Enhancing the policy relevance of scenario studies through a dynamic analytical approach using a large number of scenarios

Céline Guivarch¹, Vanessa Schweizer², Julie Rozenberg¹

¹Centre Internationale Recherche sur l’Environnement et Développement (CIRED), Paris, France
²National Center for Atmospheric Research (NCAR), Boulder, CO, USA

Abstract: We present a new dynamic analytical approach for studying scenarios produced by an integrated assessment (IA) model. Our approach involves the analysis of a large number of scenarios, which can better address three principal shortcomings of how uncertainty is traditionally handled in IA scenario studies. The shortcomings are all a result of the prevailing practice of investigating a small number of scenarios and include (1) the ad hoc nature of exploring vast socioeconomic uncertainties with only a small number of scenarios; (2) the conventional representation of alternative scenario typologies as “parallel universes,” which provide little insight on possible socioeconomic conditions that could transform scenarios appearing to match one typology into another; and (3) the inherently unrealistic determinism of IA model projections. These shortcomings may inhibit the policy relevance of IA scenario studies. As an analytical approach that may improve the situation, we describe and demonstrate a dynamic method for analysing large numbers of scenarios and provide an example application using the framework for Shared Socioeconomic Pathways (SSPs), which are new socioeconomic scenarios being developed for future climate change research. With the IA model IMACLIM-R, we systematically generated 432 scenarios and classified them as consistent with each of the five SSP typologies. We then traced their evolution through the SSP typology space dynamically over the years 2001-2090. We found that the dynamic analytical approach can reveal the influence of socioeconomic conditions that change the scenario typology classification of individual scenarios over time. Explanations for such scenario behaviour could be highly policy relevant. We describe directions for future research and conclude that the dynamic approach holds promise for better confronting common shortcomings of IA scenario studies thereby potentially enhancing their policy relevance.

Key words: scenario, uncertainty, dynamic analysis, shared socioeconomic pathways, climate change

1. Introduction

Socioeconomic scenario studies with integrated assessment (IA) models are important tools in energy and environmental change research. Nevertheless, some scholars criticize the way uncertainty is treated in such scenario studies (e.g. Morgan and Keith 2008). In this paper, we discuss three principle shortcomings of how uncertainty is customarily handled and present a new dynamic approach to analysing scenarios, which could address them.

Conventionally, a small number of socioeconomic scenarios are investigated. This is rationalized by the concern that large numbers of scenarios would provide a dizzying array of results both for the scenario analyst and for the decision-maker who hopes to learn something from the scenario study. However, the first shortcoming to this approach is that the wide variety of socioeconomic uncertainties is
inspected *ad hoc* leaving many uncertainties un-investigated. We suggest that the *ad hoc* nature of such studies may constrain their policy relevance, since it could be argued that the studies are not comprehensive (Schweizer and Kriegler 2012).

A related issue is the motivation for selecting the small number of scenarios. During the late 1990s and early 2000s, multiple high-profile global environmental change scenario assessments popularized the Story and Simulation (SAS) approach (Alcamo 2008). SAS incorporates practices that are common for strategic scenario building in the business sector – namely distinguishing alternative scenario typologies by driving factors (e.g. Ogilvy and Schwarz 1998). With the new socioeconomic scenarios currently under development for future climate change research (the Shared Socioeconomic Pathways, or SSPs), there is a move to also distinguish scenario typologies by scenario outcomes. We will discuss the SSPs in more detail in the next section and find their scenario classification scheme to be a promising development. However, the second shared limitation of classifying scenarios by their drivers (or their outcomes) is that the scenarios are treated as “parallel universes.” In other words, the scenarios depict straightforward alternative futures that are the result of different decisions made in the near term, and they provide little insight on socioeconomic conditions that could potentially transform a scenario appearing consistent with one typology during one time period into a scenario that ends up consistent with another typology during a latter time period. Information about socioeconomic conditions for such transitions could be highly policy relevant.

IA model projections can usefully represent expected outcomes such as energy demand or greenhouse gas emissions due to dominant economic influences (e.g. price signals, technology availability). However, it is problematic when a few deterministic scenarios are the objects of study over long time frames (multiple decades or a century). Thus the third major shortcoming to studying a small number of IA scenarios is that reality is much more stochastic and subject to policy interventions or technological breakthroughs that can shatter assumptions that would be perfectly reasonable on shorter time frames (Casman et al. 1999). Such discontinuities characterize the reality of socioeconomic processes underlying IA model projections. Since it is highly likely that reality will diverge from any long-term projections provided by some small set of scenarios, this may not help their policy relevance.

