Back to our future. Physical constraints on sustainable development paths in an energy-based backcasting approach

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SUMMARY

Since the publication of the Brundtland report "Our Common Future" 'sustainability' is on the political Agenda. It encompasses 'meeting the needs of the present without compromising the ability of future generations to meet their needs'. For this thesis this definition is extended by the statement that in a sustainable society an equal right per capita exists to the benefits of natural resources, irrespective of place and time of living. Thus, sustainability includes equity in space and time.

The objective of this thesis is to study bio-physical constraints on sustainable development paths; i.e. what level of consumption can be derived sustainably from the existing 'stocks' of natural resources. Given this perspective, institutional-, socio-psychological- and monetary economics issues are not specifically addressed. Natural resources are taken to consist of depletable (materials) resources like fossil fuels or ores, renewable resources like solar energy, but also of environmental quality determining resources like unpolluted air (e.g. to maintain an undisturbed climate) and well-preserved natural areas (e.g. protection of natural bio-diversity).

In Chapter 1 of this thesis, a hierarchy is suggested for global bio-physical indicators for sustainability. Energy use is chosen as the ultimate bio-physical constraint on sustainable development, since energy can be used to exploit ever leaner material ores, which in turn can be used - like energy - to counteract spatial limitations on human activity. A sound land use policy (and pollution prevention), in turn, can protect natural bio-diversity. The two main problems in energy use are *supply* and *pollution*, which are caused by the rapid increase in energy use through time. Resources of fossil fuels (our main energy source at present) are depletable, and the CO_2 emission occurring through its use is increasing the risks for an enhanced greenhouse effect. The potential supply of renewable energy sources is limited for various reasons (e.g. spatial requirements). From data on fossil fuel resources and CO_2 emissions it follows that a transition to renewable (e.g. solar) energy will have to occur sometime in the next century. In this thesis the transition to a sustainable, liveable and equitable world is studied by an end-use orientated, energy based backcasting approach.

In Chapter 2 a breakdown of world energy use is given into three main factors underlying it, i.e. population size, material wealth per capita and energy intensity. The latter two are expressed as *Service Level per Capita* (SLC) and *Energy Required per Service* (ERS). To express important differences in these factors they are quantified separately for the First- and Third World. In 1990, the ratio of SLC1 to SLC3 was 1 : 0.17, whereas the ratio of ERS1 to ERS3 was 1 : 1.35. This division allows a study of the equity concept, in which both SLC1/SLC3 and ERS1/ERS3 values become equal in a certain year. Based upon three different UN population forecasts, a maximum level of energy use per capita can be determined in a final

sustainable situation - including equity. Energy supply then largely consists of 'solar hydrogen', i.e. hydrogen generated by silicon photo-voltaic cells. Silicon based PV cells are assessed to be the best option based on materials- and spatial requirements. This final situation is used as a reference in backcast scenarios described in the next chapters.

In Chapter 3 the basic version of the Transition calculation model is introduced and a series of sample calculations is shown. The calculation model is made to investigate the physical possibilities, at an aggregated macro level, for reaching a sustainable equilibrium world society. Constraints on the possible futures are based on energy as common denominator, under the assumptions that there is a limited amount of fossil fuels available, and that the use of this amount might even be more limited due to emissions into the environment. The purpose of the "Transition" models is to calculate the amount of fossil fuels used until 2100, and the CO2 emission caused by this use, given a set of input parameters. Most input parameters relate to a transition from fossil to solar energy, sometime in the next century. The model input can be defined by the users, depending on their targets, values and beliefs. Basically the models answer the question "If...., then....". Basis is the matching of energy demand by energy supply, for every year between 1990 and 2100. The model structure is 'open', i.e. containing no feedback loops.

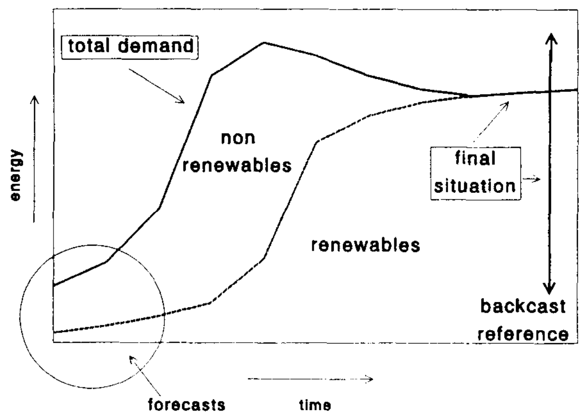

Figure S.1. The transition to renewable energy sources and references for backcasting.

