Defining climate change scenario characteristics with a phase space of cumulative primary energy and carbon intensity

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Abstract

Climate change modeling relies on projections of future greenhouse gas emissions and other phenomena leading to changes in planetary radiative forcing. Scenarios of socio-technical development consistent with end-of-century forcing levels are commonly produced by integrated assessment models. However, outlooks for forcing from fossil energy combustion can also be presented and defined in terms of two essential components: total energy use this century and the carbon intensity of that energy. This formulation allows a phase space diagram to succinctly describe a broad range of possible outcomes for carbon emissions from the future energy system. In the following paper, we demonstrate this phase space method with the Representative Concentration Pathways (RCPs) as used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5).

The resulting RCP phase space is applied to map IPCC Working Group III (WGIII) reference case 'no policy' scenarios. Once these scenarios are described as coordinates in the phase space, data mining techniques can readily distill their core features. Accordingly, we conduct a $k$-means cluster analysis to distinguish the shared outlooks of these scenarios for oil, gas and coal resource use. As a whole, the AR5 database depicts a transition toward re-carbonization, where a world without climate policy inevitably leads to an energy supply with increasing carbon intensity. This orientation runs counter to the experienced ‘dynamics as usual’ of gradual decarbonization, suggesting climate change targets outlined in the Paris Accord are more readily achievable than projected to date.

1. Introduction: mapping future climate change scenarios with an energy system phase space

The climate research community uses a framework for future scenarios based on four Representative Concentration Pathways (RCPs) (van Vuuren et al 2011a, 2012, O’Neill et al 2013, van Vuuren et al 2013, Moss et al 2010). RCPs are projections of greenhouse gas (GHG) concentrations that result in radiative forcing (RF) levels of 8.5, 6.0, 4.5 and 2.6 W m$^{-2}$. Initially, RCP modeling teams were assigned these four end-point RF targets and designed scenarios to attain them (van Vuuren et al 2011a, 2011b, Riahi et al 2011, Thomson et al 2011, Masui et al 2011). The RCPs are now supported by a series of more robust Shared Socioeconomic Pathway (SSP) scenarios (Riahi et al 2017).

The collection of integrated assessment model (IAM) scenarios based on five SSP narratives provide a conceptual foundation for conditions in global society that could lead to each level of RCP forcing (Kriegler et al 2017, Calvin et al 2017, Fujimori et al 2017, Fricko et al 2017, van Vuuren et al 2017). These IAM scenarios use the SSP storylines for their internal assumptions about technological change, resource
availability, economic and demographic trends to the year 2100 (Bauer et al 2017, Riahi et al 2017, Leimbach et al 2017, KC and Lutz 2014). When taken together, the full suite of SSP-RCP scenarios provide a common infrastructure for the studies of global change that will inform the next IPCC assessment (O’Neill et al 2016).

However, possible trajectories for carbon dioxide (CO$_2$) emissions from fossil fuel combustion may be broader than the span covered by detailed IAM scenarios. Therefore, this paper proposes a method for analyzing RCP components independently from the structure of IAMs. The cumulative amount of fossil CO$_2$ emissions internally consistent with each RCP can be reached using a constrained set of developments in the global energy system. This constraint involves a trade-off between the total amount of energy used and its average carbon content. In other words, a lower energy demand trajectory paired with a higher average carbon intensity of energy supply will arrive at the same level of cumulative CO$_2$ emissions in the year 2100 (and vice-versa).

Because the SSP-RCP scenario architecture is based on year-2100 end-points, the 21st century fossil fuel and industry (FF&I) carbon budgets consistent with each RCP can be calculated based on possible combinations of two principal factors over this period: (i) total energy resource use and (ii) its average carbon intensity. Framing RCPs in terms of these two dimensions allows a phase space diagram of global energy use to describe them.

The phase space of a dynamic system represents key parameters as axes to present the full range of its physically possible states, where each coordinate describes a unique feasible scenario outcome. In this paper, we develop a future energy system phase space to describe RCPs based on analytical solutions from a decomposition analysis of cumulative emissions (Kaya 1989). This allows for display of the fossil energy system states that correspond with RCPs across a broad range, independent of any single IAM scenario.

It is important to note that IAM scenarios of future GHGs are based on more than just CO$_2$ emissions from the industrial energy system—and can include significant contributions from land use change and non-CO$_2$ GHGs. Since the RCPs are full sets of RF components, we denote the FF&I carbon budget aspect of each as RCP$^*$ for the rest of this paper. Similar phase space approaches could be readily developed for other GHGs and tailored to specific studies of global change.

