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Implications of Limited Foresight and Sequential Decision Making for Long-term Energy System Planning: An Application of the Myopic MESSAGE Model

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Contents

Abstract

This paper presents the development and demonstration of a limited foresight energy system model. The presented model is implemented as an extension to a large, linear optimization model, MESSAGE. The motivation behind changing the model is to provide an alternative decision framework, where information for the full time frame is not available immediately and sequential decision making under incomplete information is implied. While the traditional optimization framework provides the globally optimal decisions for the modeled problem, the framework presented here may offer a better description of the decision environment, under which decision makers must operate. We further modify the model to accommodate flexible dynamic constraints, which give an option to implement investments faster, albeit with a higher cost. Finally, the operation of the model is demonstrated using a moving window of foresight, with which decisions are taken for the next 30 years, but can be reconsidered later, when more information becomes available. We find that the results do demonstrate some of the pitfalls of short term planning, e.g. lagging investments during earlier periods lead to higher requirements later during the century. Furthermore, the energy system remains more reliant on fossil based energy carriers, leading to higher greenhouse gas emissions.

Acknowledgments

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About the Authors

Ilkka Keppo was a Researcher Scholar at IIASA from 2004 to 2008. His research interests focus on the development and use of energy system models, with the scope of the studies ranging from techno-economic analyses of small energy systems to global issues, such as climate change mitigation. He is currently affiliated with the Energy Research Center of the Netherlands (ECN).

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Implications of Limited Foresight and Sequential Decision Making for Long-term Energy System Planning: An Application of the Myopic MESSAGE Model[1]

Ilkka Keppo, Manfred Strubegger

Introduction

Different energy futures and the transitions that may lead to these futures are constantly subjects of analysis, in which uncertainty concerning these transitions plays a crucial role. This role is further underlined by the mismatch between the relatively short time frames often used for the decision making and the long lasting effects these decision have for many long term issues, like the direction and pace of the energy infrastructure development, climate change and the fossil fuel availability. Additionally, unless these issues are explicitly taken into account, decisions made with a limited decision horizon and imperfect knowledge concerning long term developments may also have a negative effect on the flexibility of the energy system. Avoiding strong lock-ins and having flexibility integrated into the energy system planning allows the system to react to new information concerning, for example, new environmental requirements and technology needs.

Most technology rich energy system models, used for describing the mid- to long-term development of the global or regional energy infrastructure development, are based on a bottom-up structure, global cost minimization and on a social planner with perfect foresight (e.g. MARKAL [1], MESSAGE [2, 3] and GET [4]). With such models, uncertainty concerning the future is usually taken into account by using scenarios, which describe alternative "worlds" we could find ourselves in. The range of model results calculated for these "worlds" therefore shows an uncertainty range for different indicators that can be derived from the results. While this approach is very useful for providing the optimized, ideal transition for the energy system, across the studied spatial and temporal range, it does not fully describe and simulate the decision framework within which decision makers operate. In reality, decision makers do not act with full information for the future costs, prices and constraints and the uncertainties concerning some key developments of the energy system increase rapidly the further into the future the decisions are to be taken. This can often lead the decision maker to weight more heavily the decisions of the near term, for which there is more information available and which need to be taken soon in any case, and postpone the long term considerations for later, when new information may become available. This aspect of decision making can not be described with a model, where all information is exact and simultaneously available for the whole time horizon to be modeled. With perfect and complete information there would be no reason to postpone decisions later, or revise already

[1] This is a preprint of the manuscript submitted to Energy – The International Journal

made decisions for future time periods, since new information can not, by definition, be expected. However, in reality the "short-sightedness" of the decision maker can be of key importance, especially in the energy sector, where the long lifetimes and high capital requirements of the production and transmission capacity mean that wrong investment decisions can have major negative consequences.

In this paper we present a version of the energy model MESSAGE, where decisions are made with a limited knowledge of the future developments and for a planning horizon that is shorter than the full time frame that is being modeled. This leads to a sequential decision making setup, where new decisions can be made as time passes and new information becomes available. However, some of the decisions made previously are irreversible, since e.g. the physical investments have already been completed, but others, made for later time periods, may still be revised. Such a "limited foresight" approach provides a useful framework for studying issues such as the linkage between specific short and long term goals (e.g. interim climate targets, [5, 6], sudden changes in the operating environment (e.g. changing climate regimes, [7]) as well as path dependencies and lock-in effects resulting from the choices made (e.g. technological change in the context of greenhouse gas emissions constraints, [8]).

Although most of the energy system models assume perfect foresight, limited foresight in different forms has been applied to some models previously. In addition to models that limit foresight mostly by adding stochasticity and/or a single known branching points (e.g. [9–12]. See also [13].), some fairly recent examples of more fully myopic, but not stochastic models include IKARUS [14, 15], SAGE [16] and GET-LFL [17, 18].

The IKARUS model describes the development of the German energy system until the year 2030 by dividing the time horizon into five-year intervals and then optimizing each of these intervals separately. The decisions of the previous periods have an effect on each optimization due to the capacity accumulation and other variables that are not independent across the time intervals. Decisions do not take into account any periods that come after the period for which a decision is currently taken, therefore implying either that there is no additional information available for the following periods, or alternatively, the following periods are irrelevant for the decision making done for the current period. SAGE also uses this approach for its short term (2025) limited foresight approach, but extends the geographical scope of the model to cover the whole globe, divided into fifteen separate regions.

Of the three models mentioned above, the limited foresight version of the GET model is the closest to our approach. In this long term (2100) global model the extent of the foresight can be decided freely and the decision horizons for the optimization steps can therefore be also overlapping. For example, a new decision can be made at each decade of the modeled time frame, but instead of always considering only the 10-year step alone, each decision might also take into account the next decade. However, since a new decision is made again at the next step, the decisions concerning the second decade can still be revised. This approach offers a more flexible modeling framework, since it does not automatically assume that there is knowledge only for a single time period, but also allows this approach, if it is considered to be the most relevant.

