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Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios

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ABSTRACT

The conditional probabilistic scenario analysis combines statistical methods of uncertainty analysis at parameter level with storylines which recognize the deep uncertainty that exists for several underlying trends. The model calculations indicate that cumulative 21st century emissions could range from 800 to 2500 GtC in the absence of climate policy. This range originates partly from the underlying storylines, and partly from the probabilistic analysis. Among the most important parameters contributing to the uncertainty range are uncertainty in income growth, population growth, parameters determining energy demand, oil resources and fuel preferences. The contribution of these factors is also scenario-dependent.
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1. Introduction

Indications of possible long-term trends in the global energy system provide very essential information for policy makers. The energy system is by far the single most important driver of anthropogenic climate change, and also plays an important role in connection with several other sustainability problems such as regional air pollution and resource depletion. The future of the energy system is, however, beset with uncertainty, as it is the product of complex dynamic processes and factors, including demographic and economic development, technological change, energy policies and resource availability. Various development patterns for each of them could introduce very different futures for the energy system as a whole. Scenarios are tools used in the assessment of future developments of these complex systems that are either inherently unpredictable or characterized by large scientific uncertainties. In exploring future development of energy systems and climate change, uncertainty management therefore needs to be a constant companion of scientists and decision-makers (Hulme and Carter, 1999). Uncertainty has various causes, varying from stochastic randomness to limitations in knowledge, and ignorance and human anticipation. Uncertainty can occur on different scales: model parameters, model structures and/or complete disagreement in conceptualization among experts (see next Section 2). The question how to deal with uncertainty in model projections has, in recent years, been given considerable attention (Grübler and Nakicenovic, 2001; Schneider, 2001, 2002; Webster et al., 2002; Patt and Dessai, 2005; Dessai et al., 2007). Two approaches are most prominent in the debate on handling uncertainty in the context of climate and (energy) emissions scenarios: (*storyline-based*) *alternative scenarios* and *fully probabilistic scenarios*.

The *alternative scenarios approach* is founded on the premise that possible future developments can vary over a large and partly unknown range, among other based on fundamentally different views of the current and desired situation (De Vries, 2006). These ranges are only partly bound by relationships among variables (so-called stylized facts[1]). Usually (energy) models endogenize only a limited number of these relationships as they may be too complex to incorporate and/or lack quantitative evidence. In the scenario approach, such relationships are expressed in a "storyline"; this storyline represents a kind of underlying logic of the scenario and its main assumptions. This way of providing consistency to the complex parts of the real-world developments forces modelers (and users) to think in a more creative way about possible future developments.

The *fully probabilistic approach* to uncertainties expresses the most important model inputs in terms of probability estimates

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[1] The term "stylized facts" refers to stable patterns that emerge from many different sources of empirical data.

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and uses statistical sampling techniques to create a range of emission pathways defined by a median value and various probability intervals. This approach is easily applicable to systems that are clearly defined and for which input parameters can be meaningfully expressed in terms of likelihood. The approach has also been applied to more complex systems, as in the modeling of future greenhouse gas trajectories (Webster et al., 2002, 2003). One might say that the fully probabilistic approach operates from the positivist engineering/control paradigm (the system is known well enough to make meaningful probabilistic estimates), whereas the alternative scenario approach positions itself more in a constructivist social science tradition (one can create alternative visions of the future, but without assigning likelihood) (De Vries, 2006).

The ongoing discussion between proponents of the individual approaches has revealed strengths and weaknesses of both approaches (see Section 2.1). The methods can, in our view, best be seen as complementary, not exclusive. In fact, one could also combine the two methods by simultaneously accepting ignorance for some aspects of future development, while at the same time bringing in elements of formal uncertainty analysis. O'Neill (2004, 2005) introduced such a "*conditional probability approach*" for population scenarios, with as rationale that is more meaningful to make judgments about the likelihood of future trends in the context of a particular development path, than about the likelihood of this path itself. While O'Neill applied this approach successfully in population scenarios, hardly any attempt has, so far, been made to use a similar approach for the total energy system.

The main focus of this paper is to explore what kind of information can be provided by a conditional probabilistic approach to uncertainty. For this purpose we have applied such an analysis using statistically sampled simulations of the TIMER energy model (van Vuuren et al., 2006a) conditional to the storylines of the IPCC-SRES scenarios. We focus here, in particular, on one crucial output variable of this model, i.e. global CO_2 emissions.

