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A sensitivity analysis of the *Earth for all* model

Getting the giant leap scenario with fewer policies

Pierluigi Crescenzi¹  | Giorgio Gambosi² | Lucia Nasti¹ | Aurora Rossi³ | Emanuele Natale³

¹Gran Sasso Science Institute, L'Aquila, Italy

²Dipartimento di Ingegneria dell'Impresa "Mario Lucertini", University of Rome "Tor Vergata", Rome, Italy

³IS & INRIA d'Université Côte d'Azur, COATI Team, Sophia Antipolis, France

Correspondence

Pierluigi Crescenzi, Gran Sasso Science Institute, 67100 L'Aquila, Italy.
Email: pierluigi.crescenzi@gssi.it

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Abstract

Integrated assessment models (IAMs) are popular tools used to predict the evolution of human society, a challenging question that science has long tried to address. The World3 model is a popular IAM, designed in the seventies by several scientists convened by the Club of Rome and mostly known for its usage to analyze the so-called limits to growth. The recent Earth for all (E4A) model has been initiated by one of the major co-authors of the World3 model, Jørgen Randers. It is substantially more complicated than the relatively simple World3 model, and it has been used to compare two different and opposite world development scenarios: the too little too late scenario, in which current policies are assumed to continue, and the giant leap (GL) scenario, in which 21 policies related to five turnarounds are identified to produce significant improvements in six indicators of human well-being. By using global and local sensitivity analyses of the E4A model, we suggest that the evolution of the six indicators in the GL scenario can be approximately reached by focusing on just six policies and three turnarounds (namely, the energy, the inequality, and the poverty turnarounds). The evolution of the six indicators can be even improved by investing "reasonably" more on three of these six policies and by keeping unchanged the remaining three. From a methodological point of view, we exploit both global (Sobol) and local sensitivity analyses to identify the policies that most influence the six indicators, and we subsequently execute a scenario analysis of the identified policies to confirm that they can produce a similar (or even a better) evolution of the indicators themselves.

KEYWORDS

computer simulation, integrated assessment model, limits to growth, local sensitivity analysis, system dynamics, Sobol analysis

1 | INTRODUCTION

The *limits to growth* concept was introduced in the seventies and argues that, given the current development model and the related exploitation of the limited available resources, a set of global issues will arise, affecting the quality of life of future generations. This concept was explicitly

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Indicator	1980	TLTL 2100	GL 2100
AWBI	0.6724	0.7215	3.1237
GDPP (K\$)	6.3545	46.5366	55.8780
INEQ	0.6073	0.7743	0.3671
OW (deg C)	0.4000	2.3485	2.0106
POP (M)	4420.0000	7282.5170	5984.4509
STE	1.3000	1.2999	1.0906

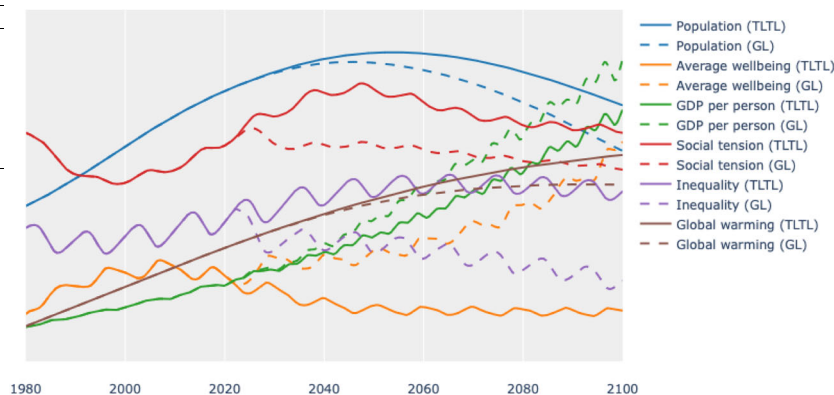


FIGURE 1 The evolution of the six indicators in the too little too late (TLTL) and the giant leap (GL) scenarios (underlying data for this figure are available in the folder `simulations` of the source repository mentioned in Section 2.4). AWBI, average well-being index; INEQ, inequality index; GDPP, GDP per person; POP, population; STE, social tension index; OW, observed warming.

formulated in the well-known report *The Limits to Growth* for the Club of Rome (Meadows et al., 1972, 1974), which “is regarded as one of the most influential books of the twentieth century” (Bardi, 2011). In the report, the authors proposed WORLD3, a complex global simulation model, based on the system dynamics approach to understanding the behavior of complex systems (Forrester, 1971). WORLD3 consists of a set of interacting components (such as demographic, economic, and natural), which allowed them to investigate different scenarios of the evolution of the world’s system from 1900 to 2100. These scenarios range from the so-called *business-as-usual*, in which it is assumed that no changes will take place with respect to the policies of the past thus leading to the *collapse* of the system (Bardi, 2019), to several different scenarios in which, by adopting specific policies, the collapse can be avoided and equilibrium states of the system can be reached. Note that models like WORLD3 are now called *integrated assessment models*, and several have been proposed in the literature to analyze the evolution of our society on the basis of the interactions between different sectors, such as agriculture, climate, economy, and energy (Hughes, 2019; Huppmann et al., 2019; Nordhaus, 2013; Plambeck et al., 1997; Sverdrup et al., 2021; Wang et al., 2017; Weyant, 2017).

During the last 50 years, the WORLD3 model has undergone several changes (Meadows et al., 1993, 2004), to several sensitivity analyses (Heath et al., 2019; Jochaud Du Plessix, 2019; Vermeulen & de Jongh, 1976), and to several forecast verifications (Herrington, 2021, 2022; Turner, 2008). Very recently, a new global (that is, one-region) model, called *Earth for all* (in short, E4A), has been proposed by a group of researchers still convened by the Club of Rome (Dixon-Declève et al., 2022). The E4A model is much more complex than the WORLD3 model. Indeed, this latter model contained (in its last version) 231 variables and 74 parameters, while the E4A model includes 481 variables and 283 parameters. It is worth noting that the two ancestors WORLD1 and WORLD2 of the WORLD3 model, which were proposed in Forrester (1970, 1973), were in turn much simpler than the WORLD3 model and included 41 (respectively, 81) variables and 15 (respectively, 29) parameters (see Supporting Information S1). Nevertheless, all these models share the common property of being structured into several sectors interacting with each other via some specific common variables. For example, the WORLD3 model is structured into five sectors (agriculture, population, pollution, non-renewable resources, and capital), while the E4A model is structured into 12 sectors (climate, demand, energy, finance, food and land, inventory, labor market, output, population, public, well-being, and other performance variables).