In this paper we present a limited foresight formulation of the MESSAGE model, built upon the full MESSAGE model used in previous scenario studies (e.g. [19]), but modified in several ways to accommodate the new modeling approach. The following section presents the general methodology for and the most significant new characteristics of the model. After this we present some example results for a chosen scenario and illustrate the effect limited foresight has on the results. In the final chapter we provide some conclusions and suggest possible directions for future research.

Methodology

In this section we present in brief the methodological changes implemented in the new formulation of the model. The first part of this section will present how the mathematical formulation has been changed to limit the foresight, how this was done in practice and how these limitations can be interpreted. The second elaborates on some additional flexibility measures that have been added to the existing MESSAGE model to improve its possibility to respond to sudden changes. We concentrate on the characteristics of the model that have been changed to include the option to limit foresight, but do not present the underlying, unchanged MESSAGE model in full. The interested reader is encouraged to consult [2] for a full mathematical description of the standard, perfect foresight model. However, in the third part of this section we briefly discuss the issue of model verification, result interpretation and the uncertainties involved.

Formulation for the choice of foresight

The linear optimization model MESSAGE is, as most bottom-up energy system models, a cost minimization model. The total discounted costs of the energy system over the studied time frame are summed and minimized. All the imposed constraint concerning, e.g. resource availability, energy transmission and distribution infrastructures and possible environmental restrictions need to be also fulfilled. In this formulation, the foresight, or the decision horizon[2], therefore corresponds to the whole time frame that is being modeled. If the decision horizon is decoupled from the full time frame under study, the problem becomes a sequential decision making problem. Figure 1 illustrates the different approaches.

With case a) in Figure 1, the decision horizon and the full modeled time frame are equal, from the year 2000 to the year 2100. In this case all the information is available for the full time frame, from the beginning to the end, and the information is taken into account when the single decision for the complete time frame is being taken. There is no need to revise the decision at a later point, since no new information can, by definition, become available.

Case b) is an example of decision making under limited foresight. In this case a decision is first taken only for the first 50 years, without considering any time period extending beyond this in any form. A second decision will be taken for the time period from 2050 to 2100, but all the decisions made for the first half of the century are irreversible and unchangeable, as if the latter decision is being taken in 2050.

Case c) simulates a decision making process that may be, of these three approaches, the closest to what can be observed in reality. In this case decision is taken always for 30

[2] We use the terms "decision horizon" and "foresight" interchangeably; they both refer to the time frame the cost of which is being minimized.

years at a time and after each 10-year time step, another decision for the next 30 years is taken. This leads to decision making, where activities are always planned for the next 30 years, but only the decisions for the next 10 years are irreversible. In this approach, the new information that is being revealed as the 30-year "decision window" moves forward can be used for revising some, but not all, of the earlier decisions.

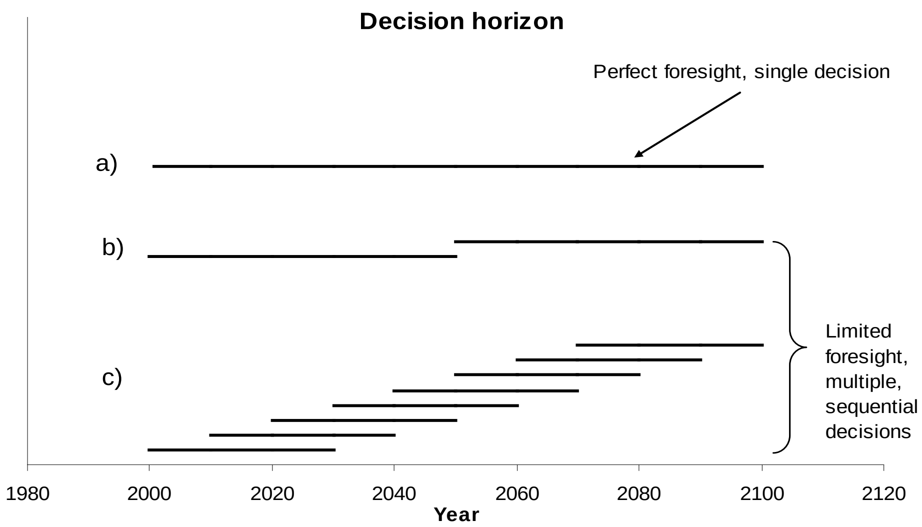

Figure 1: Three different decision horizon alternatives for a 2000 to 2100 time frame.

From the methodological perspective, when limited foresight and sequential decision making is assumed, the original single optimization problem is transformed into a set of optimization problems, where the solutions of the previous problems need to be taken into account for the latter ones (in terms of e.g. existing capacities, growth constraints etc). This also means that the final results of this iterative process are not optimal for the full time frame, but only for the individual optimization problems, which only considered a shorter time frame each. Equation 1 shows the general formulation for a linear optimization problem.

$$\min \sum_{t=t_1}^{t=t_2} \frac{C_t x_t}{(1+r)^t}$$

$$\text{s.t.} \quad A_t x_t \le b_t, \quad x_t \ge 0_t \tag{1}$$

In the objective function being minimized in Eq. (1), x_t is a vector of continuous variables for time period t, C_t the corresponding cost vector and r the discount rate. A_t is a matrix of coefficients for time period t and b_t is a vector of coefficients for the right hand sides.