Using RCPs as benchmark pathways of GHG concentrations provides distinct benefits to the research community by decoupling climate model runs from the extensive development process needed for fully integrated scenarios of their underlying drivers. Though the SSPs now present a highly-detailed foundation for RCP scenarios, a phase space approach contributes additional conceptual support for their use in scientific studies since the RCPs are independent of any single IAM scenario or model structure. Further, this method can be applied to complement IAM scenarios, ensuring they provide sufficient coverage of future energy system uncertainties within the RCP framework.

To demonstrate the RCP phase space method, we focus on fossil fuel emissions from energy system ‘no policy’ reference cases. Reference cases intend to understand plausible hypotheses for future developments in global energy use which could precede climate policy. Subsequently, these reference cases are applied as ‘baseline scenarios’ for climate impact assessments and policy analysis (Bauer et al 2017, Clarke et al 2014).

The original RCP scenarios presented RCP8.5 as the sole pathway in the absence of any climate policy, while the other RCPs depicted various interventions aimed at mitigation (IIASA 2009, van Vuuren et al 2011a). However, the range from RCP4.5–RCP8.5 was initially identified as a plausible span for future reference case scenarios (van Vuuren et al 2011a). This plausible ‘no policy’ range is further reinforced by the outcome of the SSP development process which also produced reference cases leading to RF within this spectrum (Riahi et al 2017, Riahi and van Vuuren 2016). Therefore, the phase space in this paper is based on RCP4.5, 6.0 and RCP8.5. RCP2.6 is excluded because it can only be achieved with explicit climate policy.

The ‘no policy’ IAM reference cases preceding mitigation in AR5 WGIII result in total emissions that correspond to the range between RCP6.0 and RCP8.5. When this set of AR5 WGIII and SSP-RCP marker scenarios are presented in total, they illustrate how IAMs collectively orient outlooks for our global energy future as the origin of cost and technology assessments for reducing future carbon emissions, and the challenges any policy goal will face in efforts to limit warming.

The following work describes the method for producing and reading an RCP phase space (section 2) and then places AR5 WGIII reference case scenarios within it (section 3). Analyzing large sets of global change scenarios with a phase space approach allows data mining techniques, such as the $k$-means cluster analysis we apply, to rapidly distill their key characteristics (section 3.2). This is demonstrated by mapping IAM outlooks for fossil resource use consistent with the identified clusters (section 3.3). Section 4 concludes by summarizing results of the cluster analysis in the context of mitigation cost estimates.

2. Developing an energy system phase space for climate change scenarios

The total amount of global carbon emissions ($F$) that could result from combustion of fossil fuels over the next century can be depicted by a two-dimensional phase space diagram (figure 1(a)). This phase space expresses the average carbon intensity of energy supply (F/E) with the horizontal axis, and total primary
Figure 1. (a)–(c) RCP phase space for years 2016 through 2100. (a) RCP phase space diagram: future global energy scenarios consistent with RCP*8.5 (red), RCP*6.0 (blue) and RCP*4.5 (green) plotted by cumulative total primary energy (TPES) in exajoules (EJ) (vertical left axis) and mean carbon intensity in megatons carbon dioxide per exajoule (MtCO₂/EJ) (horizontal axis) with average primary energy resource use over all 84 years (right axis). (b) Points of reference within the phase space: two points provide reference within this phase space for hypothetical scenarios of stasis from the year 2015 with no additional change in rate of energy use or carbon intensity (blue open circle), and an historical baseline trend signal projected through to the year 2100 (purple star), three vertical gray lines represent the carbon intensity values for a total primary energy supply consistent with 100% gas (short dashes), 100% oil (dashes) and 100% coal (solid line). (c) IAM scenarios in the phase space: the original RCP8.5 MESSAGE marker scenario is presented as a red diamond and IAM marker scenarios for the SSPs as squares: SSP5 (purple square), SSP4 (yellow square), SSP3 (red square), SSP2 (blue square) and SSP1 (green square).
energy resource use (E) with the vertical axis. The (x, y) coordinates at each point in the phase space summarize a single fossil fuel carbon emission scenario for the years 2016 through 2100. These coordinates are \((F/E, E)\), and so when multiplied they equal a specific amount of cumulative CO₂ emissions across these 84 years.