The aim was to provide insight into the following questions:

1. What range of emissions would result from a probabilistic approach to uncertainty?
2. What elements of uncertainty contribute most to these emission ranges?
3. How do results of a conditional probabilistic approach compare to other approaches of uncertainty?

Obviously, the answers to these questions depend on the modeling tool applied. A more complete account of uncertainties would be achieved by including more than one model (Nakicenovic and Swart, 2000; van Vuuren et al., 2006b). However, even then, some of the uncertainties will not be captured by any of the models. In the next section, we will discuss in more detail the value added and limitations of the conditional scenario. In brief, we feel that this article adds to existing literature by: (1) contributing to a discussion of methods for characterizing uncertainty in future emissions, (2) providing estimates of the influence of uncertainty in parameters, and (3) discussing the relationship of parameter uncertainty and storylines. The paper will contribute to but clearly not be the last word in the debate how different methods for uncertainty analysis can be used.

2. Methods

2.1. Sources of uncertainty and earlier applications of uncertainty methods in scenario approaches

Uncertainty originates from various causes and can be classified in different ways (NRC, 1996; Rotmans and de Vries, 1997; Moss and Schneider, 2000; Dessai and Hulme, 2001, 2004; Van der Sluijs et al., 2003; Patt and Dessai, 2005). One classification is based on the nature of the uncertainty (NRC, 1996; Petersen, 2006). *Ontic uncertainty* (a) refers to natural randomness, which can generally be expressed in mean estimates and their ranges of likelihood (for instance, uncertainty originating from chaotic behavior in complex systems). This type of uncertainty cannot be easily reduced. Its influence can sometimes be empirically determined (e.g. distribution of extreme weather events), although there is no guarantee that the same distribution will hold in the future. *Epistemic uncertainty* (b), in contrast, comes from incomplete knowledge (for instance, ultimately available oil resources). In the case of energy scenarios, an important part of the uncertainty originates from not knowing how the techno-economic and socio-cultural context of the energy systems evolves. There are various subcategories of epistemic uncertainty based on the way it is handled (mostly subjective) statistical expressions (b1); conditional statements (b2) or recognized ignorance (b3). A special form of epistemic uncertainty comes from (c) *disagreements among experts* (Patt, 2007). The latter may also come from value pluralism of experts (Rotmans and de Vries, 1997). A special category (with ontic and epistemic elements) is *human reflexive uncertainty* (d) originating from unknowns in human response to and anticipation of changes (Dessai and Hulme, 2004). Here, even when historical analysis suggests certain estimates by comparison and analogy, there is no guarantee that such an approach is valid for the time to come. All uncertainties together may result in total *ignorance or deep uncertainty*. Here, there is no agreement on the description of the system, the probability distribution of important drivers of the system or the value system used to rank alternatives (Lempert et al., 2004).

Other classifications of uncertainty can also be made: one refers to scale and distinguishes uncertainty in *model parameters* (1), uncertainty about *model structure* (2) and uncertainties that arise from (3) *disagreements conceptual theories on an even larger scale.*

As indicated, various methods have been introduced to deal with uncertainty in scenario development. In the field of greenhouse gas emission scenarios, focus was originally on "business-as-usual" emission trajectories, with simple variations for the main driving forces (e.g. Leggett et al., 1992). The two prominent approaches today, the *alternative scenario approach* and the *fully probabilistic approach*, can both be seen as an improvement to these early projections. The *alternative scenario* approach emphasizes the need for consistent assumptions and the handling of ignorance (cat. b2, b3, c, d), while the *probability approach* places the variations in the framework of a more structural assessment of plausible futures (cat. a, b1).

The IPCC-SRES scenarios, as most well-known application of the *alternative scenario approach*, map out a range of possible emission trajectories based on the wide variation in assumptions structured around four main storylines. Consistent with the basic premise of the approach, Nakicenovic and Swart (2000) indicate that it is not meaningful to assign probability estimates to these scenarios based on ignorance and the influence of societal choice (deep uncertainty). The SRES scenarios, however, formed the start of a lively debate. Schneider (2001, 2002) and Webster et al. (2002) argued that policy analysts and decision-makers need probability estimates to assess the risks of climate change impacts resulting from these scenarios; this is to decide how to respond to these risks. Even when probability estimates are subjective, in their view researchers (experts) are better equipped to make an assessment than the users (non-experts) of these scenarios. A counter argument from the SRES team (Grübler and Nakicenovic, 2001) that social systems (important in emission scenarios) are

fundamentally different from natural science systems is dismissed by their critics: in both cases often probability estimates need to be made for systems that cannot be measured (Schneider, 2002). The absence of probability assignments in SRES also resulted in ambiguities in follow-up work such as in the probabilistic statements on temperature change made Wigley and Raper (2001), who decided to assign an equal likelihood to the scenarios.

