIOM MODEL; https://www.globiom.org/

In addition to the 11 geographical regions, in MESSAGE there is a global trade region where market-clearing of global energy markets is happening and international shipping bunker fuel demand, uranium resource extraction and the nuclear fuel cycle are represented.

An important application of MESSAGE besides its usage within the global model was the one for the **Commission of the European Communities** (**CEC**). The CEC application emphasized the disaggregation of global results. This was achieved by splitting IIASA's Regions into "Europe of the Nine" and "Rest of the Region" using a modified model loop. The results of the IIASA models were then compared with the "bottom-up" model runs performed by the CEC. Other applications underway (such as for **Brazil**, **Bulgaria**, the **FRG**, and **Hungary**) seem to prove that the definition of MESSAGE is general enough to serve as a basis for a great variety of applications.

About challenges, working with some specific government, it is not always easy to have direct communication and interaction. Indeed, with some countries, using the MESSAGE model involves **larger** and **indirect effects**.

6.10 Role of beneficiaries and technological providers

To describe the role of beneficiaries and technological providers it is important separate the data aggregation phase from the implementation one:

- For the process of data aggregation, there are not outside service providers involved.
- In the structure and design process of the regional model, ministries and government officials can be involved. For instance, recently a **MESSAGE model was built in collaboration with the Indian government**, specifically for the Indian South Continent, working with Indian ministries, environment local authorities and energy administrations. **In general, collaboration depends on which model, or which version or instance of the model, is requested, and the local authorities of the requester.**

Even for the global model than for each of the region model, the scope is to find good data from national or regional authorities. Actually, this process is not very structured because of the inability to do this data search regularly, mainly due to a lack of resources.

6.11 Social and economic outcomes

Providing sufficient amounts of energy has become a problem for many countries, despite minor fluctuations and short-term improvements. Furthermore, the longer the time horizon in view, the more difficult it is to work out schemes to meet prospective energy demand. MESSAGE is a systems engineering optimisation model used for the planning medium to long-term energy systems, analysing climate change policies, and developing scenario, for national or global regions.

Typical scenario outputs provide information on the utilisation of domestic resources, energy imports, and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions (traditional indoor and outdoor air pollutants as well as greenhouse gases), and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. MESSAGE is also increasingly used for detailed analysis of energy demand issue, such as for policy analysis of energy access in the residential sector.

More specifically, the MESSAGE model has the following series of **key benefits**:

- its developed scenarios minimise the total systems costs under the constraints imposed on the energy system;
- it configures the evolution of the energy system from the base year to the end of the time horizon (medium/long term system);

- it provides the installed capacities of technologies, energy outputs and inputs, energy requirements at various stages of the energy system, costs, emissions, etc.;
- it is used in applied projects and scientific studies around the world;
- scenarios developed with it have been used in, for example, the assessments and special reports of the IPCC and the GEA;
- it was used to generate one of the four Representative Concentration Pathways (RCPs) currently being used to estimate future climate change in the context of the IPCC 5th Assessment Report[137];
- a special agreement between IIASA and the International Atomic Energy Agency (IAEA)[138] allows MESSAGE model to be used for country studies within the IAEA and its Member States.

6.12 Scalability, replicability and transferability considerations

MESSAGE model is used mainly at the **global level**. MESSAGE was developed to be used for geographical regions with the size of continents. It may also be applied to **smaller regions** or **countries**, provided that some care is taken in supplying the input data and in interpreting the model results. A particular problem that may arise comes from the continuity of the model variables that, for small countries, may very likely result in sizes of energy conversion facilities that are unrealistically small. In addition, in some regions or countries, the energy system may have some peculiarities, which have not been considered in the general model formulation.