While global energy scenarios are usually depicted as time-series lines rather than points, this phase space suppresses the time dimension in order to provide a clean display and analysis of many scenarios at once. A more traditional presentation of the IPCC AR5 database (DB) scenarios as time-series is provided in supplementary online material—section 1 available at stacks.iop.org/ERL/13/024012/mmedia. For a ready comparison to today, the right axis of figure 1(a) shows the average level of primary energy used across the next eight decades (2016–2100).

As noted in the introduction, the RCP scenarios are designed as end-points for RF in 2100. Therefore, they could result from many different combinations of energy use and its carbon intensity. To depict the range of possible fossil CO₂ emission scenarios that could result in each RCP, the cumulative carbon emissions consistent with RCP8.5 (red), RCP6.0 (blue) and RCP4.5 (green) are plotted as lines in figure 1(a) using the methods described in supplementary information 1. This section proceeds by adding consecutive layers of detail in this RCP phase space to describe its capabilities as a tool for analyzing global change scenarios.

2.1. Placing reference points in the phase space

In figure 1(b) we add points of reference that can orient the reader, and assist with interpreting the meaning of each scenario in the phase space. The open blue circle, labeled \(\text{stasis}\), represents repetition of today’s energy use pattern for the rest of the century. This stasis point is a purely hypothetical condition—it does not account for underlying ‘dynamics as usual’. The stasis point merely provides a starting point for understanding future scenarios of global change in relation to today’s world, but does not express a plausible scenario.

The purple star, labeled 50 year baseline, is a hypothetical projection that reflects continuation of two major late 20th century energy system trends to 2100: (i) a gradual steady reduction in the carbon intensity of primary energy supply and, (ii) a slow deceleration of the primary energy supply growth rate. These trends produce a 50 year baseline signal, calculated using all available data from the 2017 BP Statistical Review (BP 2017). Further detail on this baseline signal is provided in supplementary online material—section 2 and in the supplementary information II spreadsheet.

These two reference points are depicted as outlines since they are simple trend extrapolations, rather than fully articulated scenarios generated by an IAM. In supplementary online material—section 1 the primary energy and carbon emission trajectories of the stasis and baseline signals are plotted as time-series.

2.2. Phase space reference lines

Each point along the horizontal axis of figures 1(a)–(c) represents an average carbon intensity that results from a mix of fuels used to meet energy demand. The carbon intensity of each point primarily reflects various combinations of oil, gas and coal (supplementary information 1). Therefore, we can denote oil as \(O\), gas as \(G\) and coal as \(C\), where the proportion of each fossil fuel in the primary energy mix \((E_{\text{primary}})\) is given by \([\Omega, \gamma, \kappa]\):

\[
\frac{O}{E_{\text{primary}}} = \Omega, \quad \frac{G}{E_{\text{primary}}} = \gamma, \quad \frac{C}{E_{\text{primary}}} = \kappa.
\]

Three vertical gray lines in figure 1(b) depict values for the carbon intensity equivalent to an energy system of 100% gas \([\gamma = 100\%]\) (gray short-dash line), 100% oil \([\Omega = 100\%]\) (gray long-dash line), and 100% coal \([\kappa = 100\%]\) (gray solid line).

These lines are simple markers that can be achieved through many combinations of fossil energy, renewables, nuclear or carbon capture which would result in the same coordinates.

2.3. IAM scenarios in the phase space

An IAM scenario of future carbon emissions \((F)\) from fossil fuels can be represented as a single point in the phase space by:

(i) summing its projected total primary energy use for the remainder of this century—giving it a coordinate on the vertical axis \((E)\);

(ii) summing its projected annual emissions from oil, gas and coal for the remainder of this century and dividing by \(E\)—giving it a coordinate on the horizontal axis \((F/E)\).

Several IAM scenarios of the global energy system are added to figure 1(c). The five SSP marker scenarios are designated as squares: SSP5 (purple square), SSP4 (orange square), SSP3 (red square), SSP2 (blue square) and SSP1 (green square) (Riahi and van Vuuren 2016, Riahi et al 2017). The red diamond (labeled Year 2100 RCP8.5 Marker) is the original RCP8.5 marker scenario developed by the MESSAGE IAM, which was the only no policy reference case originally provided to illustrate the RCPs (van Vuuren et al 2011a, Riahi et al 2011).

2.4. Mapping energy system transition in the phase space

This formulation produces a map of the energy system developments consistent with future levels of climate change based on relative movements to 2015
along the x and y-axes by increased or declining shares of carbon-intensive energy sources. In figure 1(c), if the scenario trajectory is upwards, there will be more energy use. If it moves to the right—more carbon intensive, and if to the left, less carbon intensive. The legend on the right of figure 1(c) provides a guide to this movement in the phase space diagram. In general, a scenario with a greater proportion of coal (κ⁺) or oil (Ω⁺) leads to a higher carbon intensity, while a scenario with a greater proportion of gas (γ⁺) leads to a lower carbon intensity.