If we assume that the full time frame under study is $[t_0,T]$, in a perfect foresight formulation the summation in Eq. (1) would be done for this full time period and the constraints would have to be fulfilled for all the time periods from t_0 to T. In a limited foresight case the range being optimized, $[t_1,t_2]$, differs from this full time frame and the parameter matrix and vector, A_t and b_t, respectively, are altered to take into account the effect decisions made before t_1 have for the time frame under study. Such effects might be related, for example, to the available energy infrastructure built before period t_1 or to the amount of remaining fossil resources at the beginning of the time frame. In other words, some of the decisions made before the time t_1 limit the range of options available for the latter periods. In the framework of an energy system model, this may also translate into a technology lock-in, where new, possibly superior, technologies are not adopted due to the earlier investments that have brought in and established older technologies in the market. The lack of long term perspective further reduces the incentive to switch to the new, alternative technology.

Based on the approach given above, our formulation requires as input parameters for each step the values of t_1 and t_2, i.e. the first and the last point in time to be considered in the optimization. Furthermore, for each step the value of t_1 has to be higher than for the previous step, therefore making some of the previous decisions irreversible. However, the value of t_2 for step n can be larger than the value of t_1 for step $n+1$, therefore leading into overlapping decision horizons (see case c) in Figure 1). The length of the decision horizon, $t_2 - t_1$ can be decided freely and it can differ from one step to another. Figure 2 shows the basic principle of the algorithm used.

In Figure 2 the first box, for which $n=1$, represents the first step of the limited foresight optimization ($f(x)$ being the objective function to be minimized for step n). The results of this step define the initial state, the result vector $^*x_{n+1}$, in Figure 2, for the next step $n=2$. This algorithm is then followed until the last step $n=N$ is reached.

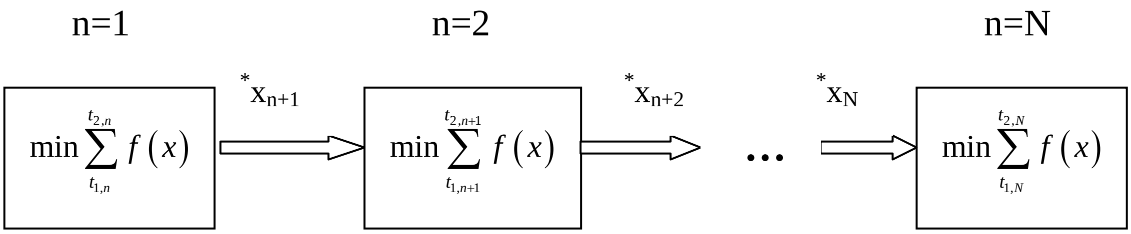

Figure 2: Flow of the limited foresight simulation algorithm.

We implement this approach using a set of unix shell files and a subprogram written in the programming language Python [20]. These subprograms require as inputs the number of steps to be used ($n = N$ in Figure 2) and the corresponding values for the start (t_1) and end (t_2) point for each of the N steps. We have also implemented a possibility to give new information for the model at any step n. This information could, for example, give new estimates for future investment costs of technologies or update environmental restrictions. With this approach it is possible to simulate how the model adjusts to such a changing environment and evaluate how severe, or difficult to break, some of the lock-in effects might be. In addition to gradual adjustments in the information, the updates can also be used to evaluate the effect of, and the reaction to, more drastic surprises or shocks, e.g. sudden reductions in the gas imports from Russia to Western Europe, sudden downscaling of estimated oil reserves etc.

Flexible dynamic constraints

MESSAGE includes a set of constraints, usually referred to as dynamic, or growth, constraints. These constraints are used for limiting the activity of a variable during time period t based on its activity during the previous time period, $t-1$. Depending on the variable in question, the activity may refer to, for example, power production from a certain kind of power plant, the length of gas pipeline that is built during a year or to the oil extraction at an existing oil field. These constraints can either limit how quickly the activity of a technology can increase or alternatively how steeply the activity can decline between the two time periods. The formulations for these constraints are shown in equations 2 and 3.

$$a_t - \alpha_g \cdot a_{t-1} \leq \delta_g \tag{2}$$

$$a_t - \alpha_d \cdot a_{t-1} \geq -\delta_d \tag{3}$$

Eq. [2] shows that the activity at time period t, a_t, can be no more than the activity in the previous period times the allowed growth rate ,α_g (range (1,∞)) plus the increment activity, δ_g, which is usually used to represent the initial activity[3]. Eq [3] shows a similar formulation for the constraint that is limiting the speed with which the activity can decline, with α_d being in the range (0,1).

For the limited foresight application of the MESSAGE model we have extended the above formulation in order to allow a more detailed and flexible representation of the growth limitations. This is especially relevant for the model with limited foresight model, since it may need to be able to react fast to the new information that is being revealed. Our new formulation gives the growth constraint in two steps; the first step is as before while the second step allows an increase for the maximum growth. However, for each unit of activity that goes beyond the levels of what the initial growth rate would allow, an extra cost related is paid[4]. The decline constraints are similarly extended to allow a faster decline. Equations 4 to7 show the formulation of the new dynamic constraints.

$$a_t - \alpha_g \cdot a_{t-1} - \beta_g \cdot g_{t-1} \leq \delta_g \tag{4}$$

$$g_{t-1} \leq a_{t-1} \tag{5}$$

$$a_t - \alpha_d \cdot a_{t-1} - \beta_d \cdot d_{t-1} \geq -\delta_d \tag{6}$$

$$d_{t-1} \leq a_{t-1} \tag{7}$$

A dummy activity, g_{t-1} is added to the growth constraint in Eq. [4]. Since the maximum value for this dummy technology matches the activity of the underlying technology (Eq. [5]), this new formulation increases the highest allowed growth rate from α_g to α_g + $ß_g$. Eqs [6, 7] show the formulation for the dynamic constraints for decline.

These new constraints are added to the existing model setup using a set of Python subprograms. The input file for the main subprogram requires the list of technologies for which the constraints are to be altered, how much additional growth is allowed (i.e. the value for ß), how much higher are the costs for the activity that goes beyond what

[3] Without such an increment, the growth constraint would force the activity to remain at zero, if it ever did have this value for a time period. For the constraint in decline, the increment δ_d correspondingly allows the activity to drop to zero instead of allowing it only to asymptotically approach it.