Several studies have applied the contrasting *probabilistic approach* to emission scenarios (Manne and Richels, 1994; Nordhaus and Popp, 1997; Scott et al., 1999; Webster et al., 2002, 2003; Richels et al., 2004; Kouvaritakis and Panos, 2005; Pepper et al., 2005; Sweeney et al., 2006). An important critique formulated against this approach is that attempts to assign subjective probabilities in a situation of ignorance forms a dismissal of uncertainty in favor of spuriously constructed expert opinion (Grübler and Nakicenovic, 2001; Grübler et al., 2006). Moreover, it is also argued that while the fully probabilistic approach provides more (seemingly) readily useable information, the alternative scenario approach provokes creative thinking of decision-makers about possible futures and strategic choices. Finally, uncoupled sampling within distribution ranges of input parameters may result in inconsistent combinations. Clearly, the handling of uncertainty and the appropriateness of assigning subjective probabilities to scenarios is a matter of lively debate and an important, unresolved, challenge in the application of climate scenarios (Dessai et al., 2007; Groves and Lempert, 2007).

2.2. Uncertainty approach used in this paper

This paper applies the conditional probabilistic approach, as indicated in the Introduction, which is a combination of the scenario approach with formal uncertainty analysis. The approach attempts to combine the strength of the scenario approach in providing consistent descriptions of more fundamental uncertainties with the strengths of the formal uncertainty approach where appropriate. The rationale is that the reduction of the uncertainty space, with help of divergent storylines, will make uncertainties more suitable for a formal uncertainty method. For example, while it is difficult to assign meaningful probabilities to the future economic growth rate (as this depends on fundamentally uncertain factors such as trends in globalization), if one restricts the set of possible futures to only those in which globalization proceeds rapidly, the probability distribution of future economic growth rates is likely to narrow down. The approach was applied earlier to population scenarios by O'Neill (2004, 2005).

Obviously, the method proposed leaves some crucial questions open: (1) is it is possible to derive meaningful estimates of the parameter range conditional upon the scenario storyline, and (2) how can information derived by the method be used (also vis-à-vis other methods of uncertainty analysis).

On the first point, one should realize that both the pure alternative scenario method and the full probabilistic approach need to make "arbitrary" estimates on how different variables evolve in the future (based on an interpretation of their past behavior). In the storyline approach this translates into a set of consistent assumptions of co-evolving parameters; in the fully probabilistic approach assumptions need to be made about reasonable sampling ranges. In that sense, the current approach adds by making these arbitrary choices somewhat more explicit. This allows for interpreting a "high growth storyline" by using a confined range of high economic growth assumptions and combining these with parameter ranges that are relatively plausible with such high growth, for instance, fast(er) technology change and a (more) rapid demographic transition. Admittedly, the degree of correlation between such ranges of qualitative storyline assumptions and model parameters are based on expert judgments—but as argued above: some mixture of expert elicitation and educated guesswork exists in any method that attempts to explore future developments.

As to their purpose, both the alternative scenario method and the derived method presented here are similar in that they do not intend to evaluate the likelihood of the underlying storylines. It still requires users to either accept that there are these fundamentally unknown elements or to make their own interpretation of the most appropriate storyline for their specific question (see Section 2.1 for the discussion between Schneider and SRES authors on the type of information that is needed (Grübler and Nakicenovic, 2001; Schneider, 2002)). The method, however, can be used to:

- Explore mission pathways—with ranges for different storylines and using statistical information for those parameters for which it is available.
- Allow for the analysis of robust strategies across different storylines—including the ranges that are associated with these storylines.
- Exploring the consistency of different storylines—and the role of individual parameter uncertainty within each storyline.
- As compared to the unconditional probabilistic approach: explore the impacts of linkages among different parameters (which are usually ignored) and making the sampling of parameters ranges more explicit.