Decarbonization describes a transition toward futures left of the blue open circle—these scenarios result in a primary energy supply fuel mix with lower fossil share, and/or a fossil composition with declining share of coal and rising share of gas. Re-carbonization describes a transition toward the right of the blue open circle—illustrating higher shares of oil or coal in the primary energy mix. Steady-state scenarios describe futures immediately above or below the open blue circle, where average carbon intensity of energy supply stays the same, evolution of fossil contribution to TPES remains static, or coal replaces declining shares of oil and gas.

Any degree of energy system decarbonization or re-carbonization also depends on the role of non-fossil energy sources. The 50 year baseline signal captures the gradually expanding share of non-fossil energy sources, a slowly declining proportion of coal, and a moderately increasing fraction of natural gas in decarbonizing the global primary energy (supplementary online material—section 1). However, non-fossil energy has tended to play a subsidiary role in IAM no policy reference cases, so we focus on fossil energy for the remainder of this paper.

With this general framework and notation established for analyzing and communicating fossil combustion scenarios, the energy system phase space can be populated by each IAM no policy reference case from AR5 WGIII.

3. IPCC AR5 DB energy system reference cases: a K-means cluster analysis of IAM no policy scenarios

To understand how AR5 ‘no policy’ reference cases orient projections for fossil carbon emissions, we collect necessary inputs to each equation in supplementary information 1 from scenarios in the AR5 DB (IPCC WGIII 2014)⁵.

3.1. Populating the RCP phase space with AR5 scenarios

Each IAM reference case scenario is represented as a gray diamond in figure 2(a), with darker shading indicating overlapping scenario end-points. In figure 2(a) box plots of cumulative energy use and carbon intensity for the full series of IAM reference cases correspond with each axis. The AR5 database reference case mean scenario falls within the range of feasible solutions for CO₂ forcing between RCP8.5 and RCP9.8⁶ with a carbon intensity of 67 MtCO₂/EJ and cumulative energy use of 80 000 EJ, indicating a trend of moderate re-carbonization across the entire dataset.

3.2. k-means cluster analysis of AR5 scenarios

Describing each IAM scenario as a set of energy system coordinates in this RCP phase space allows for ready application of data mining techniques that can summarize the main characteristics of the full dataset. Accordingly, we conduct a k-means cluster analysis (supplementary information II).

K-means cluster analysis groups individual scenario data points into unique clusters with shared characteristics. This identifies groups in large data sets organically, rather than through the application of pre-specified labels or narratives. Our k-means cluster analysis identifies three distinct energy system scenarios in the AR5 WGIII database—further labeled as Groups A, B and C⁷. The cluster centers plotted in figure 2(b) summarize hundreds of IAM reference case scenarios.

Group A represents the RCP8.5 consistent scenarios of faster growth in energy demand that IAMs commonly solve through reliance on coal and consequently re-carbonization (F ≥ RCP8.5). Group B corresponds to intermediate growth in energy demand, solved with scenarios that range from decarbonization, steady-state, and re-carbonization (RCP6.0 < F < RCP8.5). Group C describes scenarios with the lowest growth in energy supply and exhibit gradual re-carbonization (F ≈ RCP6.0). In figure 2(b) dotted lines depict transition paths between the Year 2015 static case and each cluster⁸. The dotted line that tracks the 50 year baseline signal indicates gradual decarbonization while each AR5 cluster depicts transition toward re-carbonization.

Mapping scenarios with clusters provides insights into the defining characteristics of each group. We explore these further in the following section through

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⁵ Full 21st century scenarios in the AR5 database are generated by a series of 16 IAMs (n=221). We draw on the IAM runs from EMF27, LIMITS, AME, AMPERE2, AMPERE3, and ROSE model intercomparison exercises, alongside results from GEA and REMIND. These AR5 WGIII scenario reference cases are plotted as time-series alongside the static year-2015 trend and 1965–2015 baseline signal projections in supplementary online material—sections I and II.

⁶ Some scenarios fall between RCP4.5 and 6.0 but when the other RF components are included, these scenarios are within a range with total RF of at least 6.0.

⁷ Alternative results for the k-means algorithm with twelve cluster centers (k = 12) are provided in supplementary online material—section III. More clusters simply result in redundant iterations of these three points. Further, we provide detailed k-means results for 2 ≤ k ≤ 12 in the supplementary information II spreadsheet.