[4] For most of the technologies in our model the reference cost is the levelized costs of the underlying technology and the additional cost is defined as a percentage of this reference cost.

the initial constraint would've allowed and whether both, the decline and the growth constraints are to be altered. In addition to this main subprogram, other smaller programs have been written to create internal datasets for the rest of the model (e.g. defining time and region dependent levelized costs for the chosen technologies, reporting results for the dummy activities etc). The implementation allows also the use of more than one additional growth step, therefore permitting to describe the maximum growth rates as a function of additional costs. This approach provides a much more detailed description for the investment and production options available, since it does not exclude even considerably quick and large structural changes within the energy system, but does consider such changes costly.

Long term energy models and uncertainty of scenarios

In this paper we discuss how changing the decision environment, namely the decision horizon, may affect model results. In order to be complete, we in this part briefly discuss a full, perfect foresight energy model from the perspective of uncertainty and the interpretation of the results retrieved using such a model.

A large technologically rich model reaching over a time span of 100 years does, by definition, include a vast number of assumptions, simplifications and aggregations of data (see also [21] on modeling and system thinking). Estimates will have to be given not only for very specific technological details, such as the costs of specific types of power plants for the future, but also to larger developments, like regional population and GDP growth and how these may affect energy demand. Considering the vast number of assumptions one has to make, it is clear that a scenario created with such a model should not be considered a forecast (see e.g. [22] for examples on failed long-term energy forecast and prediction attempts). In the terminology of IPCC, the emission scenarios, often quantified using also large scale energy models, "[They] represent pertinent, plausible, alternative futures" [23]. The language is carefully chosen, since this clearly suggests that the scenarios are not meant to be used as forecasts, but as alternative, plausible descriptions of future developments. This character of the scenarios is further emphasized by the fact that often more than one scenario is presented and each of the scenarios assumes a new set of parameters. This is illustrated in Figure 3, which shows global population and GDP projections, the emission paths for CO_2 and the initial, and final oil resources, for three alternative scenarios, with widely differing assumptions concerning demographic, economic and technology development (taken from [19, 24]). Furthermore, is it not suggested that even this would cover the range of plausible developments.

As discussed above, the results of a scenario should not be considered a forecast, but internally plausible and consistent development paths, which are always conditional on the input assumptions. And the set of input assumptions that have to be made, not to mention the alternative combinations of them, indicate that this range can be enormous, therefore underlining the huge uncertainty concerning how the real energy system will, in the end, develop. This also shows why an error analysis would not be possible to do – it is not suggested that the model would *predict* how the global energy system will develop, since on this level of detail this would be practically impossible, and even if it were feasible, the results could only be judged once this unique event, development of the energy system over predefined years, had taken place[5].

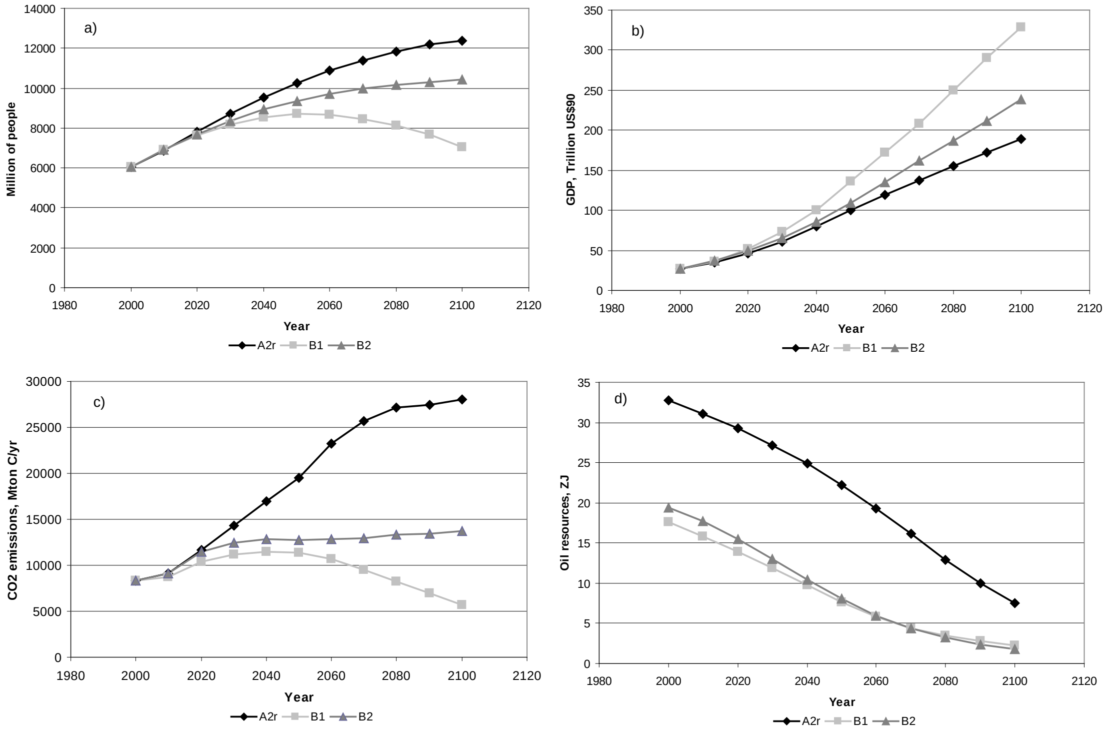

Figure 3: Global population (panel a), GDP at market exchange rate (panel b), CO_2 emissions (panel c) and remaining oil resources (panel d) for three alternative scenarios (Source: [24, 19]).