The current method is not meant to replace the existing methods as they are used for different purposes and respond to different types of uncertainty. It rather provides a complementary tool to deal with large and hard-to-quantify uncertainties. We come back to the limitations and use of the method in the Discussion section.

In terms of the actual application, we based our analysis on the IPCC-SRES scenarios (Fig. 1) (Nakicenovic and Swart, 2000). These scenarios are described in Section 2.3. The scenarios and storylines considered in this paper all represent so-called baseline scenarios; i.e. we assume no climate policy. Uncertainties with respect to technologies such as carbon capture and sequestration (CCS), which are only relevant in a world that includes climate policies, are therefore not included in the analysis. We also consider only CO_2 emissions from energy use. Our conditional probabilistic analysis consisted of the following four steps:

1. Identification of parameters subject to uncertainty analysis.
2. Assessment of the conditional probability ranges associated with these parameters.
3. Use of Monte-Carlo sampling to calculate uncertainty results and TIMER model runs.
4. Identification of ranges for model outcomes and of determinants adding to model uncertainty.

For step 1, we used the results of an earlier uncertainty analysis on the TIMER energy model that was based on the NUSAP method (van der Sluijs et al., 2002). This analysis used several techniques to identify elements of uncertainty in TIMER, including a formal sensitivity analysis, a 2-day expert elicitation workshop, and model comparison and interview techniques with different model developers. Based on this study, we identified the most relevant model parameters to include in a formal uncertainty analysis (either based on relevance or sensitivity). Step 2 was to quantify the probability functions of those model parameters conditional to the scenario storyline of the model (see Section 2.5).

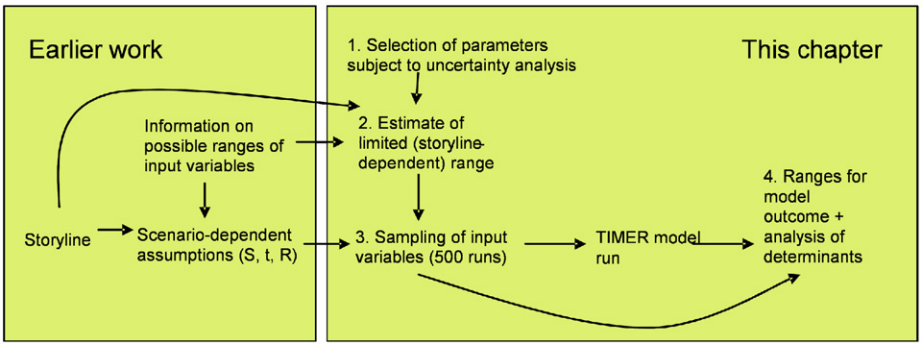

Fig. 1. Overview of the analysis (S = scenario, t = time; R = region).

Next (step 3), we applied Monte-Carlo sampling of input data for 750 model runs and estimated (step 4) the probability range for outcome parameters, and the contribution of the uncertainty ranges assigned to different parameters (see Section 2.6).

2.3. The TIMER energy model

In this analysis we used the TIMER 2 energy model (Van Vuuren, 2007). TIMER is a system-dynamics simulation model at an intermediate level of aggregation: 17 world regions, five energy-demand sectors and around 10 different energy carriers. TIMER is a simulation model: it simulates year-to-year investment decisions based on specific rules about investment behavior, fuel substitution and technology. The time horizon in the present analysis is the period from 2000 to 2100, while model calibration is performed on the basis of historical data for the 1971–2000 period.

In the model, energy demand is calculated on the basis of changes in sectoral value-added and GDP, population, income elasticities, autonomous-energy efficiency improvement (AEEI) and price-induced efficiency improvement (PIEEI) (see Fig. 2). Market shares of various energy carriers in each sector are determined by means of multi-nomial logit equations, taking into account changes in price and/or subscribed fuel preferences. Demand for electricity and hydrogen are forwarded to submodels that simulate investments in various technological options (both fossil-fuel based, bio-energy based and non-fuel-based technologies) to produce these final energy carriers. The decisions on investments and fuel use are derived from the relative (perceived) costs of each option, according to a multi-nomial logit formulation. Demand for primary energy carriers (fossil fuels and bio-energy) are finally fed into different production models that simulate their production and trade. The costs of energy carriers result from an interplay between depletion and learning dynamics. Depletion leads to increasing production costs, as a function of cumulative production of fossil fuels or of the ratio between actual and maximum potential in the case of renewables. Learning-by-doing leads to a decrease in production costs.