⁸ Each of these points does not intend to constitute a single specific scenario but is representative of the wider range of AR5 reference cases.
Figure 2. (a) and (b) RCP phase space populated with AR5 energy system reference case scenarios. (a) Each AR5 reference case (gray diamond) is plotted based on mean carbon intensity across 2016–2100 (horizontal axis) and cumulative energy use (vertical axis) with transparent overlay of SSP marker scenarios. (b) Cluster analysis identifies three groupings of A (F ≥ RCP*8.5), B (RCP*6.0 < F < RCP*8.5), C (F ≈ RCP*6.0) AR5 scenarios; the final cluster centers for each group of AR5 scenarios are plotted as solid dots—A (red), B (orange), C (blue); dashed lines represent the degree of decarbonization or re-carbonization transition from the static base year point to the cluster scenario for the 21st century energy system.

delineating the cumulative oil, gas and coal supply scenarios of each cluster.

3.3. AR5 reference case clusters: characteristics of oil, gas, and coal combustion
To further define these three AR5 clusters figures 3(a)–(c) plots each IAM scenario of future oil, gas or coal combustion as a dot, shaded by the cluster membership identified in section 3.2. Carbon budgets consistent with RCPs are overlaid on each figure as horizontal lines. These outlooks for each fuel source are indexed to today’s knowledge of their conventional reserves and resources with vertical black lines (BGR 2015)9.

9 BGR identified ‘resources’ denote geologically available quantities of oil, gas and coal that may be recoverable in the future with technological change and sufficient economic conditions, as well as ‘geologically possible’ quantities which have yet to be verified but are likely to exist due to the characteristics of known regions.

10 The designation of conventional generally denotes that production is possible with ‘classic technologies’, while extra-heavy oil, bitumen and shale oil are ‘unconventional’ because they require a different set of extraction technologies.

Supplementary online information—section IV provides further detail on the BGR (2015) resource estimates.

Scenarios in Group C tend to cluster around combustion of all conventional oil reserves and resources (figure 3(a))10. Group B scenarios equate to combustion of all conventional oil with some or most unconventional reserves and resources. Group A scenarios are less optimistic about future oil supply than technological change and sufficient economic conditions, as well as ‘geologically possible’ quantities which have yet to be verified but are likely to exist due to the characteristics of known regions.
Figure 3. (a)–(c) Cumulative oil, gas and coal combustion in AR5 reference cases with respect to total carbon emissions shaded by cluster grouping (2016–2100)—oil [O] (figure 3(a)), gas [G] (figure 3(b)) and coal [C] (figure 3(c)); BGR (2015) resource estimates marked with vertical black lines; note axis break from 40 000–80 000 EJ on figures 3(a) and (b).
Table 1. Summary of fossil energy system reference case characteristics applied by AR5 WGIII scenarios to describe RCP ranges.

| RCP carbon budget range | AR5 cluster | Approximate range SSP marker | Primary energy—E [Growth] | Carbon intensity—F/E [Transition illustrated] | Conventional and resources* |
|-------------------------|------------|-------------------------------|---------------------------|----------------------------------------------|-----------------------------|
| $F \geq \text{RCP}^\ast 8.5$ | A          | SSP5                          | High                      | Re-carbonization                             | Oil 1.0 x 0.7 x 3.7 x      |
| RCP*6.0 < $F < \text{RCP}^\ast 8.5$ | B          | SSP2/SSP3/SSP4                | Medium                    | Steady-state/Moderate Re-carbonization        | Gas 1.4 x 1.0 x 1.8 x      |
| $F \approx \text{RCP}^\ast 6.0$ | C          |                                | Low                       | Gradual Re-carbonization                      | Coal 1.0 x 0.7 x 1.5 x     |

* Cluster mean use of BGR (2015) conventional fossil energy reserves and resources (supplementary online material—section IV).

b These SSP marker scenarios fall into the RCP carbon budget ranges, but may not reproduce the same characteristics of each AR5 cluster (supplementary online material—section V).

Group B—many of the Group A oil scenarios draw clear lines at 8000 EJ (corresponding to all conventional oil reserves) and 16000 EJ (corresponding to all conventional oil reserves and resources).