6.13 Conclusions

Issues relating to energy are among the most important and difficult challenges confronting the world today. In this context, a key issue to face these major global challenges in a holistic way is **the integration of sectoral models**. Indeed, traditionally separated tools were used for energy supply, demand and end-use analysis, as well as "top-down" and "bottom-up" analytical representations. These tools can be increased integrating or linking them with other models, like MESSAGE, creating an ensemble model integration to assess important interrelations and feedbacks. In particular, the energy model **MESSAGE**, can be used in conjunction with the land-use model **GLOBIOM**, the air pollution and GHG model **GAINS**, the aggregated macro-economic model **MACRO** and the simple climate model **MAGICC**, creating a framework that covers all major sectors, including agriculture, forestry, energy, and industrial sources, permitting a concurrent assessment of how to address major sustainability challenges.

Several lessons learned has been identified over the last decades.

- **Renovation of software and tools adopting an open source choice**: in the last years, the software used for the model turned out to be not in line with best practices anymore. A complete **reimplementation of the software framework** that powers the MESSAGE model was needed, trying to follow **the best practices of collaborative scientific programming and open source.** It represents a huge success story because it makes it easier to get collaborators from different universities and research institutions. Indeed, The MESSAGE model was always used in many institutions and distributed by the international energy agencies, but starting to work in open source and collaborative programming has made all these steps easier;
- **Collection of business needs:** In addition, since the model developers interact with the scientists and local decision-makers (users), they collected feedback on the **best graphic interface** to apply to different types of users. Indeed, previously they had less knowledge about details and mechanic indications of the model. **Local experts help them to improve the system**

137 IPCC 5th Assessment Report; https://www.ipcc.ch/report/ar5/syr/
138 The International Atomic Energy Agency; https://www.iaea.org/

representation or face issues, which they would not consider from their global perspective;

- **Policy dialogues and informed choices:** The model is used by different countries to build or design their energy strategies at the national level. The modelling results provides the quantitative bases for different ministries to define and discuss the national targets. Scenarios provided by the model are useful to **initiate policy dialogues** and **make informed choices**, based on scientific insights, and show to the decision-makers the possibilities between these different choices. It is considered an important lesson learnt because it allows for understanding the power of the model.

6.14 APPENDIX – MESSAGE Regions and Sources

Table 6: 11 MESSAGE regions[139]

11 MESSAGE regions	Definition	List of countries
NAM	North America	Canada, Guam, Puerto Rico, United States of America, Virgin Islands
WEU	Western Europe	Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom |
PAO	Pacific OECD	Australia, Japan, New Zealand
EEU	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia, Estonia, Latvia, Lithuania
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
CPA	Centrally Planned Asia and China	Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
PAS	Other Pacific Asia	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa
MEA	Middle East and North Africa	Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
LAM	Latin America and the Caribbean	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela

[139] IIASA ENERGY PROGRAM: https://readthedocs.com/projects/iiasa-energy-program-message-doc/downloads/pdf/latest/

11 MESSAGE regions	Definition	List of countries
AFR	Sub Saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe

Sources

- International Institute for Applied Systems Analysis website: https://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html;
- EnergyPLAN website: https://www.energyplan.eu/othertools/global/message/;
- IIASA web archive: https://webarchive.iiasa.ac.at/Research/ENE/model/message.html;
- The Abdus Salam International Centre for Theoretical Physics - Joint ICTP-IAEA Workshop on Uncovering Sustainable Development CLEWS; Modelling Climate, Land-use, Energy and Water (CLEW) Interactions HOWELLS Mark Idwal (30 May - 3 June, 2011): http://indico.ictp.it/event/a10145/session/29/contribution/17/material/0/0.pdf;
- International Institute for Applied Systems Analysis - Message Documentation Release 1.0 – IIASA Energy Program (11 July, 2019): https://readthedocs.com/projects/iiasa-energy-program-message-doc/downloads/pdf/latest/;
- LEDS Global Partnership website: https://ledsgp.org/resource/model-for-energy-supply-system-alternatives-and-their-general-environmental-impacts/?loclang=en_gb;
- Leo Schrattenholzer - The energy supply model message (December, 1981): http://pure.iiasa.ac.at/id/eprint/1542/1/RR-81-031.pdf.