In summary, the policy relevance of small sets of IA model projections may be constrained by their partial exploration of socioeconomic uncertainties, the limited information that they provide on conditions that may mark significant socioeconomic transitions, and their unrealistic determinism. We propose that systematically generating a large number of scenarios and investigating them in a dynamic manner could better address these challenges to analysing socioeconomic uncertainties. In section 2, we describe a systematic approach for such a method. In section 3, we present example results and comment on possibilities for future research. In section 4, we conclude with a discussion of how the dynamic
approach attends to the above shortcomings and could improve the policy relevance of quantitative scenarios.

2. Methodology
A general description of our proposal for a dynamic approach to scenario analysis can be summarized in four steps.

1. Develop or identify a scenario typology scheme
2. Generate a large number of scenarios
3. Develop indices for classifying scenarios within the typology scheme
4. Develop criteria for inspecting scenario evolution within the typology scheme

In the subsections below, we discuss each of these steps and use the framework for the new SSPs as an example.

2.1. Development or identification of a scenario typology scheme
In this demonstration, we utilized an existing scenario typology scheme, but generally speaking, one could develop a typology scheme of interest. For new SSPs, their fundamental logic is rooted in two key uncertainties: socioeconomic conditions that contribute to challenges for mitigation, and socioeconomic conditions that contribute to challenges for adaptation (Core Writing Team 2011). Additionally, the scientific community decided that the scenario space should be divided into five typologies as shown in Figure 1 (O’Neill et al. 2011). Three typologies correspond to futures where mitigation and adaptation challenges co-vary (domains containing SSP1, SSP2, SSP3), while two typologies are mixed futures where adaptation challenges dominate (domain containing SSP4) or mitigation challenges dominate (domain containing SSP5). Although socioeconomic conditions that contribute to mitigation or adaptation challenges could be scenario drivers, the classification of any particular scenario as representative of any of the five domains could also depend upon its outcomes. A read of the draft scenario narratives from the Boulder meeting report (O’Neill et al. 2011) supports this interpretation.
2.2. Generation of a large number of scenarios

We used the IA model IMACLIM-R to generate a large number of scenarios. We chose to systematically vary assumptions for values of 7 groups of parameters (or scenario drivers). Brief descriptions of the groups of parameters appear below; more detailed descriptions of the parameters and the IMACLIM-R model can be found in the Appendix.

1. Parameters regarding economic growth of the leader country (3 alternatives: low, medium or fast)
2. Parameters regarding the convergence of low-income countries (3 alternatives: low, medium or fast)
3. Parameters on the rigidities of labour markets (2 alternatives: low rigidities or high rigidities)
4. Parameters on the availability of coal and coal-to-liquids (2 alternatives: low availability or high availability)
5. Parameters regarding energy consumption behaviours (2 alternatives: energy-sober or energy-intensive)
6. Parameters regarding induced energy efficiency (3 alternatives: slow globally; fast in rich countries but slow catch-up in low-income countries; fast globally)
7. Parameters on the availability of low carbon technologies (2 alternatives: low availability or high availability).

The combinations of these alternative assumptions generated 432 scenarios ($432 = 3^3 * 2^2 * 3^2 * 2^2$), which we analysed over the period 2001-2090.
2.3. Development of indices for classifying scenarios in the typology scheme

In order to draw conclusions from the large number of scenarios generated, it is necessary to devise a way to relate qualities of the scenarios back to the scenario typology scheme. We found the visual layout of the SSP scenario space useful, so we developed indices and domain boundaries that would correspond to the axes and domains depicted conceptually in Figure 1. Many choices are available for interpreting the axes and domains.

Indices for the axes could be composite (e.g. Schweizer and O’Neill, in review) or individual quantitative indicators (e.g. Rozenberg et al., in review). For the sake of conciseness and clarity, we limit our exploration to one example of indicator choices. In this example, we do not argue in favour of one indexing approach or one indicator over another but instead simply demonstrate a method for implementing the dynamic analysis of many scenarios. In this case, we interpreted challenges to mitigation as annual global CO2 emissions (as climate change is directly related to the quantity of CO2 accumulated in the atmosphere) and challenges to adaptation as the inverse of developing countries’ GDP per capita in a given year, i.e., the lower GDP per capita is in the poorest countries, the higher the challenges for adaptation. As depicted in Figure 2, we then normalized results for these quantitative indicators to arrive at indices for the SSP scenario space with domain and range [0,1].