Figure 3(b) plots gas supply cases of each scenario group, highlighting that each cluster is less confident about production of future unconventional gas than unconventional oil. On average, Groups A and C use 70% of conventional gas reserves and resources. Group B clusters around the use of all conventional reserves and resources with some unconventional gas11. 85% of the Group A scenarios present a stringent boundary for natural gas at 14 000 EJ across multiple models, representing a strong consensus on how an IAM can be configured to illustrate end-of-century targets for levels of forcing that meet or exceed RCP*8.5.

AR5 reference cases in Group C use most or all modern hard coal and lignite reserves (figure 3(c)). These levels of coal combustion roughly correspond to the total coal reserves reported by Rogner et al (2012). Group B scenarios use at least all hard coal reserves while Group A scenarios are optimistic about future coal supply and demand, projecting the combustion of 33 500–79 000 EJ of coal. Coal is the dominant fossil resource for each group of reference case scenarios (supplementary online information—section IV). The strong linear relationship in figure 3(c) indicates that coal combustion is the primary determinant of cumulative carbon emissions in AR5 DB reference case scenarios.

3.4 Summary of AR5 energy system reference case characteristics

The fossil energy system characteristics of each scenario cluster are summarized in table 1. Within the phase space, cluster analysis identifies three distinct groups of energy reference cases that harmonize with RCP carbon budget ranges:

- **Type A** ($F \geq \text{RCP}^\ast 8.5$) scenarios are consistent with *rapid re-carbonization* and high growth in energy use where the global energy system uses less natural gas and increasing amounts of coal.
- **Type B** ($RCP^\ast 6.0 \leq F < \text{RCP}^\ast 8.5$) scenarios generally describe *steady-state and modest re-carbonization* energy system reference cases with little change in the carbon intensity of energy supply, combustion of 80% more coal than indicated by modern reserves, significant production of unconventional oil and use of all conventional gas.
- **Type C** ($F \approx \text{RCP}^\ast 6.0$) scenarios illustrate a mild-growth global energy system that transitions toward *gradual re-carbonization* with steady expansion of coal combustion, and very limited production of unconventional oil and gas.

4. Summary and conclusion

This paper has offered a simple means to compare and display future scenarios of fossil carbon emissions within the SSP–RCP framework (section 2). The RCPs are end-of-century values for radiative forcing, which can be solved analytically and graphically, independent of an IAM scenario or SSP storyline. The phase space approach for RCPs provides new insights on how IAMs solve for these end-point targets. Such phase space methods offer a new approach to assessments which draw from large data sets or model outputs.

This phase space analysis shows that AR5 WGIII reference cases largely generate carbon emissions consistent with total forcings above 6 W m$^{-2}$ by departing from the ‘dynamics as usual’ signal of slowing primary energy demand growth and gradual decarbonisation (section 3). Achieving high re-carbonisation rates of RCP*8.5 or greater leads several IAMs to exhibit near unanimity in limiting recoverable oil and gas while relying on coal production that greatly exceeds current reserve estimates (section 3.3).

Our cluster analysis indicates that AR5 no policy reference cases are collectively bullish about future coal resources, independent of RCP scenario or model (section 3.4). The IPCC AR5 WGIII DB is therefore dominated by scenarios oriented toward re-carbonization rather than the historical baseline trend which leads in the opposite direction. Recent
findings on the economics of coal cast doubt on whether this outlook is still valid since recovering more than today’s reserves is very unlikely, and global per-capita coal use has remained in relative steady-state since the early 20th century (Ritchie and Dowlatabadi 2017a, 2017b).

An RCP phase space also provides a clear picture of whether IAM energy system scenarios provide sufficient coverage of relevant uncertainties for robust climate policy formulation in preparation for future IPCC assessments. A full consideration of uncertain developments must undoubtedly involve scenarios that recognize the possibility of a global energy supply which evolves in steady-state, or toward re-carbonization—late 20th century trends in the global energy system may not continue. However, to remain a useful guide for policy and technology, the forthcoming IPCC AR6 and AR7 WGIII scenario database mean will need to capture the momentum of past ‘business as usual’, inducing a shift toward the left in the energy system phase space. The SSP2, SSP4 and SSP1 marker scenarios have provided a useful guidepost in this regard.

To improve coverage of the uncertainties illustrated by the phase space developed in this paper, we propose that future sets of energy reference cases for climate research should explore additional groupings, such as: Type D (RCP*4.5 < F < RCP*6.0) scenarios explicitly characterizing passive decarbonisation that follows the late 20th century trend-lines for decelerating primary energy supply growth and gradual substitution of energy carriers with lower carbon intensity; and Type E reference cases (F ≤ RCP*4.5) characterizing futures where renewable energy sources are more competitive than coal or unconventional oil, and energy services are provided with more efficient technologies and dematerialized demand patterns.