2.4. Storylines of the IPCC-SRES scenarios

Nakicenovic and Swart (2000) provide a detailed description of the SRES scenarios, organized around the two major uncertainties in the direction that the world could evolve. These are globalization versus regionalization, and economic orientation versus orientation towards social development and environmental protection (resulting in four scenario families A1, A2, B1 and B2). Other dimensions are considered to be implicitly or explicitly related to these two dimensions, for instance, technology and governance.

The storyline of the A1 scenario is based on an assumed continuation of globalization trends and a focus on market processes and economic objectives. Within the logic of the storyline, economic growth is assumed to be high. As this could spur on the demographic transition, population growth in turn is low. In terms of the energy system, the scenario is characterized by rapid technology development but also by energy-intensive lifestyles. Within the A1 storyline, there are three variants based on the emphasis in technology development: (1) balanced (A1b), (2) fossil-intensive (A1FI) and (3) focused on renewable technology (A1T). The A2 storyline, in contrast, emphasizes regional (energy) security and cultural identity. Here, it is assumed that trade protectionism and barriers between world regions will slow down technical innovations and economic growth, which will, in turn, tend to slow down the demographic transition in low-income regions. The B1 storyline describes a convergent world with emphasis on global solutions to environmental and social sustainability, including concerted efforts towards reduction of economic inequity, and less energy- and material-intensive products and lifestyles ("dematerialization"). Finally, on the basis of its position with respect to the major uncertainties, the B2 storyline emphasizes regional sustainable development. However, for practical reasons this scenario is mainly implemented as a combination of medium assumptions for several trends.

Although the SRES scenarios as originally implemented are still broadly consistent with the literature, new insights have emerged for some parameters (van Vuuren and O'Neill, 2006). For instance, current expectations for population and economic growth for low-income regions are now generally lower than that assumed in SRES. Against this background, a set of updated scenarios was recently developed using the Integrated Model to Assess the Global Environment (IMAGE), the integrated assessment modeling framework of which TIMER forms the energy model (van Vuuren et al., 2007) (see Fig. 3). These scenarios form the starting point of the analysis presented here. We have decided to comply with the tradition of sometimes placing the B2 storyline in the middle of the three other, more explicitly focused, storylines. We assume that the alternative variants in the A1 world (A1B, A1FI and A1T) can be generated in the analysis by varying technology parameters on the basis of statistical uncertainty analysis in the A1 storyline—and thus need not to be specified explicitly.

2.5. Parameter values and their ranges

The most sensitive parameters identified in the quantitative and qualitative uncertainty analysis for the TIMER model reported by van der Sluijs et al. (2002) has been used as starting point for