By using the E4A model, the authors analyze two drastically different scenarios. The too little too late (TLTL) scenario, in which no changes are made to the current policies, and the giant leap (GL) scenario in which five big turnarounds are implemented (concerning poverty, inequality, empowerment, food, and energy). The two scenarios are evaluated by mostly referring to six variables of the model, called *indicators*, that is, the GDP per person (GDPP), the observed warming (OW), the population (POP), an inequality index (INEQ), a social tension index (STE), and an average well-being index (AWBI) (Collste et al., 2023; Dixon-Declève et al., 2022). Figure 1 shows the evolution of these six indicators in the two scenarios in the period 1980–2100 (the figure has been generated by using the Julia implementation of the E4A model (Crescenzi et al., 2023), which is in turn based on the Julia `WorldDynamics` package (Crescenzi et al., 2024)). It is evident how, in the GL scenario, the INEQ, STE, and AWBI perform much better than in the TLTL scenario, the OW increases less, the POP decreases more, and the GDPP increases more. Note that the two scenarios diverge approximately at year 2022, since this is the year in which the authors apply the policies that generate the five turnarounds (the E4A model was published at the end of 2022), but similar results would be obtained if this turning point is shifted by a couple of years (i.e., to 2024). It is also worth noting that both the average well-being and the GDPP indicators increase in the GL scenario, somewhat contrasting with the idea that securing human well-being may necessitate abandoning economic growth as an objective (Costanza, 2023; Hickel et al., 2022) (see also Collste et al. (2021/ed) for an analysis of how the GDPP relates to some well-being indicators).

We argue that a behavior of the six indicators not too far from the one in the GL scenario (or even better for several indicators) can be reached by focusing only on a small set of policies related to three specific turnarounds. This claim is sustained by a preliminary global sensitivity analysis of the E4A model,

followed by a more focused local sensitivity analysis, and, finally, by an extensive analysis of the possible policies. In particular, we conclude that applying only six specific policies involved in the poverty, energy, and inequality turnarounds produces an evolution of the six indicators not too far from the one generated by the GL scenario. If what is saved from investing in the other policies is used to implement three of the selected ones in a more effective way, we maintain that it is even possible to reach a better evolution of some of the six indicators. Note that this does not imply that some policies or turnarounds are more important than others: The main result of the paper is providing evidence that a similar (or even better) evolution of the six indicators can be obtained with fewer policies (and turnarounds).

2 | MODEL AND METHODS

2.1 | The E4A model

As mentioned, the E4A model consists of the following sectors: climate, demand, energy, finance, food and land, inventory, labor market, output, other performance variables, population, public, and well-being. Each sector contains a set of algebraic or differential equations, where a dependent variable of the sector acquires value through an equation involving one or more independent variables, not necessarily of the same sector. Indeed, the sectors interact with one another through variable dependencies. Each such dependency consists of at least one dependent variable of one sector being used in at least one equation of the other sector as an independent variable. For example, the population sector depends on the climate sector because of the effect of climate change on life expectancy; that is, the observed warming (which is a dependent variable of the climate sector) is used in the life expectancy equation (as an independent variable). Overall, the model uses 481 variables and 283 parameters: The list of all variables and equations and of all parameters is available at <https://www.pilucrescenzi.it/e4asa/e4a.html>. Twenty-one such parameters (each corresponding to a specific *policy*) are modified to generate the GL scenario, as explained in (Collste et al., 2023): Three of them are defined in the climate sector, seven in the demand sector, four in the energy sector, three in the food and land sector, two in the output sector, one in the population sector, and one in the public sector. According to the authors of the model, these parameter changes correspond to five turnarounds: the *poverty* turnaround (involving one demand parameter, the two output parameters, and the public parameter), the *inequality* turnaround (involving four demand parameters), the *empowerment* turnaround (involving two demand parameters and one population parameter), the *food* turnaround (involving the three food and land parameters), and the *energy* turnaround (involving the four energy parameters and one climate parameter). The remaining two climate parameters are not explicitly associated with a turnaround. In Table 1 (taken from the Supplementary information of Collste et al. (2023)), we list the 21 parameters involved in the five turnarounds: The name of each parameter is the one used by the authors of the E4A model in the Vensim implementation of the model itself (available at <https://earth4all.life/the-science/>), while the acronym is the name of the parameter in the Julia implementation of the E4A model we refer to in Section 2.4 (in the following, we will refer to each parameter by either its name or its acronym). The parameters in boldface are the ones selected for generating our alternative scenarios.