The power of such models is therefore elsewhere. It lies in providing a systematic, consistent and detailed description of the energy system, with all its interdependencies and dynamics. This offers a great platform for studying how the energy system might react to changes in the modeled environment, e.g. changes in environmental regulations, fossil fuel resource estimates, technology costs or, as in this paper, the decision making horizon of the modeled social planner. Furthermore, this is also where the model can be best judged; do these changes in assumptions lead to changes in results that we, after seeing the results, find plausible? Do the dynamics shown by the model results have a counterpart in real life and if so, are the drivers of these dynamics, qualitatively, the same in reality as in the model?

If a complete analysis of the full model itself was to be done, this could be approached from the perspective of a sensitivity analysis, where parameters are altered, dynamics of the changes studied and a qualitative judgment is made on the plausibility of the description coming out from the model. However, due to the enormous amount of

[5] Another possible way to evaluate the model would be to study the dynamics of the model, e.g. does the technology diffusion and replacement in the model correspond to what we have observed in the history, does the heterogeneity in the use of the energy sources appear plausible, based on the past? However, these characteristics are also results of unique moments in the development of the energy system in the past and may therefore not repeat themselves in the same manner in the future. Additionally, the most important characteristics in this vein are inbuilt in the model calibration.

relevant parameters included in a model, one would most likely still have to key on only some of them, on the ones that seem most important. Such a thorough sensitivity analysis, extending even far beyond a full analysis across alternative scenarios, is clearly beyond the scope of this paper. However, the model we develop and document in this paper changes one of the (usually unchanged) key assumptions, the decision horizon, and then briefly studies the effect on the results, therefore contributing to such an evaluation of the modeling tool.

The implications of limited foresight, an example

In this section we will briefly demonstrate how the change to a limited foresight approach can influence the results and what these differences might imply.

In order to do illustrate some possible implications of the limited foresight, we run MESSAGE for the same B2 scenario assumptions, based on the scenario presented in [19], but using two different assumptions concerning the decision horizon; a run where perfect foresight is assumed for the full time frame under study (case a in Figure1) and a run where decisions are made at each ten year time step and always for a decision horizon of 30 years (case c in Figure 1). The flexible dynamic constraints described earlier in this paper are implemented for both, the perfect and limited foresight cases, but no other restrictions or constraints are assumed (e.g. there is no climate constraint).

Our intention for this paper is not to conduct a full scenario analysis, but to point out some differences, which illustrate some of the effects of altered decision horizon. It is also important to note that a different definition for the limited foresight (e.g. case b in Figure 1) might provide, at least quantitatively, different results and therefore the findings presented in this section should mainly be considered to be related to the exact setup used. However, the more general differences across the perfect and limited foresight scenarios are unlikely to be changed.

Energy sources and carriers

In the perfect foresight setup all information concerning the future is available for each point in time until the end of the time frame studied. This means that within this decision framework, for example, the possible depletion of resources is fully considered already decades before the issue becomes urgent. Also the development of energy demands is known far into the future and will influence also the decisions that are made for the first time periods. All this information is lacking from the limited foresight model. It operates within a time frame of 30 years and although the initial decisions can still be reconsidered due to the overlapping decision horizons, the long term perspective is lacking in the decision making.

Due to the limitations of oil resources, the pattern of crude oil consumption is bound to peak no matter what definition of foresight is assumed. The lack of foresight concerning the availability of cheap conventional oil resources leads to a situation, where the oil consumption grows more rapidly until a peak is reached and after that new energy options have to be, correspondingly, more rapidly introduced (Figure 4). In the case of perfect foresight, the patterns are qualitatively similar, but the peak is not as sharp; since it is possible to foresee the depletion of low cost resources, alternatives for oil are being developed earlier and the experienced oil peak is smoother. A stronger reliance on existing, mature energy solutions, as long as this is possible, is typical for the limited foresight solutions[6]. Gas consumption shows similar patterns as the oil consumption, although the peak is not as sharp and experienced much later (2080 for the limited foresight case, 2090 for the case with perfect foresight).

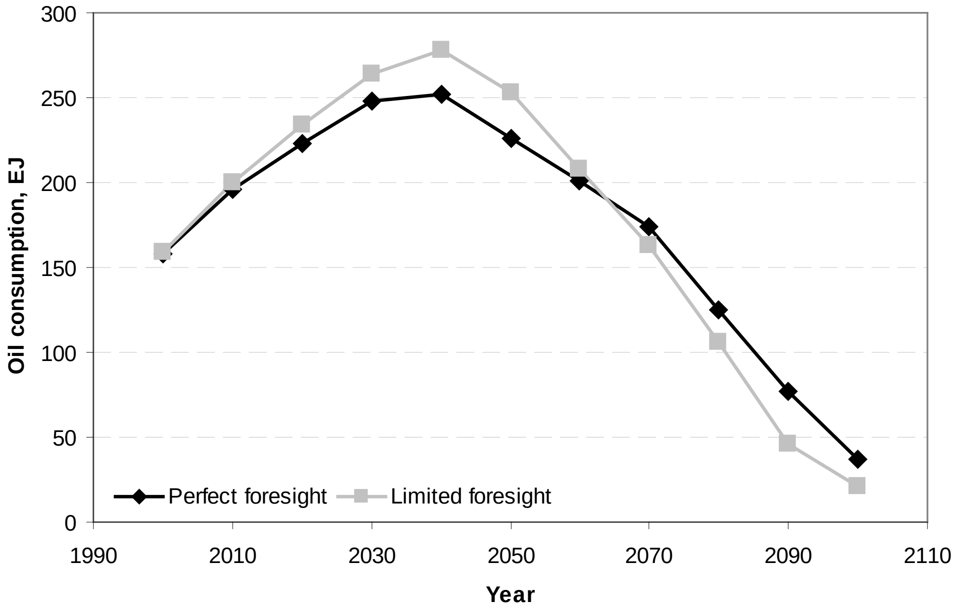

Figure 4: The global consumption of crude oil.