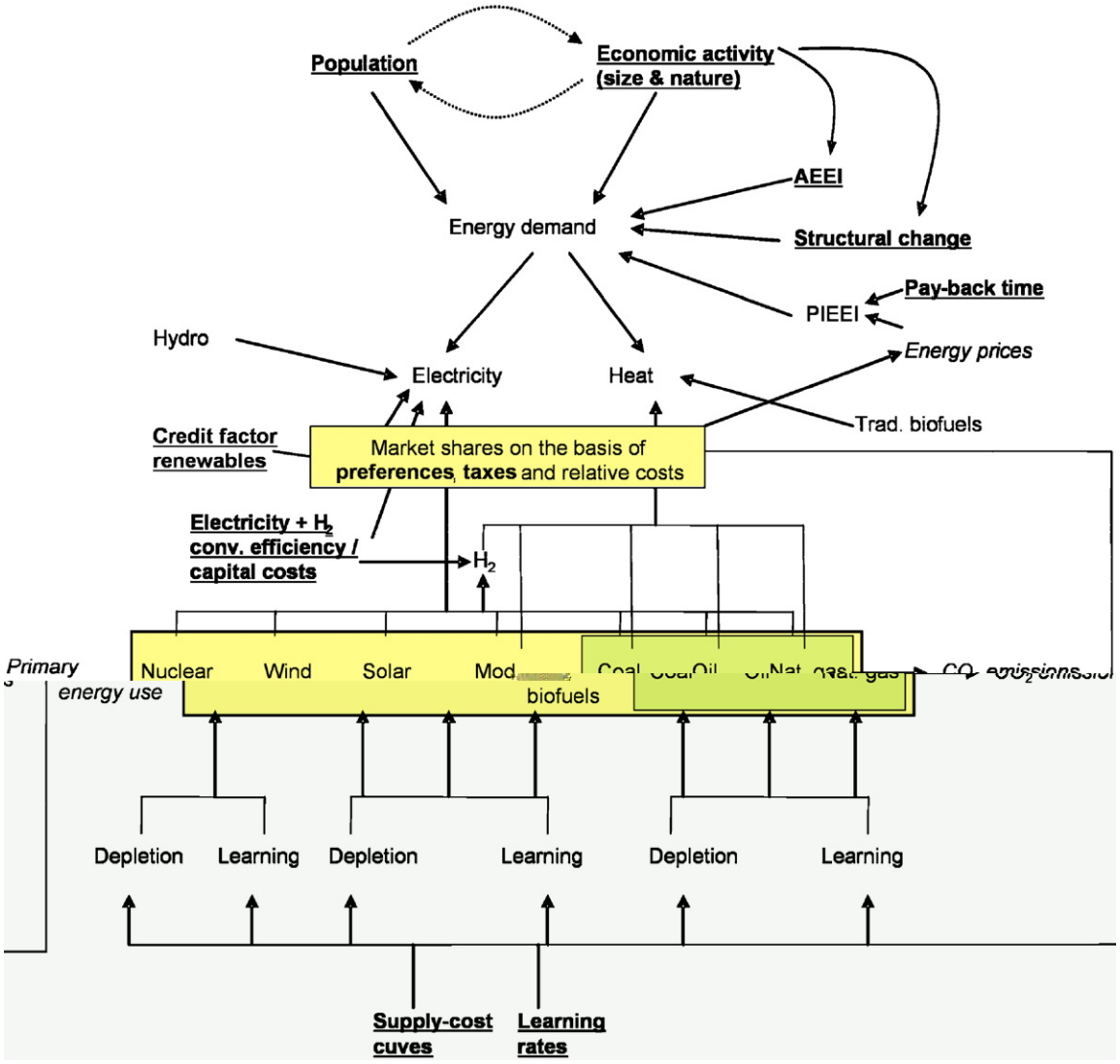

Fig. 2. Representation of the TIMER model, indicating important model connections (factors included in the uncertainty analysis are ''underlined'', while important output variables are in ''italic'').

selecting uncertainty parameters considered in this study.[2] Moreover, their expert elicitation was used in the specification of useful parameter ranges. The list of input parameters is given in Table 1 (see also Fig. 2). Assumptions for our uncertainty analysis were made on a global scale, unless additional information was available that allowed regional specification. Webster and Cho (2006) recently showed that using a more limited correlation of regional growth rates (i.e. correlation only bound by the empirically observed level) led to a considerably reduced range of outcomes for CO_2 emissions compared to the original work of Webster et al. (2002) (which assumed full regional correlation). As a result, also the full correlation assumed here may result in broader ranges in output variables than in the situation where no perfect correlation has been assumed.

For each parameter, we use as mean value the assumptions of the recent TIMER elaboration of the IPCC-SRES scenarios (van Vuuren et al., 2007). The sampling ranges around these means have, as far as possible, been based on ranges indicated in the literature, such as historical fluctuations or explicit statements on their distribution. In the Appendix A, we explicitly describe the sampling ranges of the different parameters and the reasoning behind the choices made. In each case, we believe that the range chosen does adequately represent the storyline of the scenario—also in light of the purpose of the method (see Section 2.2). As indicated in Table 1, for most parameters, the sampling range is set the same for all scenarios and regions. Population and economic growth form an exception, as here the sampling ranges are also scenario- and region dependent.

It should be noted that estimating the sampling range is complex. If ranges (or even probability distribution functions (pdfs)) are found in the literature, these often refer to what are meant as unconstrained situations (i.e. not depending on certain storylines). This introduces an element of arbitrariness as these estimates need to be interpreted in the context of our storylines (see also Section 2.2). Although expert elicitation would be a preferred instrument to do this, for the sake of simplicity and time, the ranges here were only partly based on expert elicitation (van der Sluijs et al., 2002) and partly by interpretation of available literature by the authors of this paper. The overall scheme used in this interpretation process is shown in Fig. 4. As an example an unconditional range is shown on the left-hand side

[2] Some parameters (technology assumptions for H_2, wind/PV resources and capacity credit) were added later in association with model additions made more recently.