2.2 | Sensitivity analysis and Sobol's method

Performing sensitivity analysis on a model is a critical process aimed at assessing the influence of each input parameter on the model's output variable. This analysis can be executed according to two different approaches. In the *local* sensitivity analysis (Borgonovo & Plischke, 2016; Gustafson et al., 1996), parameters undergo incremental adjustments one at a time. At each iteration, a designated parameter is perturbed by a small increment, and the resulting alteration in the observed output variable, denoted as *quantity of interest* (in short, QoI) is scrutinized. In the *global* sensitivity analysis (Borgonovo & Plischke, 2016; Saltelli et al., 2002, 2007), parameters undergo simultaneous variations across the parameter space, enabling the estimation not only of each individual parameter's relative contribution to the model's response change but also of the effects stemming from interactions between different parameters. Sobol's method is a global sensitivity analysis technique rooted in variance decomposition principles, offering a quantitative assessment of input-to-output variance contributions. The method operates by decomposing the variance of the QoI into incremental variances of input parameters across ascending dimensionalities. More precisely, the model is analyzed from a probabilistic perspective that considers the input as a random vector $X = (X_1, X_2, \dots, X_s)$ of the input parameter values. Each parameter is assumed to range over some finite interval (which may be assumed, after rescaling, to be $[0, 1]$) and it is considered a uniformly distributed random variable (with all the parameters mutually independent). The QoI, denoted as Y , is a function $Y = f(X)$ dependent on the input X , and in itself constitutes a random variable characterized by its mean and variance. For any non-empty subset of parameter indices $I \subseteq \{1, \dots, s\}$, we let $X_I = \{X_i : i \in I\}$. As usual, $E[Y|X_I]$ is the conditional mean of Y given X_I (which is a random variable on the domain of X_I) and $\text{Var}[E[Y|X_I]]$ is the variance of such variable (with respect to X_I). Sobol's analysis is based on the variance decomposition $\text{Var}[Y] = \sum_{I \subseteq \{1, \dots, s\}} V_I$, where $V_I = \text{Var}[Y|X_I] - \sum_{I' \subset I} V_{I'}$ (Sobol, 1993). The term V_I is the contribution to the overall variance $\text{Var}[Y]$ of all parameters in I , when only common variations of such parameters are considered. The Sobol index associated with the subset I , denoted as S_I , is defined as the ratio between the contribution of the interaction among the components of I to the

TABLE 1 The parameters involved in the turnarounds of the giant leap (GL) scenario.

Name	Acronym	Sector	Turnaround	TLTL value	GL value
Direct air capture of CO ₂ in 2100 GtCO ₂ /year	DACCO22100	Climate	Energy	0.000	8.000
Extra empowerment tax from 2022 (share of NI)	EETF2022	Demand	Empowerment	0.000	0.020
Extra general tax rate from 2022	EGTRF2022	Demand	Inequality	0.000	0.010
Extra pension tax from 2022 (share of NI)	EPTF2022	Demand	Empowerment	0.000	0.020
Extra rate of decline in CH ₄ per kg crop after 2022 1/year	ERDCH4KC2022	Climate		0.000	0.010
Extra rate of decline in N ₂ O per kg fertilizer from 2022	ERDN2OKF2022	Climate		0.000	0.010
Extra ROC in energy productivity after 2022 1/year	EROCEPA2022	Energy	Energy	0.002	0.004
Extra transfer of government budget to workers	ETGBW	Demand	Inequality	0.000	0.200
Fraction of extra taxes paid by owners	FETPO	Demand	Inequality	0.500	0.800
Fraction of government debt cancelled in 2022 1/year	FGDC2022	Demand	Poverty	0.000	0.100
Goal for crop waste reduction	GCWR	Food and land	Food	0.050	0.200
Goal for extra fertility reduction	GEFR	Population	Empowerment	0.000	0.200
Goal for extra income from commons (share of NI)	GEIC	Demand	Inequality	0.000	0.020
Goal for fraction of CO ₂ -sources with CCS	GFCO2SCCS	Energy	Energy	0.200	0.900
Goal for fraction new electrification	GFNE	Energy	Energy	0.500	1.000
Goal for fraction new red meat	GFNRM	Food and land	Food	0.100	0.500
Goal for fraction regenerative agriculture	GFRA	Food and land	Food	0.100	0.500
Goal for renewable el fraction	GREF	Energy	Energy	0.500	1.000
Max imported ROTA from 2022 1/year	MIROTA2022	Public	Poverty	0.000	0.005
Unconventional stimulus in PIS from 2022 (share of GDP)	USPIS2022	Output	Poverty	0.000	0.010
Unconventional stimulus in PUS from 2022 (share of GDP)	USPUS2022	Output	Poverty	0.000	0.010

Abbreviations: CCS, carbon capture and storage; PIS, private sector; PUS, public sector; ROC, rate of change; ROTA, rate of technological advance, TLTL, too little too late.

model variance, and the total variance itself, that is, $S_I = \frac{V_I}{\text{Var}[Y]}$. A Sobol index lies within the interval [0,1] by definition. The Sobol indices $S_{\{i\}}$ are referred to as the *first-order* indices, denoting the individual effect of each parameter X_i . Finally, to measure the full contribution of X_i to the variance of Y , accounting also for the interactions with other parameters, the *total indices* are estimated, which are defined as $S_i^T = \sum_{C \subset \{1, \dots, s\}; i \in C} S_C$.

2.3 | Sensitivity analysis and parameter value ranges

While executing the local sensitivity analysis, we apply the following algorithm for computing, for each parameter, its variability range. Let p be a parameter among the 21 involved in the five turnarounds, let $v_p(\text{TLTL})$ (respectively, $v_p(\text{GL})$) be the value assigned to p in the TLTL (respectively, GL) scenario, and let δ_p be $v_p(\text{GL}) - v_p(\text{TLTL})$ (note that it always holds that $v_p(\text{GL}) > v_p(\text{TLTL})$ and, hence, that $\delta_p > 0$). The *base* (respectively, *low* and *high*) value of p is $v_p(\text{GL})$ (respectively, $v_p(\text{TLTL})$ and $v_p(\text{TLTL}) + 2\delta_p$). Note that if p has to be at most 1, its high value is 1. For example, if p is the maximum imported rate of technology advance from 2022, we have that the low value of p is $v_p(\text{TLTL}) = 0$, its base value is $v_p(\text{GL}) = 0.005 = \delta_p$, and its high value is $v_p(\text{TLTL}) + 2\delta_p = 0.01$.

2.4 | Source code

To perform our analysis, we made use of the Julia implementation of E4A (Crescenzi et al., 2023), which is in turn based on the Julia WorldDynamics package (Crescenzi et al., 2024). We simplified the source code available at <https://github.com/worlddynamics/Earth4All.jl> by including all the equations of the model into one single sector. All our code is available at <https://github.com/piluc/Earth4AllISA>. To perform the Sobol sensitivity analysis, we used the Julia package GlobalSensitivity (Dixit & Rackauckas, 2022). Moreover, a Julia notebook is available at <https://github.com/piluc/Earth4AllISA/tree/nb>, which allows the reader to interact with the scenarios proposed in this paper and to graphically see the effect of modifying any of the 21 parameters of Table 1 on the evolution of any variable of the model.