The more rapid consumption of oil and gas resources in the limited foresight case implies that some other primary energy sources are developed less. Figure 5 illustrates how the nuclear power production, while clearly increasing also in the limited foresight case, never manages to reach the development path deemed optimal in the perfect foresight case.

As Figure 5 shows, the limited foresight approach leads to a slower implementation of nuclear and the gap to the planning with perfect foresight widens so that by the end of the century the perfect foresight case has almost 40% more nuclear production. Similar patterns emerge also for other energy sources, such as centralized solar power plants, that are assumed to have relatively slow capacity build up.

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[6] It should also noted that in this “moving window” approach we apply, and which may be correspond better to the decision environment of and actual decision maker , the 30 - year long time steps overlap each other. This allows the model to reconsider its decisions for a given time period, as more information becomes available, and this makes the differences to the perfect foresight case smaller. For example, the first time the model planned for the time period starting 2070 was while planning for the 30-year window starting in 2050. At this time the optimal oil consumption for 2070 was suggested to be 244 EJ. However, in 2070, when the final, irreversible decision had to be made and more information was available for the time periods after 2070, only 162 EJ, close to the 174 EJ of the perfect foresight case, was extracted. This example also illustrates how strongly the exact definition of how the limited foresight is applied effects the results.

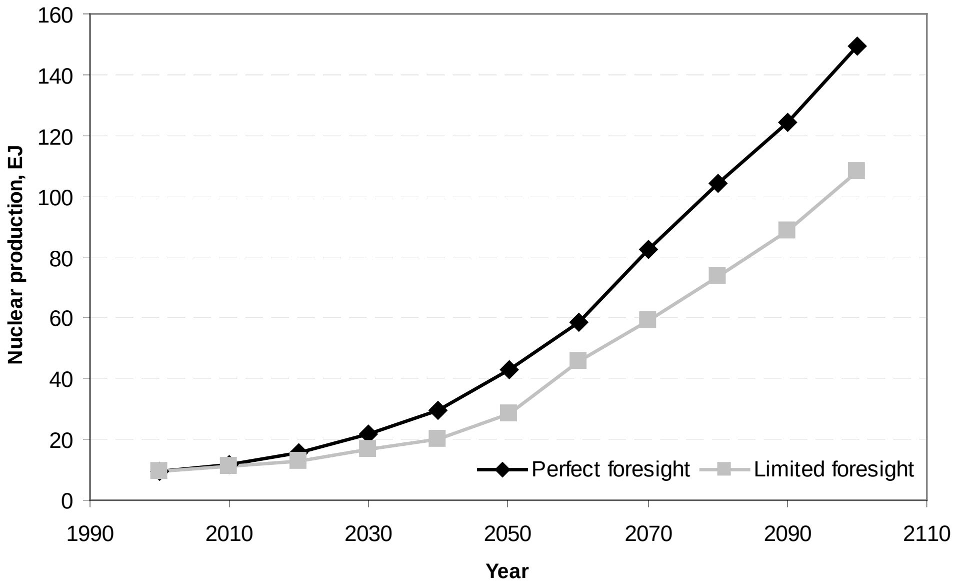

Figure 5: Global electricity production with nuclear power.

The limited foresight solution leads to a more rapid consumption of oil and gas resources, while at the same time solutions requiring slower build-up of capacity remain less developed. Due to this, by the end of the century, when no cheap oil or gas resources are available and production of nuclear power lags behind the perfect foresight case, a stronger reliance on coal emerges.

Both of the scenarios have coal consumption remaining approximately constant until 2050 after which it starts to quickly increase, partially due to the limitations concerning other available, low cost, fossil options. However, due to the lack of other developed options, the limited foresight case has to rely on coal much more than the perfect foresight case; by the end of the century the annual coal consumption is more than 50% above the perfect foresight case. This, in turn, leads to increased emissions, shown in carbon equivalent units for all greenhouse gases in panel b of Figure 6. Limited foresight leads to some 20% higher carbon equivalent emissions in 2100 and the difference for CO_2 emissions is even larger, over 25%.

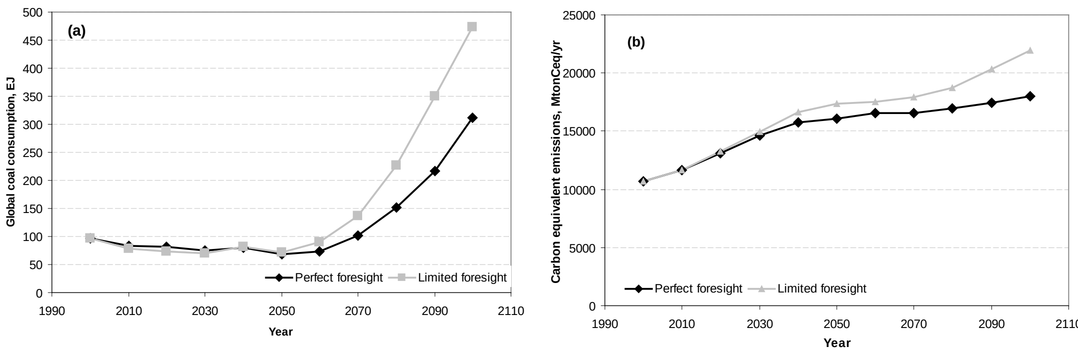

Figure 6: Global coal consumption (a) and the total carbon equivalent greenhouse gas emissions (b).

On the side of the energy carriers used at the end-use level, the differences may sometimes be fairly subtle, but on the other hand also more descriptive of the effects, once results are studied in more detail. For example, the final use of electricity does not differ much between the scenarios. However, there are clear differences in how the electricity has been produced and some of these differences do spill over to other sectors as well. Figure 7 presents snapshots of the electricity production in 2050 and 2100.