![Figure 2. Translation of indicator plots to domains in SSP scenario space](image)

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1 Poor communities, and in particular those who live in developing countries, are considered the most vulnerable to climate change. Even though this indicator does not differentiate between different categories of households within a country, it is a first approximation of these populations’ vulnerability. The developing countries that we include are those of the following regions: Africa, Asia (except China, Japan, and Taiwan), and Latin America (except Brazil).
Since our scenarios were derived from one model, we interpreted domain boundaries relative to the distribution of the 432 scenarios (mean, median, middle of extremes). It should be noted that the scenarios are not equally distributed in the SSP scenario space defined by their extreme values. Thus another interpretive choice must be made between creating uniformly sized domains (e.g. Schweizer and O’Neill, in review), which implies that some domains contain more scenarios than others, and drawing domain boundaries such that each domain contains roughly the same number of scenarios (e.g. Rozenberg et al., in review). In this analysis, we chose to specify same-sized domains with a diamond-shaped domain corresponding to SSP2. The boundaries between the domains for SSP3 and SSP5, as well as SSP1 and SSP4, are demarcated by the midpoint of the normalized interval \((x = 0.5 \text{ and } y = 0.5)\). The boundaries of the SSP2 domain were chosen such that all five domains would have the same area.

A final important detail, which the conceptual descriptions of the SSP framework do not specify, is the time, or year, in which to do scenario classification. Since the socioeconomic scenarios will eventually be combined with climate scenarios for integrated analyses of mitigation and adaptation options as well as impacts, it would be reasonable to choose a year at the end of the 21st century (in our case, 2090). Figure 3 shows the classification of the 432 IMACLIM-R scenarios in the SSP scenario space for global CO2 emissions in 2090 (normalized) versus the inverse of developing countries’ GDP per capita in 2090 (normalized). This begs the question of why wouldn’t one choose other benchmark years that could be of interest such as 2050 or 2030. Would it make a difference if one chose an alternative benchmark year? Such questions inspired us to investigate the IMACLIM-R scenarios dynamically.

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\(^2\) We credit the idea for a diamond-shaped domain corresponding to SSP2 to Jae Edmonds of the GCAM modelling group at the Joint Global Change Research Institute.
2.4. Development of criteria for inspecting scenario evolution

As discussed in section 2.3, the boundaries for the domains in the SSP scenario space were drawn around the distribution of the 432 scenarios. Thus the performance of a scenario relative to others determines its classification in the scenario typology scheme in any given year. Additionally, the typology of SSP2, which had candidate names during the Boulder meeting such as “Current Trends Continue” or “Middle of the Road” (O’Neill et al. 2011 p. 10), provides an additional clue for how one could begin to examine a large number of scenarios in the SSP scenario space dynamically.

The 432 scenarios could be considered an ensemble of runs of the IMACLIM-R model. As is customary in physical climate modelling, it would therefore be possible to compare the performance of any individual model run against the ensemble mean. The concept of an ensemble mean could be useful for IA modelling, since there has long been controversy over whether any scenario could be considered business-as-usual (e.g. see the discussion of probabilistic futures in Carter et al. 2007). As discussed in section 1, socioeconomic processes in reality are some amalgamation of predictable long-term trends punctuated with unpredictable discontinuities. In a sense, the ensemble mean can serve as an agnostic representation of the middle-of-the-road scenario across the 432 cases and would occupy the centre of the SSP scenario space at all times (i.e. at each time step of a dynamic analysis).

During the first time step (in our example, when \( t = 2001 \), as this is the calibration date of the IMACLIM-R model), all scenario trajectories have the same starting point and are equal to the ensemble.
mean. When placed in the SSP scenario space and considered dynamically, this means that all scenarios begin in the centre domain corresponding to SSP2. With each progressive time step, individual scenario runs spread away from the ensemble mean across the five SSP domains. Visually, one can trace this divergence by performing a transformation on the indicators discussed in section 2.3 with the equation:

\[ \forall t, X_t = \frac{x_t - \bar{x}_t}{\max(x_T) - \min(x_T)} + \frac{\bar{x}_T - \min(x_T)}{\max(x_T) - \min(x_T)} \]

Where \( x_t \) is the indicator at time \( t \), \( \bar{x}_t \) is the midpoint of the distribution of values at time \( t \), \( X_t \) is the transformed indicator at time \( t \), and \( T \) is the year of the time slice (i.e. some year of interest).

With this transformation, at time \( T \),

- if \( x_T = \min(x_T) \) then \( X_T = 0 \)
- if \( x_T = \max(x_T) \) then \( X_T = 1 \)

Figure 4 shows a dynamic representation of the trajectories in the SSP scenario space for year 2090 when global CO2 emissions and GDP per capita of low-income countries act as the indicators of challenges to mitigation and adaptation respectively. Note that the scenario typology classification given by the endpoints of the trajectories exactly correspond to the static scenario typology classification shown previously in Figure 3.
Now that the method for revealing dynamic trajectories across scenarios has been established, we provide an example in section 3 of what type of research could be done with a dynamic analytical approach to scenarios.