The line of reasoning in the Transition Modelling Framework starts with setting a target for sustainability in the future, including equity[1]. A range is then specified for energy use within environmental (scarcity and pollution) constraints for this final, sustainable equilibrium. This is shown in Figure S.1: the energy use in the final situation varies between low and high assessments. From this range, some backcasting scenarios are devised that relate the end point to the present situation. These

1. Though equity and a full transition to renewable energy need not be reached simultaneously.

scenarios include combinations of population development, development of service level per capita and energy required per service (e.g. including equity), which dictate the position of the line representing *total energy demand*. They also include assessments of the rate of exploitation of renewable resources, which constitute the line representing *supply from renewable resources*. All scenarios are bounded by limits on available fossil fuel resources (in the sample calculations three classes of resources limits are presented[2]) and by limits on CO2 emissions (the IPCC 1990d limit is used; for sensitivity assessments also limits twice as large and twice as small are shown). These two constraints dictate the *size of the area* between the *supply line of renewable energy sources and the total demand. From estimates or* expectations on all but one of the factors introduced before, the range of possible values for the last factor can be calculated. If only a few factors are assessed up front, this leads to a series of possible values for the remaining factors. I.e., estimates on population growth and the year in which equity be achieved can be combined with a chosen transition path to renewable energy. These estimates lead to maximum values for the product of service level per capita (SLC) and energy required per service (ERS), related to the chosen data on fossil fuel resources and maximum allowable CO2 emission. Since by incorporating equity the levels for ΔSLC3 and ΔERS3 are automatically set for a given ΔSLC1 and ΔERS1, results of the calculations are presented in the form of constraints on the combinations of ΔSLC1 and ΔERS1, given sets of assumptions on the other factors mentioned above. This is shown in Figure S.2 and S.3.

Figure S.2 gives typical results for a group of scenarios in which ΔSLC1 is varied. Scenarios outcomes are considered unsustainable if either the fossil fuel requirements lie to the right of the chosen available resource class, or if the required CO2 retention[3] relative to the chosen limit lies above the maximum assessed as feasible (50% retention of cumulative CO2 emission to 2100 is used as a high estimate). The figure shows that under these assumptions, positive ΔSLC1 values would lead to a requirement of over 50% CO2 retention, consuming more than the proven amount of fossil fuels - and even more than speculative resources at high ΔSLC1 values in combination with an L2 transition[4]. Similar diagrams could be constructed for e.g. other values for ΔERS1 (more efficiency improvement leading to a higher growth potential). In Figure S.3 calculation results are translated into constraints on ΔSLC1 and ΔERS1, for the medium UN population forecast, equity in 2050, two different transition paths to solar energy (i.e. E1 or L2) and two different

2. Proven reserves, speculative + proven resources, or all conventional oil + gas resource bases + marginal coal resources.

3. E.g. dumping of CO2 into deep sea or 'emptied' gas wells, or sequestering of CO2 via reforestation.

4. E1: exponential transition from 2000 to 2050; L2: linear transition from 2050 to 2100.

assessments of feasible CO2 retention (i.e. 0 or 50%)[5]. These diagrams can be constructed for any CO2 limit one wants to refer to[6]. Thus, backcasting sets targets for those factors that are not assessed in advance.