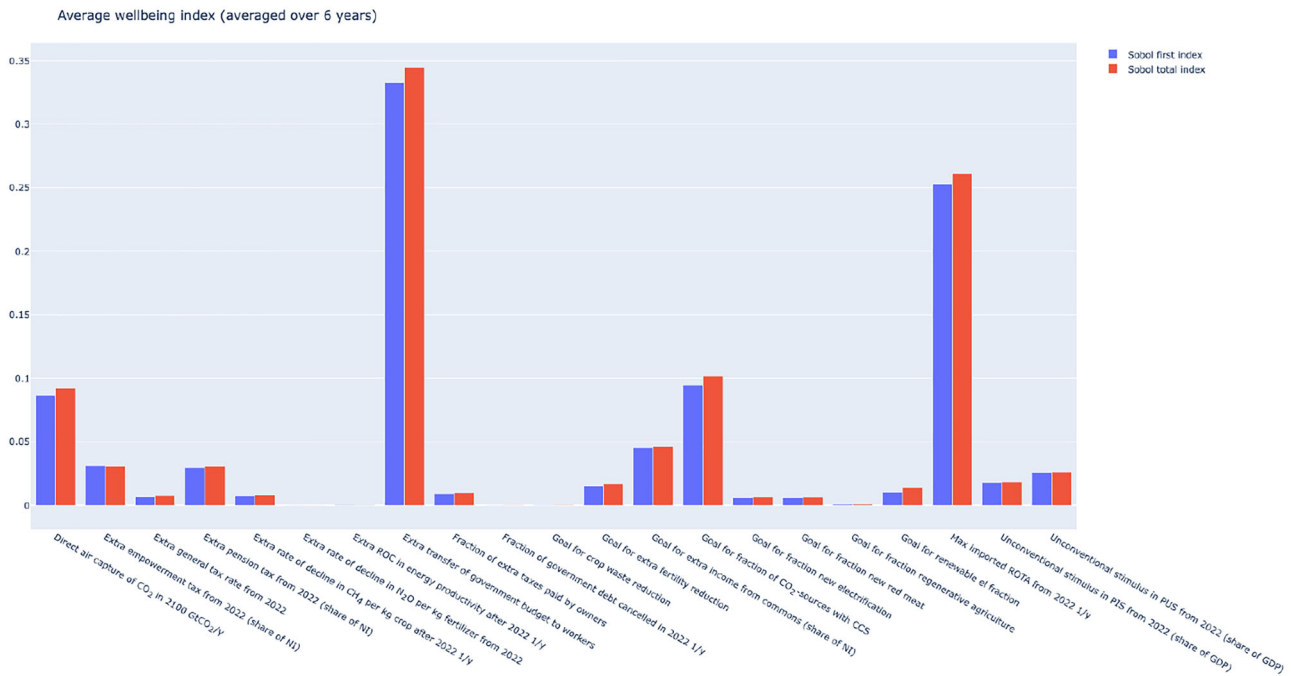


FIGURE 2 The first and total Sobol indices for the average value over 6 years of the average well-being index (underlying data for this figure are available in Table 2 and Table S2 of Supporting Information S4.2).

3 | RESULTS

As a preliminary observation, we noted that simply ignoring 3 of the 21 parameters related to climate, food and land, and energy sectors, respectively, a scenario approximately equal to the GL one can be reached. The three parameters to be excluded are the extra rate of decline in N₂O per kilogram of fertilizer from 2022, the extra rate of change in energy productivity after 2022, and the goal for crop waste reduction. Let us call GL18 the scenario generated by excluding these three parameters and by applying the same policies of the GL scenario to the other parameters. By considering the maximum relative error (in short, MRE) over the entire simulation from 1980 to 2100, we confirmed that the six indicators of Figure 1 (mentioned in Section 1) perform almost exactly in the same way in the two scenarios. Indeed, the MRE of AWBI is 0.0063; the one of the GDPP and the INEQ is 0.0005; the one of the OW is 0.0017; the one of POP is 0.0001; and the one of STE is 0.0009.

3.1 | Sensitivity analysis of the E4A model

Motivated by the above observation, we now perform a sensitivity analysis of the E4A model to identify the parameters that most influence the six indicators: These parameters will be then used to generate alternative scenarios (see also the figure in the Supporting Information summarizing our methodological approach).

3.1.1 | Sobol sensitivity analysis

We carry out a global sensitivity analysis of the six indicators of the E4A model as functions of the 21 parameters involved in the five turnarounds. To this aim, we refer to the Sobol method to determine the contribution of each parameter to the output variance of the six indicators (Sobol, 1993). For each indicator and for each parameter, the output of the Sobol sensitivity analysis includes two non-negative numerical values (i.e., the first index and the total index): The bigger the values, the stronger the influence of the parameter on the indicator. In Figure 2, we show, as an example, the result of the Sobol sensitivity analysis on the average well-being index (averaged over the last 6 years of the simulation) as the output indicator. From the figure, we can conclude that the two parameters that most influence this indicator are the extra transfer of government budget to workers and the maximum imported rate of technology advance from 2022, followed by the goal for the fraction of sources of CO₂ with carbon capture and storage.