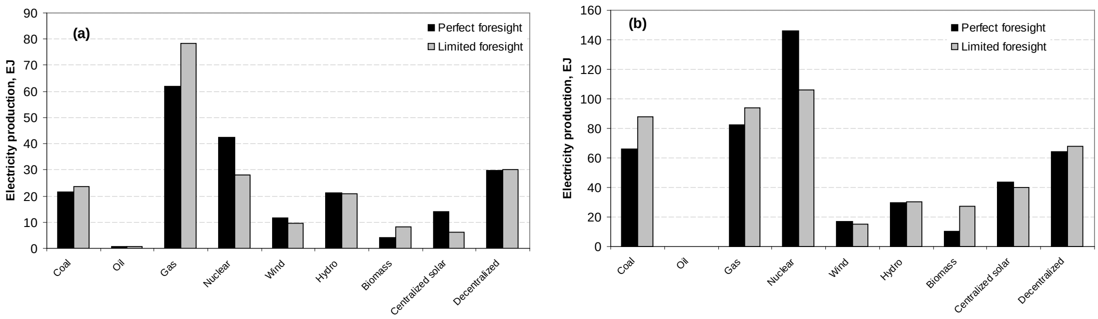

Figure 7: Global electricity production in 2050 (a) and 2100 (b).

In the mid-term the biggest difference is that the limited foresight scenario uses more gas for electricity production, whereas the perfect foresight scenario has more nuclear. In the long term the availability of low cost natural gas limits its use for electricity production and therefore also coal and biomass based electricity production is larger in the case with limited foresight. This, in turn, has an effect for the transport sector, where the depletion of cheap oil resources forces to introduce alternative solutions.

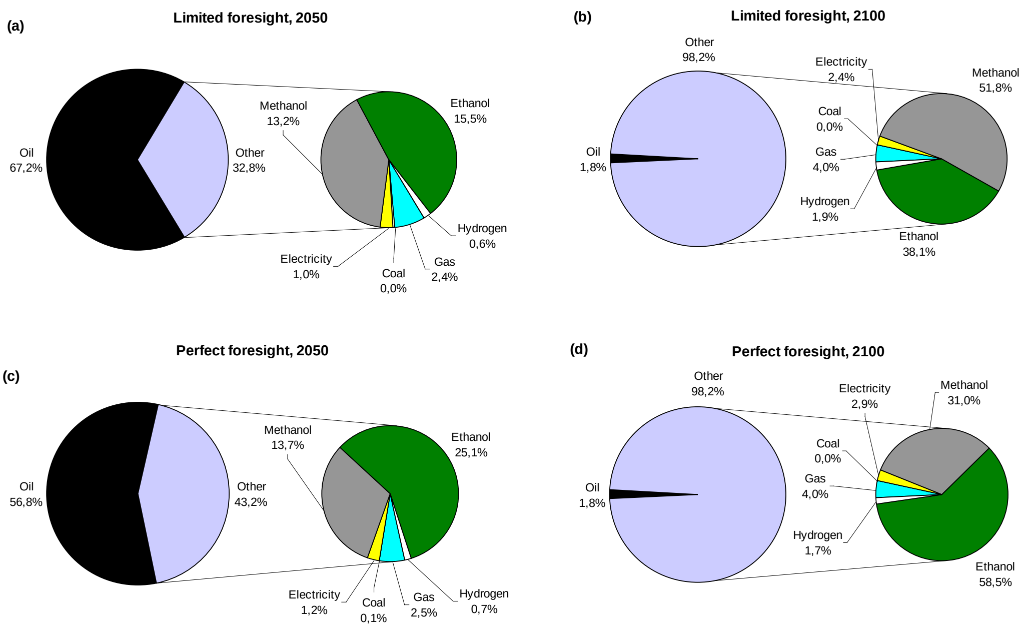

Figure 8: Fuels in the transport sector in 2050 and 2100 (for reference, the share of oil in 2000 is above 95 %).

In both perfect and limited foresight cases, the replacement for oil in the transport sector is alcohol. However, there are also clear differences between the two scenarios. For example, although both scenarios introduce fossil fuel based methanol and biomass based ethanol, by the end of the century methanol, which by then is produced mainly from coal, is the dominating one in the limited foresight case and ethanol in the perfect foresight one. This is, among other things, due to the higher consumption of biomass in the power sector in the limited foresight case, which leaves less affordable bioenergy resources for the transport sector. Furthermore, in the perfect foresight case ethanol replaces more of the oil already in mid term; it has in 2050 a market share of 25% in the perfect foresight case and a 15% share in the limited foresight case. To cover the difference, the limited foresight case does not develop e.g. methanol production more aggressively, but uses oil instead.

The dynamics described above show how short term planning may lead to a lock in, or a lock out, of certain technologies, or at least considerably change the balance of such technologies. In the example presented above, ethanol is the most important fuel for the long term, if perfect foresight is applied. In the limited foresight case, while still important, the possibility of an even larger share of ethanol is locked out, due to the decisions made until the mid term in this sector (i.e. stronger reliance on oil) as well as other sectors (e.g. lower penetration of nuclear in part leads to extended use of bioenergy for electricity, leaving less for transport). In this case, the lack of foresight concerning the need to develop alternative options more aggressively leads to a solution that is, by the end of the century, although fairly similar on a macro level, also clearly different from the perfect foresight solution for some important sectors and indicators.

Costs and prices

In a linear optimization decision framework, the perfect foresight case, by definition, leads to the lowest total costs, while simultaneously taking into account all the other constraints. When limited foresight is included, the model will not take into account the future far beyond its decision horizon and will therefore concentrate on minimizing the costs for the few “visible” decades alone. The more limitations there are for the future states and the more these limitations require early actions, the more costly this lack of foresight becomes. Discounting, however, has a mitigating effect on the differences, especially if no additional constraints effecting also long term are set (e.g. climate targets). Figure 9 shows how investment patterns change across the two cases.