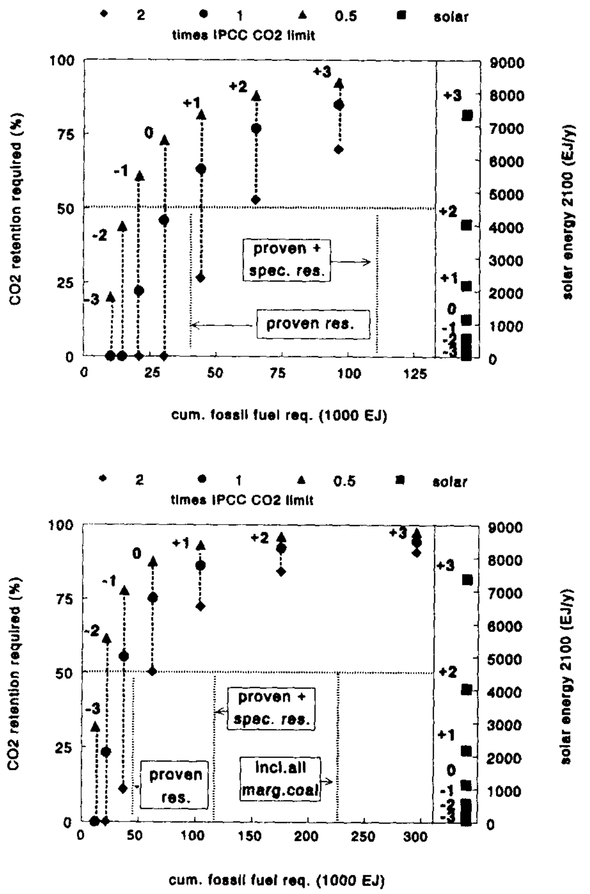

Figure S.2. Typical results for a group of scenarios varying in ΔSLC1 values (indicated by the numbers -3 to +3, in %/a). Shared assumptions: ΔPOP = "med", ΔERS1 = -1%/a (1990-2050), equity in 2050. The upper diagram represents E1 transitions (exponential from 2000 to 2050); the lower diagram represents L2 transitions (linear from 2050 to 2100). CO2 limits refer to the IPCC 1990d constraint, and to limits of twice or half this amount. For a classification of fossil fuel resources see Footnote 2. Please note the difference in the scale of the X-axis between the upper and lower diagrams. The final solar capacity in 2100 (given as solar hydrogen supply) does not depend on the transition path (thus, there is no difference between upper and lower diagram).

In Chapter 4 the focus is on the Energy Supply System. The energy requirement for energy supply (ERE) is visualized, leading to a separate factor in energy demand

5. Compared to the IPCC 1990d limit.

6. Even the effect of ignoring CO2 emissions altogether could be shown, in which case one could relate to the different estimates of fossil fuel resources only.

(next to POP, SLC and remaining ERS). E.g., the energy requirements to build and maintain a photo-voltaic energy supply system, including transformation to hydrogen for storage and transportation are taken into consideration. The energy required to construct solar cells has to be partly obtained from non-renewable sources (energy 'investments' must precede energy 'returns'). This means that a part of the remaining fossil fuel resource base can not be 'consumed' but has to be 'invested'; the actual amount being dependent both on total energy demand to supply services as on technical assumptions with regard to solar energy supply systems. Fossil fuels will have to remain in use throughout the energy transition period. However, although the constraints are slightly tightened in comparison with the result from the Basic Model, no new fundamental physical problems arise in achieving a sustainable future.

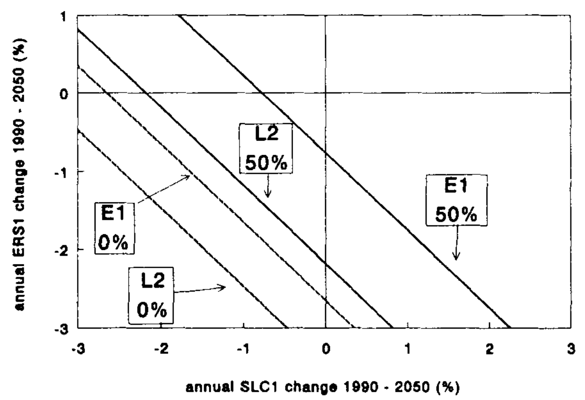

Figure S.3. Transition constraints on ΔSLC1 and ΔERS1 1990-2050 (equity in 2050; medium ΔPOP; E1 or L2 transition; 0 or 50% CO2 retention). Combinations lower/left of the lines are sustainable.

Chapter 5 presents the Materials-Extended model version. Here the effects of a trade-off to energy in materials supply is visualized. Factors (directly or indirectly) affecting energy demand for materials supply are: total demand for materials (which, if rising, increases scarcity phenomena); scarcity (leaner ores require a higher energy input); recycling (which, if improving, lowers energy demand and scarcity increase); and, finally, substitution of one material for another and changes in production efficiency (both of which can influence energy demand in either way). Various assumptions concerning these factors are studied. Examples include: recycling optimization versus continuation of recycling at the current level; an optimistic and a pessimistic scarcity assessment including a stepwise function for increasing energy requirements for mining versus cumulative materials use, and substitution of copper by aluminum. Materials demand was modelled as Materials Required per Service (MatRS, by analogy with the ERS values), while efficiency improvements in production processes were expressed as an annual percentage. In most medium to high growth scenarios, scarcity prevails over recycling, leading to an extra demand for energy, thereby increasing constraints on potential service levels. Only in low to medium growth scenarios in combination with an optimistic scarcity assessment it is the other way around: recycling offers some leeway for growth of service level.