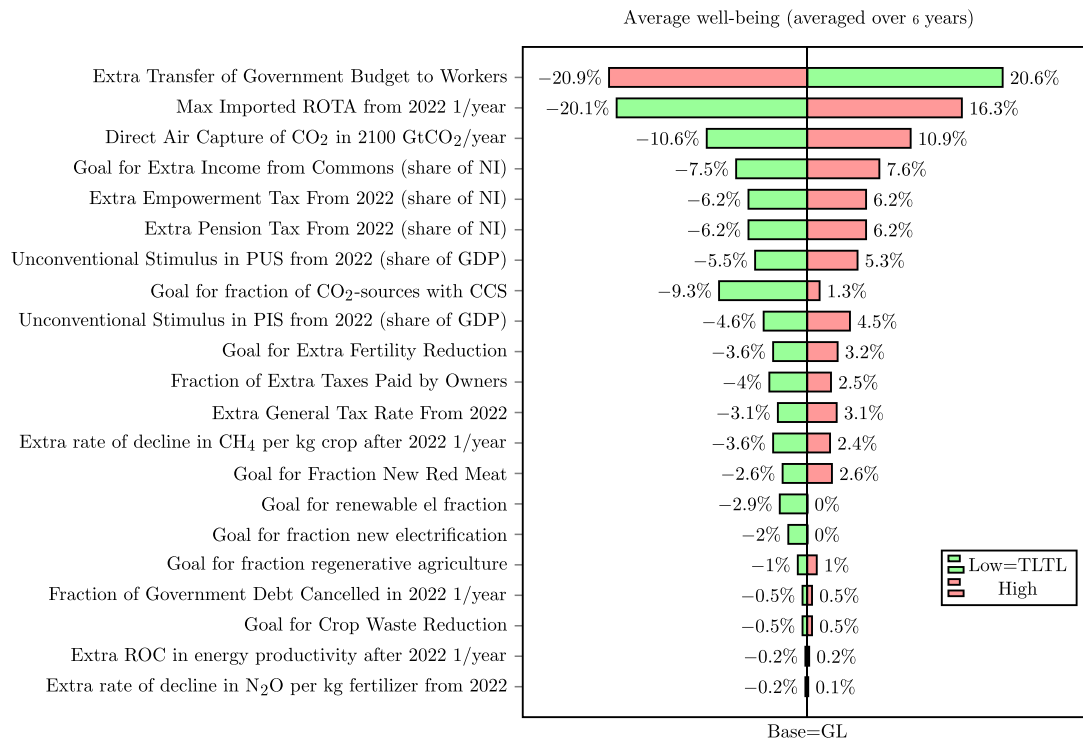


FIGURE 3 The tornado diagram with the average well-being index as the output variable, where we computed the changes in percentage, with respect to the base case, of the average value of the index over the last 6 years of the simulation (underlying data for this figure are available in Table S4 of Supporting Information S5.1). CCS, carbon capture and storage; PUS, public sector; PIS, private sector; ROC, rate of change; ROTA, rate of technological advance.

We have computed the values of the Sobol first and total indices for all indicators, averaged over the last 6 and 12 years of each simulation. For all parameters and for all indicators, there is basically no difference between averaging the last 6 years and averaging the last 12 years. Moreover, apart from very few exceptions, the Sobol first index and the Sobol total index are very close: This suggests that the influence of any parameter on any indicator does not depend so much on its interaction with the other parameters.

In Table 2, we summarize the Sobol first index values, averaged over the last 6 years of each simulation, for any combination of one of the six indicators and one of the parameters in Table 1 (for the 12 years' table, see Supporting Information). As can be seen, only very few combinations correspond to a Sobol first index value at least equal to 0.05 (these are the values in boldface in the table). This suggests that alternative scenarios should be produced by focusing only on the parameters participating in these combinations.

3.1.2 | Local sensitivity analysis

The results of the Sobol sensitivity analysis can be further confirmed by executing a local sensitivity analysis of the E4A model. By leaving 20 parameters unchanged, with respect to their values corresponding to the GL scenario, and by letting the remaining parameter change from the value corresponding to the TLTL scenario up to (approximately) twice the value corresponding to the GL scenario, according to the procedure described in Section 2.3, we can observe how much this parameter, by itself, influences the six indicators. Clearly, we would expect that greater values of this parameter result in better values of the six indicators (i.e., e.g., greater values of the AWBI or smaller values of the INEQ).

We ran three simulations by assigning to all 20 parameters different from p their base values and by assigning to p its low, base, and high value, and we computed the change in percentage, with respect to the base case, of the average value of each of the six indicators over the last 6 years of the simulation (we refer to these three simulations as low, base, and high).

A quite popular way of representing the results of such simulations are tornado diagrams (Eschenbach, 1992), like the one shown in Figure 3, which refers to the AWBI (averaged over the last 6 years of the simulation) as the output variable. We can see that the maximum imported rate of technology advance from 2022 influences this indicator more significantly than the goal for crop waste reduction (which basically has no influence on the indicator). Moreover, its influence is in the "right direction," since greater values of the parameter imply greater values of the AWBI. On the contrary, the extra transfer of government budget to workers strongly influences the AWBI in a negative way (which probably is not what one would expect). The tornado diagrams with all the other indicators as output variables are included in Supporting Information.

TABLE 2 The Sobol first index value, averaged over the last 6 years of each simulation, for each combination of one of the indicators and one of the parameters involved in the turnarounds of the GL scenario (values at least equal to 0.05 are shown in boldface).

	DACCO- 22100	EETF- 2022	EGTRF- 2022	EPTF- 2022	ERDCH4- KC2022	ERDN2- OKF2022	EROCE- PA2022	ETGBW	FETPO	FGDC- 2022	GCWR	GEFR	GEIC	GFCO- 2SCCS	GFNE	GFNRM	GFRA	GREF	MIROT- A2022	USPIS- 2022	USPUS- 2022
AWBI	0.09	0.03	0.01	0.03	0.01	0.0	0.0	0.33	0.01	0.0	0.0	0.02	0.05	0.09	0.01	0.01	0.0	0.01	0.25	0.02	0.03
GDPP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.14	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0	0.0	0.0	0.79	0.01	0.02
INEQ	0.01	0.04	0.01	0.04	0.0	0.0	0.0	0.0	0.05	0.0	0.0	0.08	0.05	0.01	0.0	0.0	0.0	0.0	0.55	0.07	0.08
OW	0.4	0.0	0.0	0.0	0.03	0.0	0.0	0.02	0.0	0.0	0.0	0.0	0.0	0.41	0.02	0.02	0.0	0.03	0.0	0.0	0.0
POP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.99	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.0	0.0
STE	0.3	0.0	0.0	0.0	0.02	0.0	0.0	0.26	0.0	0.0	0.0	0.02	0.0	0.27	0.02	0.01	0.0	0.04	0.03	0.0	0.0

Abbreviations: AWBI, average well-being index; INEQ, inequality index; GDPP, GDP per person; POP, population; STE, social tension index; OW, observed warming.