Type D reference cases have recently been illustrated with the fossil energy supply scenarios developed for the Shared Socioeconomic Pathway 1 (SSP1) narrative of ‘green growth’ and sustainable development (Bauer et al 2016, 2017, van Vuuren et al 2017). These scenarios are plotted in figure 1 (green square) and in the supplementary online material—section V. However, the SSP1 scenarios are also consistent with the IEA’s reference case outlook, which intends to present the expected outcome from today’s ongoing developments in the energy sector rather than an explicit storyline of green growth. Several AR5 WGIII reference cases also correspond to Type D projections but they do not register a distinct k-means cluster because the database is biased toward re-carbonization.

Further research is needed to determine if plausible high emission reference cases consistent with RCP*8.5 could be developed with scenarios that do not lead to steady-state or re-carbonization. Though it is unlikely given the current understanding of energy system costs that IAM teams could construct such reference cases since these factors are generally understood to be consistent with lower total levels of future CO2 forcing (van Vuuren et al 2017).

RCPs, SSPs and similar sets of emission pathways are often described in the literature as equally plausible: they carry no explicit probabilistic elements because any single forcing pathway can result from a diverse range of socioeconomic and technological development possibilities for which distributions are considered unknown (Grübler and Nakicenovic 2001, van Vuuren et al 2011a, 2012, Riahi et al 2017, Nakicenovic et al 2000). Thus, it is interesting that the full collection of WGIII scenarios applied within this framework have illustrated each RCP range with energy policy reference cases using such tightly coupled combinations of fossil energy inputs, regardless of the IAM applied or intercomparison exercise (couplings described in table I are also plotted in supplementary online material—section IV).

Since many scenarios cluster around clear levels of oil, gas and coal combustion, this suggests the IAM community has developed a strong consensus on how to configure model reference cases to meet the end-point constraints of the SSP-RCP framework. In this context, scientific studies that present SSP5-RCP8.5 (Group A) affirm bullish expectations for coal (O’Neill et al 2016), running counter to analogous reference cases in recent global energy outlooks (EIA 2016–2017, IEA 2014–2017, IEA 2017). For comparison, supplementary online material—section V places International Energy Agency (IEA) reference case scenarios in the RCP phase space alongside AR5 DB and SSP scenarios, and contrasts their prospects for oil, gas and coal resource use.

As the phase space in this paper illustrates, the carbon emission reference cases exceeding RCP6.0 in AR5 WGIII are producing only a few of the possible trajectories for a 21st century energy system that would precede climate policy. The SSP scenarios have improved coverage of future uncertainties by presenting a broader range of plausible scenario archetypes that could shape global energy resource use (figure 1(c)). A similar phase space analysis of SSP no policy scenarios finds IAMs emphasize natural gas when depicting SSP1, in line with the IEA’s reference case (supplementary online material—section V). However, the bulk of the SSP IAM reference case scenarios maintain long-run outlooks dominated by coal, regardless of underlying narrative.

Based on these results, we suggest that the IAM generated energy policy reference cases used in AR5 may be overly constrained. IPCC WGIII AR5 DB mitigation policy and technology outlooks are also shaped by this condition. For example, IAM reference cases directed toward the historical baseline signal demonstrate significantly lower carbon prices for a 2° policy goal than steady-state or re-carbonization pathways (supplementary online material—section VI).
Since the global energy system reference cases used in IPCC AR5 are collectively oriented toward re-carbonization, they may overstate the difficulty of achieving end-of-century mitigation targets. This could influence undue antagonism toward international climate policy when the four RCPs and corresponding mitigation cases are communicated as in AR5 (Rogelj et al. 2016, UNFCCC 2015, Clarke et al. 2014). Therefore, evidence confirming steady-state and re-carbonization scenarios as unlikely would also indicate that ambitious policy goals will be less challenging than previously considered.