3. Example application: The (in)stability of global socioeconomic scenarios

In this section, we show some example results and briefly describe how they could be used in an analysis that may enhance the policy relevance of IA scenario studies. Following from the dynamic methodology discussed previously, in these example results, we also classified each scenario in SSP space during each time step. In other words, in addition to calculating the difference of the scenario performance from the ensemble mean, we also redrew the SSP domain boundaries around all of the scenarios at each time step. Since scenario locations in the SSP space are based on their indicator values, which are also a function of time, this enabled us to observe the stability of scenario typology classifications over the 2001-2090 period.

In Figure 5, we superimpose the SSP domain classification of scenarios in year 2020 (purple) on the domain classification of the same scenarios in year 2090 (red) and focus on the domain for SSP4 in this example. We found most scenarios corresponding to the domain for SSP4 are stable in time, i.e., they remain in the bottom-right corner of the scenario space across the 2001-2090 interval. However, there are also scenarios that correspond to the SSP4 domain in 2090 that appear consistent with alternative domains earlier in the century. For instance, three scenarios are consistent with the SSP1 domain earlier in the century, and remain so for many decades; however, they transition to the SSP4 domain after 2040 (one scenario) or after 2060 (two scenarios). Similar scenario behaviour can be seen for a number of scenarios that appear consistent with the domain for SSP2 earlier in the century.

Figure 5. Scenarios consistent with SSP domain 4 in the year 2090 (red dots) and their SSP classifications in 2020 (purple). Black dots represent the trajectory of the scenarios across two-year time steps. Most scenarios in domain 4 are classified to that domain from 2001-2090 (left panel). However, scenarios classified in other domains can also move to domain 4 (some domain 1 scenarios move to domain 4 in the middle panel; some domain 2 scenarios move to domain 4 in the right panel).
Now that it has been demonstrated that socioeconomic scenarios can traverse SSP domains over the course of the century, a natural follow-up question is what socioeconomic conditions cause some scenarios to do this? Similarly, if global socioeconomic conditions by 2025 are such that they resemble the SSP4 typology, where adaptation challenges dominate mitigation challenges, what policy interventions would show promise to extract the world from this domain? Such questions could begin to be addressed through the scenario elicitation methodology demonstrated in Rozenberg et al. (in review), where a modified version of the Patient Rule Induction Method (Friedman and Fisher 1999) is used to statistically data mine scenarios of interest and uncover their common drivers.

5. Conclusion
In this paper, we described and demonstrated a new dynamic analytical approach for investigating a large number of scenarios (432) generated by an IA model. We also presented some example results demonstrating that global socioeconomic scenario typologies are not necessarily stable (that is, the typology of some scenarios can change over time), and suggest how this finding could be part of a larger scenario study. We conclude that the dynamic analytical approach holds promise for addressing three principal shortcomings of traditional IA scenario studies, where uncertainty is explored with a small number of scenarios. Such improvements are likely to enhance the policy relevance of IA scenario studies for three reasons.

First, by systematically generating large numbers of scenarios, significantly more uncertainties are investigated. We find this to be a substantial improvement over the common practice of examining only a handful of scenarios, where large swaths of policy-relevant uncertainties are likely to be overlooked. By making the exploration of uncertainties substantially more comprehensive, the policy-relevance and credibility of IA scenario studies could be enhanced.

Second, the dynamic analytical approach moves past conventional interpretations of the two-dimensional scenario space, which delineate scenario typologies by drivers or outcomes during a target year. Instead, we introduce a dynamic view of the scenario space, which can uncover additional important information of scenarios. In our demonstration, we reveal dynamic scenario trajectories, as well as identify scenarios where their typology classifications change over time. The latter finding demonstrates that research questions are missed when scenarios are treated as “parallel universes,” and such questions could be highly policy-relevant. Examples of policy relevant questions include, can we know if we are on a desirable (e.g. the SSP1 domain) or undesirable (e.g. the SSP3 domain) scenario trajectory? How can we change from an undesirable scenario trajectory to desirable one?

IA model runs are inherently deterministic, so the ability of a study using a small number of scenarios to provide meaningful information in the face of discontinuities is limited. In our view, this
elevates the need for IA studies to examine rich sets of many scenarios that systematically vary multiple parameters to enhance their policy relevance.