Parameter	Low	Base	High	β
ETGBW	(0.0, 0.201)	(0.2, 0.0)	(0.4, -0.206)	-1.018
MIROTA2022	(0.0, -0.201)	(0.005, 0.0)	(0.01, 0.164)	36.356
DACCO22100	(0.0, -0.108)	(8.0, 0.0)	(16.0, 0.111)	0.014
GEIC	(0.0, -0.074)	(0.02, 0.0)	(0.04, 0.075)	3.713
EETF2022	(0.0, -0.061)	(0.02, 0.0)	(0.04, 0.062)	3.072
EPTF2022	(0.0, -0.061)	(0.02, 0.0)	(0.04, 0.062)	3.072
USPUS2022	(0.0, -0.057)	(0.01, 0.0)	(0.02, 0.055)	5.565
GFCO2SCCS	(0.2, -0.093)	(0.9, 0.0)	(1.0, 0.013)	0.134
USPIS2022	(0.0, -0.047)	(0.01, 0.0)	(0.02, 0.046)	4.641

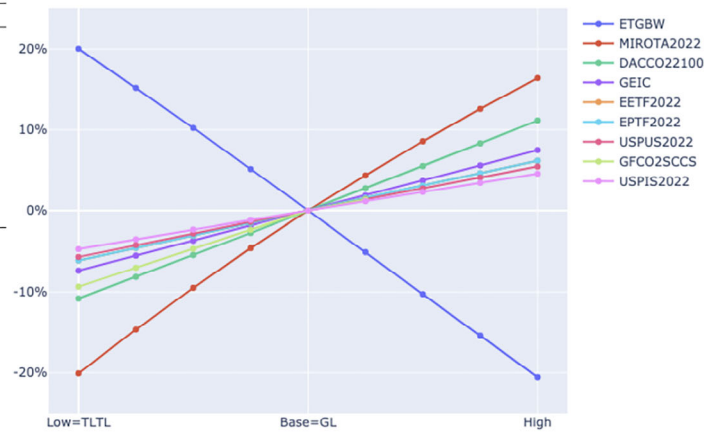


FIGURE 4 The spider plot of the average well-being index, as a function of the top nine parameters of the tornado diagram of Figure 3 (underlying data for this figure are available in Table S5 of Supporting Information S5.3).

Note that the asymmetries in the diagram of Figure 3 are due to the fact that certain parameters cannot take values greater than 1. We observe that the change in the average well-being index apparently depends linearly on the parameters that mostly influence it (an expected behavior for small enough changes), as can be verified in the spider plot shown in Figure 4. Note, however, that the slope coefficient β varies from one parameter to another,¹ as shown in the table of the figure (this is not evident in the plot of the figure because of the implicit normalization that we did in order to represent all parameters on a three-value scale, that is, low, base, and high). Note also that the extra transfer of government budget to workers is the only parameter whose value increase causes a decrease of the value of the AWBI. This is true for all the other indicators (see Supporting Information).

Understanding the effect of modifying the extra transfer of government budget to workers

As we said, increasing the extra transfer of government budget to workers decreases the AWBI. Moreover, increasing this parameter decreases the GDP and increases both OW and STE. This behavior can be explained by following the chain of equations that connects the extra transfer of government budget to workers to the indicator variables. For example, by examining this chain in the case of the AWBI, we note that increasing the extra transfer of government budget to workers increases the fraction of the government gross income devoted to the transfer payments, thus reducing the government net income. This, in turn, reduces permanent government cash inflow and public spending per person: As a consequence, the average well-being from public spending is also reduced. Note that increasing the fraction of the government gross income devoted to the transfer payments increases worker income after tax, which in turn decreases the INEQ: Hence, modifying the extra transfer of government budget to workers has a positive impact on the INEQ. However, the changes of all the six indicators caused by increasing this parameter are relatively small (see Supporting Information).

3.2 | Analyzing alternative scenarios

We maintain that, by ignoring the parameters of empowerment and food turnaround and by focusing on only three parameters of the poverty turnaround, one parameter of the inequality turnaround, and two parameters of the energy turnaround, the same policies proposed by the authors of the E4A model generate a scenario not too far from the GL one. Moreover, if this is associated with focusing more on the policies related to inequality and poverty turnarounds, an even better scenario can be reached. In the following, the POP indicator deserves a separate discussion. In all our alternative scenarios, the population systematically decreases less rapidly than in the GL scenario. Although it is controversial to say how much the world population should decrease, we note that in all these scenarios, the trend of the POP indicator is always very similar to that of the GL scenario.

¹ The value reported in the table has been obtained by running a linear regression of the nine points shown in the figure: this value is very close to the value of the angular coefficient of the first and the last point (thus confirming the linearity of the dependency in this interval).

Indicator	1980	GL 2100	GL6 2100
AWBI	0.6724	3.1237	2.4664
GDPP (K\$)	6.3545	55.8780	55.9569
INEQ	0.6073	0.3671	0.4856
OW (deg C)	0.4000	2.0106	2.1111
POP (M)	4420.0000	5984.4509	7069.5969
STE	1.3000	1.0906	1.1157

Parameter name	GL6 value
Direct air capture of CO ₂ in 2100 GtCO ₂ /y	8.000
Goal for extra income from commons (share of NI)	0.020
Goal for fraction of CO ₂ -sources with CCS	0.900
Max imported ROTA from 2022 1/y	0.005
Unconventional stimulus in PJS from 2022 (share of GDP)	0.010
Unconventional stimulus in PUS from 2022 (share of GDP)	0.010