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References

Bauer N, et al. 2017 Shared socio-economic pathways of the energy sector—quantifying the narratives. Glob. Environ. Change 42 316–30
Bauer N, Hilaire J, Brecha R J, Edmonds J, Jiang K, Kriegler E, Rogner H-H and Serra F 2016 Assessing global fossil fuel availability in a scenario framework. Energy 111 880–92
BGR 2015 Energy Study 2015: Reserves, Resources and Availability of Energy Resources vol 19 (Hannover: Federal Institute for Geosciences and natural resources (BGR)) (www.bgr.bund.de/EN/Themen/EnergieProdukte/energy_study_2015_summary_en.html)
BP 2017 BP Statistical Review of World Energy 2017 (www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html)
Calvin K, et al. 2017 The SSP4: a world of deepening inequality. Glob. Environ. Change 42 284–96
Clarke L, et al. 2014 Assessing Transformation Pathways Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 413–510 (www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter6.pdf)
EIA 2016–2017 International Energy Outlook (www.eia.gov/outlooks/eio/)
Fricko O, et al. 2017 The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. Glob. Environ. Change 42 251–67
Fujimori S, Hasegawa T, Masui T, Takahashi K, Herran D S, Dai H, Hijioka Y and Kainuma M 2017 SSP3: AIM implementation of shared socioeconomic pathways Glob. Environ. Change 42 268–83
Grübler A and Nakicenovic N 2001 Identifying dangers in an uncertain climate Nature 412 15
IIASA 2009 RCP Database v2.0 (https://ntcat.iiasa.ac.at/RCpDb/)
International Energy Agency 2012 Energy Technology Perspectives 2017 (Paris: OECD/IEA)
International Energy Agency 2014–2017 World Energy Outlook (Paris: OECD/IEA)
IPCC WGIII 2014 AR5 Scenario Database (https://secure.iiasa.ac.at/web-apps/ene/AR5DB/)
Kaya Y 1989 Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios IPCC Energy and Industry Subgroup, Response Strategies Working Group (Paris)
Kc S and Lutz W 2014 The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100 Glob. Environ. Change 42 181–92
Kriegler E, et al. 2017 Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Glob. Environ. Change 42 297–315
Leimbach M, Kriegler E, Roming N and Schwanitz J 2017 Future growth patterns of world regions—A GDP scenario approach Glob. Environ. Change 42 213–25
Masui T, Matsumoto K, Hijioka Y, Kinoishi T, Nozawa T, Ishiwatari S, Kato E, Shulka P R, Yamagata Y and Kainuma M 2011 An emission pathway for stabilization at 6 Wm−2 radiative forcing Clim. Change 109 59–76
Moss R H, et al. 2010 The next generation of scenarios for climate change research and assessment Nature 463 747–56
Nakicenovic N et al. 2000 Special Report on Emission Scenarios Newell R G and Iler S 2017 Global Energy Outlooks Comparison Methods 2017 Update (Resources for the Future) (www.rff.org/research/publications/global-energy-outlooks-comparison-methods-2017-update)
O’Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2013 A new scenario framework for climate change research: the concept of shared socioeconomic pathways Clim. Change 122 387–400
O’Neill B C, et al. 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 Geosci. Model Dev. 9 3461–82
Riahi K and van Vuuren D 2016 SSP Database (Shared Socioeconomic Pathways)—Version 1.1 (https://ntcat.iiasa.ac.at/SpDb/)
Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N and Rafaj P 2011 RCP 8.5—A scenario of comparatively high greenhouse gas emissions Clim. Change 109 33–57
Riahi K, et al. 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview Glob. Environ. Change 42 153–68
Ritchie J and Dowlatshahi B 2017a The 1000 GtC coal question: are cases of vastly expanded future coal combustion still plausible? Energy Econ. 65 16–31
Ritchie J and Dowlatshahi B 2017b Why do climate change scenarios return to coal? Energy 140 1276–91
Rogelj J, Elzen den M, Hlone N, Fransis T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris agreement climate proposals need a boost to keep warming well below 2 °C Nature 534 631–9
Rogner H-H, et al. 2012 Energy resources and potentials Global Energy Assessment—Toward a Sustainable Future (Cambridge: Cambridge University Press International) ch 7 pp 423–512 (www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter7_resources_lowres.pdf)
Thomson A M, Calvin K V, Smith S J, Kyle G P and Volkle A 2011 RCP4.5: a pathway for stabilization of radiative forcing by 2100—Springer Clim. Change 109 77–94
UNFCCC 2015 Synthesis Report on the Aggregate Effect of the Intended Nationally Determined Contributions van Vuuren D P et al. 2011a The representative concentration pathways: an overview Clim. Change 109 5–31
van Vuuren D P et al 2013 A new scenario framework for climate change research: scenario matrix architecture Clim. Change 122 373–86
van Vuuren D P et al 2012 A proposal for a new scenario framework to support research and assessment in different climate research communities Glob. Environ. Change 22 21–35
van Vuuren D P et al 2011b RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C Clim. Change 109 95–116
van Vuuren D P et al 2017 Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm Glob. Environ. Change 42 237–50