Generally speaking, when a database of many scenarios are analyzed rather than a few cases, different (and potentially more policy relevant) research questions become possible for investigation. This paper demonstrates the possibilities of a dynamic analytical methodology and provides exploratory results based on one IA model. Ideally, databases with many scenario runs from multiple IA models could help the scientific community better understand differences between the underlying socioeconomic processes captured in different models. Potentially, studies of large sets of scenarios from multi-model databases could also provide meaningful, robust, policy-relevant results.

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7. References


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8. Appendix

**Description of the IMACLIM-R model.**

IMACLIM-R is a hybrid simulation model of the world economy, which represents macro-economic and technological world evolutions in a consistent framework disaggregated into 12 regions and 12 sectors.

The growth engine is composed of exogenous demographic trends and of technical progress that increases labor productivity, as in Solow’s neoclassical model of economic growth. The two sets of assumptions on demography and labor productivity only prescribe natural growth. Actual economic growth then results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) under-utilization of production factors (labor and capital) due to the possible inadequacy between flexible relative prices (including wages) and inert capital vintage characteristics. Importantly, the model is not based on perfect expectations, but on adaptive expectations reacting on current price signals and past trends. IMACLIM-R, therefore, represents a second-best economy, i.e an economy in which factor utilization may not be optimal. For instance, actual economic growth can thus be constrained by resource availability if resource scarcity was not well anticipated.

Dynamic sub-modules in the model represent the evolution of households’ equipment and productive capacities technical characteristics, including technology explicit descriptions of the main elements of the energy system (e.g. power generation, vehicle) and endogenous technical change mechanisms (e.g. learning-by-doing, induced energy efficiency).

1. Parameters on leader country growth (3 alternatives: low, medium or fast)
   - Total population, labour force and labour productivity trends in high-income countries

2. Parameters on the income convergence of low-income countries (3 alternatives: low, medium or fast)
   - Total population, labour force and labour productivity trends in low income countries

3. Parameters on the rigidities of labour markets (2 alternatives: low rigidities or high rigidities)
- Elasticity of the wage curve

4. Parameters on the availability of coal and coal-to-liquids (2 alternatives: low availability or high availability)
   - Coal extraction: We introduce two assumptions regarding the elasticities of increases in coal price to changes in demand. Coal extraction can be either “high” or “low.” In the “high” alternative, the coal price increases more slowly with demand changes than in the “low” alternative.
   - Availability of coal-to-liquids (CTL) technology: We introduce two assumptions about the price at which CTL becomes competitive and on the rate at which it can penetrate the market. CTL technology availability can be either “high” or “low.”
   - Both assumptions are coupled: the “low” (resp. “high”) alternative for coal is assumed to go with the “low” (resp. “high”) alternative for CTL.

5. Parameters on energy consumption behaviours (2 alternatives: energy-sober or energy-intensive)
   - Development patterns: We introduce two assumptions on the evolution of households’ preferences in transportation and housing (e.g. evolution of the number of cars per capita when income increases, maximum dwelling surface per capita in developing countries) as well as on the saturation level of households’ industrial goods consumption. Development patterns are either “intensive” or “sober.” In the “intensive” case, equipment rates for personal vehicles evolve more quickly, dwelling surface per capita evolves more quickly, and industrial goods consumption saturates at a higher level than in the “sober” alternative.
   - Production choices: We introduce two alternatives on the freight content of production through alternative evolutions of the input-output coefficient representing the transportation requirement per unit of good produced. The alternatives on production choices correspond to either “constant freight requirement” or “reduced freight requirement”.
   - Alternatives on development patterns and production choices are grouped (in order to reduce the size of combinations): when development styles are sober, it is assumed that production choices correspond to “reduced freight requirement,” while the “intensive” development style is assumed to correspond with the “constant freight requirement.”

6. Parameters on the induced energy efficiency (3 alternatives: low globally, high in rich countries but slow catch-up in low-income countries, and fast globally)
   - Energy efficiency is driven by energy prices. We introduce three alternatives for the parameters describing maximum annual energy efficiency improvement in the leading country and the catch-
up speed of the others: “Slow potential in the leading country and slow catch-up”; “fast potential in the leading country and slow catch-up” (slow technological transfers); and “fast potential in the leading country and fast catch-up.”

7. Parameters on the availability of low carbon technologies (2 alternatives: low availability or high availability).
   - We build two assumptions for parameters describing the market penetration of nuclear energy, renewable resources, carbon capture and storage, and electric vehicles. These parameters include learning rates and maximum market shares throughout the simulation period. Availability of low-carbon technology can be either “high” or “low.”

The combinations of these alternative assumptions across the seven groups generate 432 scenarios over the 2001-2090 period.