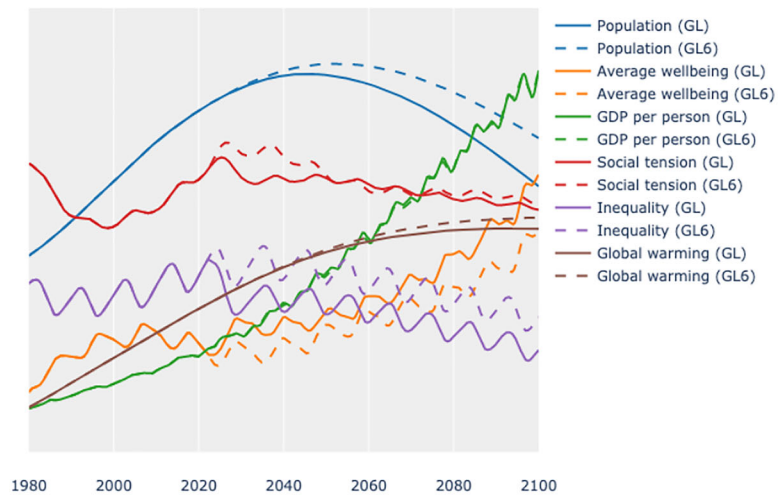


FIGURE 5 The evolution of the six indicators in the giant leap (GL) and the GL6 scenarios: In this latter scenario, the values of all parameters not included in the lower table are equal to their values in the too little too late (TLTL) scenario (underlying data for this figure are available in the folder `simulations` of the source repository mentioned in Section 2.4). AWBI, average well-being index; INEQ, inequality index; GDPP, GDP per person; POP, population; STE, social tension index; OW, observed warming; CCS, carbon capture and storage; ROTA, rate of technological advance.

3.2.1 | Selecting the six policies

On the basis of the global and local sensitivity analyses, we select a set of six parameters that seem as those that most influence the evolution of the six indicators. These six parameters, which are involved in the energy, inequality, and poverty turnarounds, are the following: the direct air capture of CO₂ in 2100, the goal for extra income from commons (as a share of the national income), the goal for the fraction of CO₂-sources with carbon capture and storage, the maximum imported rate of technology advance from 2022, the unconventional stimulus in the private sector from 2022 (as a share of the GDP), and the unconventional stimulus in the public sector from 2022 (as a share of the GDP). The six parameters were selected as follows. First, we considered only parameters whose Sobol first index (see Table 2) was *greater* than 0.05 for at least one indicator. Second, we excluded the extra transfer of government budget to workers parameter because of its “counter-intuitive” negative effect (see Section 3.1.2.1). Third, we excluded the goal for extra fertility reduction, since we believe that this policy (besides being controversial) might turn out to be quite difficult to implement. Finally, between the two parameters whose Sobol index for at least one indicator is *equal* to 0.05, we preferred to maintain the one of them (that is, the goal for extra income from commons [as a share of the national income]) that seems to influence not only the INEQ (which is true also for the fraction of extra taxes paid by owners) but also the AWBO (which is not true for the fraction of extra taxes paid by owners).

3.2.2 | The GL scenario with fewer turnarounds

By assigning to the six selected parameters the same values used by the authors of E4A model to get the GL scenario, we observe that a scenario, called GL6, not too far from the GL one can be reached. As shown in Figure 5, the GDPP does not change at all, while the POP at year 2100 increases (from 6 to 7 billion). On the other hand, AWBI, INEQ, OW, and STE perform slightly worse: In particular, AWBI at year 2100 goes from slightly more than 3 to slightly less than 2.5. However, the trends of all indicators are approximately the same.

3.2.3 | Improving the GL scenario

The previous result suggests that the energy, inequality, and poverty turnarounds can generate a scenario even better than the GL scenario, by assuming a greater attention devoted to only these turnarounds. In particular, by (approximately) doubling the values of the six parameters selected in the previous step (according to the procedure described in Section 2.3), we obtain a scenario, called DGL6, which is significantly better than the GL scenario (as shown in Fig. S11 of Supporting Information S6). Indeed, at year 2100, the AWBI almost doubles and the GDPP grows by 20%, while the INEQ, the STE, and the OW all decrease. However, it is worth noting that the AWBI, the INEQ, and the STE perform worse immediately after the implementation of the policies until approximately 2040, when their performance begins to improve.

Indicator	1980	GL 2100	DGL4 2100
AWBI	0.6724	3.1237	3.3649
GDPP (K\$)	6.3545	55.8780	62.220
INEQ	0.6073	0.3671	0.3634
OW (deg C)	0.4000	2.0106	2.1081
POP (M)	4420.0000	5984.4509	6929.0908
STE	1.3000	1.0906	1.1258

Parameter name	DGL3 value
Direct air capture of CO ₂ in 2100 GtCO ₂ /y	3.000
Goal for extra income from commons (share of NI)	0.040
Goal for fraction of CO ₂ -sources with CCS	0.900
Max imported ROTA from 2022 1/y	0.005
Unconventional stimulus in FIS from 2022 (share of GDP)	0.020
Unconventional stimulus in PUS from 2022 (share of GDP)	0.020

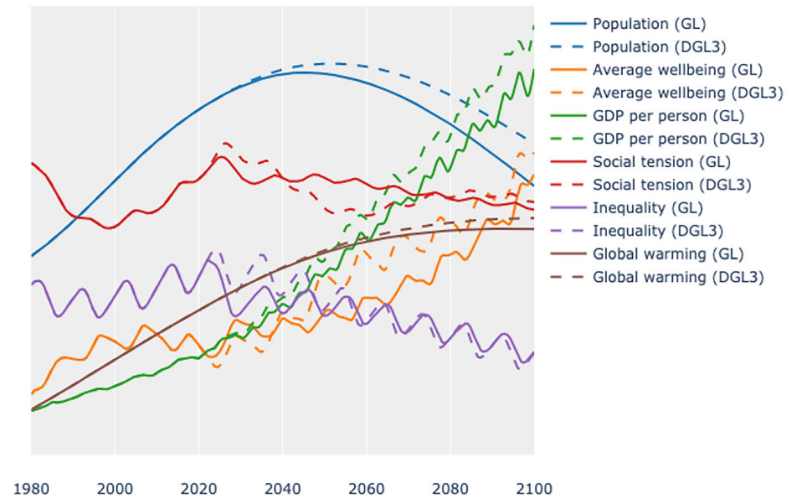


FIGURE 6 The evolution of the six indicators in the giant leap (GL) scenario and in the DGL3 scenario: In this latter scenario, the values of all parameters not included in the lower table are equal to their values in the too little too late (TLTL) scenario (underlying data for this figure are available in the folder *simulations* of the source repository mentioned in Section 2.4). AWBI, average well-being index; INEQ, inequality index; GDPP, GDP per person; POP, population; STE, social tension index; OW, observed warming; CCS, carbon capture and storage; ROTA, rate of technological advance.