In addition to confirming the previously demonstrated results concerning the long term, fossil heavy structure of the limited foresight solution, figure 9 also points out the difference concerning the timing of the investments made. With perfect foresight, decisions are not based only on the current needs, and therefore a need for alternative solutions for later decades can be identified and early investments can be directed to such upcoming technologies. This leads to slightly higher short and mid term total energy investments (3 – 4%), but the long term investments are respectively lower. Fossil fuel related investments are higher in the limited foresight case; the cumulative difference throughout the century is almost 17%. This again emphasizes, how in the limited foresight case the decisions based on a short term view alone, can lead to a lock-in, or a lock-out, which may increase the costs in the long term.

In addition to total cost numbers, another indicator can be used to reflect the economic consequences of the limited foresight. Marginal costs, represented by the shadow prices of the energy carriers, give an indication of how the market prices of fuels might be affected by the changed decision horizon.

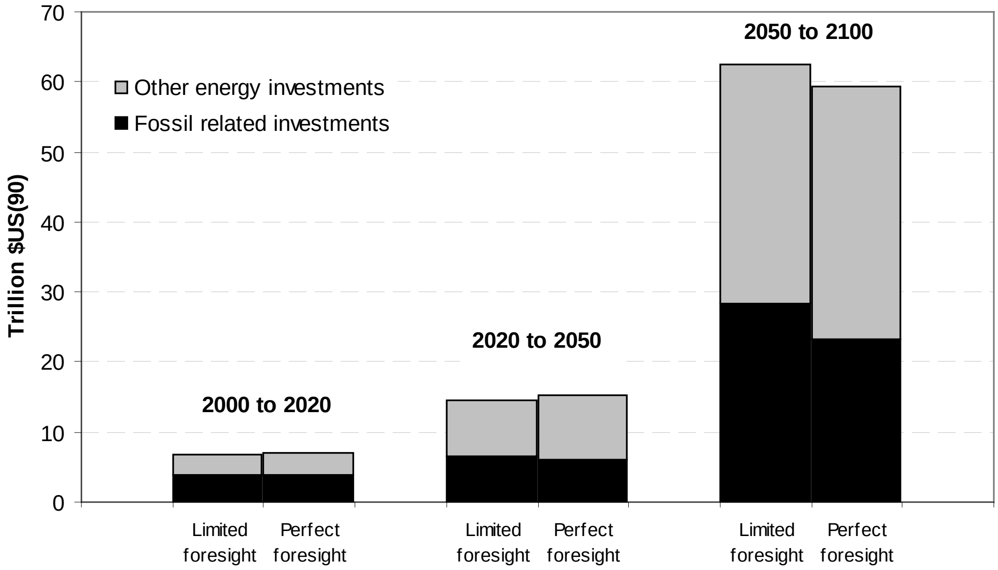

Figure 9: Cumulative global fossil and other energy investments in the short, mid and long term.

By 2050 the higher demand of oil in the limited foresight case leads to crude oil prices that are around 40 $US(90)/barrel[7] and some 5 – 10% above the perfect foresight case, depending on the region[8]. For other energy carriers, however, the results are much more mixed for 2050; for the three regions, chosen here to represent the results of the industrialized world (Western Europe) and the developing world (Sub-Saharan Africa and Centrally planned Asia), the prices of other fuels in 2050 might be higher or lower than in the perfect foresight case and there is no clear trend across the regions concerning which fuels might have their prices increased or decreased. This is all, however, changed by 2100. In 2100 and in the limited foresight case, the oil prices are around 120 $US(90)/barrel for most regions, while in the perfect foresight case a representative price is around 25% lower, some 90 $US(90)/barrel. Furthermore, for the three regions studied in detail, prices of all energy carriers are in 2100 higher than those of the perfect foresight scenario, the fuel and region dependent range of increase being from 10% to over 50%.

The brief look into the results presented in this section has illustrated some of the characteristics that can be expected from such a setup and which can also be identified in real life decision making; postponement of investments in new technologies, stronger reliance on conventional energy sources and the slowly increasing difficulties in

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[7] This price reflects only the extraction and distribution costs of the fuel that are represented in the model and does not therefore take into account many of the drivers that affect the high oil prices of today.
[8] The differences are mainly due to trade inefficiencies and restrictions assumed in the formulation of the model.

providing the required energy demand economically. The decision time frame used in this example for the limited foresight approach was 30-years with a possibility to reconsider the decisions made for two further time periods. Although it can be expected that the general trends of the results presented here would be visible also if other definition for the foresight was used, the exact quantitative impacts would most likely differ.

Conclusion and outlook

In this paper, we develop and demonstrate a limited foresight version of the MESSAGE model. This new model allows the study of how decision making time frames and incomplete information may effect energy transitions. We furthermore reformulate parts of the model in order to allow a more flexible description for the introduction and decline of technologies. This new formulation, based on sequential decision making, permits us to describe the situation of a decision maker more realistically, without complete information and with the emphasis on the less uncertain near future.

In order to describe some of the effects a shorter decision horizon may have, we develop, based on previous work, two scenarios; one using the standard perfect foresight setup and another that assumes a moving, 30-year decision window and sequential decision making. We discover that the altered model does demonstrate many of the possible pitfalls that may face the decision maker, who bases the decisions only on the needs of today; investments in new technologies are postponed and misdirected and the early savings in investments lead to higher investment needs in the future. Due to the heavy reliance of the limited foresight case on fossil fuels, it can be speculated that these cost effects would be even stronger in a climate constrained world, unless appropriate policies are implemented to offset the lack of foresight. An interesting topic for future work might therefore be, for example, to study how climate mitigation decisions done for the next few decades might effect the options available for further mitigation later and what kind of final climate targets are being excluded, if actions are not taken early enough. On the methodological front, a potentially fruitful direction might be to combine the limited foresight version developed here with a stochastic setup. Such a model would allow not only to describe limitations on the extent of foresight, but also on the quality of it.

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