3.2.4 | Keeping three parameters unmodified

The values of the two parameters related to the energy turnaround in the GL scenario might turn out to be already very costly to be reached (IEA, 2023; Metz et al., 2005; Sekera, June and Lichtenberger, Andreas, 2020). Moreover, estimating the cost of implementing the policy related to the maximum imported rate of technological advance is not easily done on the basis of the documentation of the E4A model. By not increasing the values of these three parameters and by still doubling the values of the other two parameters involved in the poverty turnaround and the value of the parameter involved in the inequality turnaround (always with respect to the values used by the authors of the E4A model to get the GL scenario), a new scenario, called DGL3, can be obtained (see Figure 6). In this scenario, the GDPP and the AWBI perform better than in the GL scenario, while the INEQ and the STE perform in a very similar way. Observed warming increases by approximately 5%, while population has the same behavior as in the previous two alternative scenarios (i.e., GL6 and DGL6). As in the case of the DGL6 scenario, the AWBI, the INEQ, and the STE perform worse between 2022 and approximately 2040, when they start performing in a comparable (or even better) way.

4 | CONCLUSIONS

In this paper, we have executed a global (Sobol) and local sensitivity analysis of the E4A model, to determine the policies that most influence the evolution of the six indicators used by the model's designers to evaluate alternative scenarios. As a result of this analysis, we propose several scenarios that are comparable to or even better than the GL scenario. The following is the list of the different scenarios we analyzed in the paper (the values of the six parameters for each scenario are summarized in Table S7 of Supporting Information S7).

- TLTL: a business-as-usual scenario in which no new policy is introduced with respect to the past.
- GL: a giant-leap scenario in which five turnarounds (poverty, inequality, empowerment, food, and energy) are implemented through 21 policies.
- GL18: a GL-based scenario in which the values of the three parameters ERDN2OKF2022, EROCEPA2022, and GCWR are assigned the same value as in TLTL (this scenario performs almost the same as GL).
- GL6: a scenario in which the six parameters in bold in Table 1 are assigned the same value as in GL, while the other parameters are assigned the same value as in TLTL (this scenario performs slightly worse than GL but preserves all trends of the output indicators).
- DGL6: a GL6-based scenario in which the values of the six parameters in bold in Table 1 are doubled, apart from GFCO2SCCS, which is set to 1 (this scenario performs much better than GL but it might be out of reach given the current state of technology related to the direct air capture of CO₂ and the carbon capture and storage).
- DGL3: a DGL6-based scenario in which the two energy turnaround parameters in bold in Table 1, that is, the DACCO22100 parameter and the GFCO2SCCS parameter, and 1 poverty turnaround parameter, that is, the MIROTA2022 parameter, are maintained equal to 8, to 0.9, and to

0.005, respectively (i.e., their values in the GL scenario). This scenario is better than the GL scenario for two indicators (i.e., the GDPP index and the AWBI), very similar to other two (i.e., the INEQ and the STE), and slightly worse for another (i.e., OW), while producing the same trend for POP.

It is worth noting that, in the case of the DGL6 and the DGL3 scenarios, at the beginning of the implementation of the policies, some indicators perform worse than in the GL scenario, and they start performing better in the mid-2000s. We believe that this behavior merits deeper qualitative analysis.

In Bernstein et al. (2023), it is stated that “the five turnarounds must be committed to and implemented simultaneously to achieve the” GL scenario. The results summarized above suggest instead that the same scenario can be, with good approximation, reached by restricting the turnarounds to three and that by focusing more on them an even better scenario can be achieved. In particular, focusing more on fighting inequality and poverty can lead to better results in terms of GDPP and AWBI, still keeping under control INEQ, STE, and OB in a way similar to the giant leap scenario. It is, however, worth noting that the relevance of the policy recommendations (in the present paper as well as in the original E4A publications) depends directly on the robustness of the E4A model, in particular with respect to its modeling choices.

In our opinion, the DGL3 scenario seems to be the one that deserves deeper analysis, in terms of cost-effectiveness. We believe that a main limitation of our results is the lack of a feasibility analysis and a robust and accurate cost-effectiveness analysis of the scenarios. However, this limitation is inherent in the E4A model. Indeed, as stated in Dixson-Decleve et al. (2022), the E4A model can be improved in several ways (such as developing better climate and energy sectors). One important suggested improvement is to better account for the cost of the turnarounds, that is, for assigning to the 21 involved parameters' specific values. This would allow us to compare the costs and the gains of different scenarios: For example, it would be very useful to compare the GL scenario and the DGL3 scenario in terms of costs. Indeed, while for some of the parameters involved in the DGL3 scenario the cost of assigning a specific value is quite clear (such as the percentage of the GDP devoted to sustain the private and the public sector), in the case of other parameters (such as, e.g., the maximum imported rate of technology to be imposed), determining this cost seems to be more difficult. Moreover, a better climate and energy sector along with a clear cost assignment would allow us to better determine the values of the parameters involved in the energy turnaround and their influence on the six output indicators. It would also be worth analyzing the behavior of the scenarios proposed in this paper with respect to the indicators used in Bernstein et al. (2023) to examine the progress of the sustainable development goals (UN, 2024): These indicators, according to the authors, can be derived from variables of the E4A model or can be easily added to the model itself. Finally, it would be interesting to apply our analysis to the 10-region version of the E4A model, which has also been developed (or it is under development) according to the authors of the global model (as far as we know, these regional versions of the model are not yet publicly available).

AUTHOR CONTRIBUTIONS

Pierluigi Crescenzi and Giorgio Gambosi supervised all simulations and sensitivity analyses and wrote the paper. Emanuele Natale conceived of the presented idea and had final control over the paper. Aurora Rossi checked the code and the experimental results. Lucia Nasti worked on a preliminary version of the sensitivity analysis while affiliated with the Gran Sasso Science Institute (until mid November 2023). All authors discussed the results and commented on the manuscript. Pierluigi Crescenzi, Giorgio Gambosi, Emanuele Natale, and Aurora Rossi revised the original manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Pierluigi Crescenzi  <https://orcid.org/0000-0001-8789-3195>

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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