A discussion on the various model structures is given in Chapter 6. The models have a high level of aggregation, which is both their strength and their weakness. The transparency of the basic model makes it very suited for policy support, and management- and educational purposes; users are forced to make their expectations explicit. Both extended model forms are somewhat less transparent, but do generate more insight in the mechanisms of transition and trade-offs to energy. Future work could show more of these trade-off mechanisms, e.g. by modelling a growing energy demand for fresh water supply. External links are possible to ECCO and MARKAL models, like there are also links to the concept of Environmental Space. To magnify the educational profits from the transition models, a provisional version of an educational game based on the *Toolbox for Tomorrow* methodology is described. This game has two parts to be used in a workshop; an example model narrating the sad (but true) story of the decline of Easter Island, in which alternative endings can be implemented; and a global energy transition/equity model, which can be used to study relevant aspects (actors, reactivities, events) involved in the current global -energy- situation.

In Chapter 7 the results of the sample calculations with the transition model are discussed, and they are compared to literature forecast scenarios. The results from the example calculations show a transition to a sustainable society in 2050 to be *physically* possible, if a number of pre-conditions is met. These pre-conditions relate to world population growth (until 2100), and to the level of energy efficiency improvement compared to the growth of service level per capita in the First World, until 2050. Early transitions to solar energy generate a higher potential for development of service levels. The transition limits are more stringent than the limits on the final equilibrium that can be derived from a top-down supply-side oriented approach. This means there may still be a potential for future growth beyond the time horizon of this backcast model (in the example calculations no statements are made about growth potential beyond 2050; if all underlying assumptions are satisfied no *decline* in energy use per capita will have to occur). During the transition, the limits imposed by *pollution control* (i.e. limiting CO_2 emissions) are more stringent than the absolute amount of fossil fuel *resources*.

Since most (literature) forecast models only have limited time horizons (cf. Figure S.1), they do generally not give information on the potential long term sustainability of their underlying assumptions (e.g. those relating to economic growth in First- or Third World). Most scenarios studied do not satisfy the IPCC CO_2 emission limit used in this thesis if they are extended to e.g. 2050 - not even if a transition to solar energy is modelled to take place immediately after the original time horizon of the forecast. From the group of energy scenarios studied, only the scenarios presented by Goldemberg seem to offer a path that leaves open the possibility for reaching equity without surpassing environmental thresholds of the type considered here. However, this scenario is based on a low population forecast, which e.g. leaves room for a large scale use of biomass without endangering food supply. The Greenpeace Fossil Free Energy Scenario might, in its stated conservatism, also contain the potential to reach equity and sustainability within the next century, even with a higher population growth than assumed in Goldemberg's scenarios. The other scenarios (i.e. WCED, IIASA, CPB) show the unsustainability of (near) business-as-usual developments in various degrees. These scenarios will either surpass environmental thresholds, or require a decrease in energy use per capita (especially in the First World) like is depicted in the 'crash course' "B" in Figure S.4, sometime in the next century.

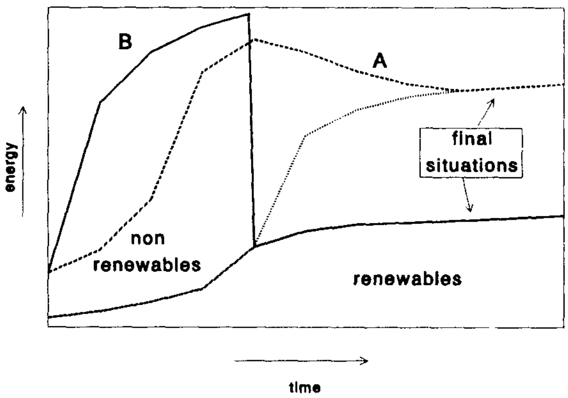

Figure S.4. Two possible transition paths to a sustainable energy system (units of time and energy chosen arbitrary). Path A will lead to a higher sustainable energy level than the crash course B.

The results suggest the existence of a sustainable development dilemma. If the historic trends in the growth of service level and energy efficiency improvement are continued and combined with equity - even including a transition to solar energy - it implies the depletion of fossil-fuel resources to such an extent that greenhouse issues become much more serious and the requirements for renewables and CO2 mitigation become almost unsurmountable. Such problems seem only avoidable at the expense of maintaining the gap between the rich and the poor for another century. Neither solution can simultaneously be labelled as sustainable, equitable and liveable. The challenge for structural change is set; current energy forecasts or scenario studies do not yet provide a full answer to this. Delays in changing present trends will narrow the solution space because energy use levels will grow, low target values for SLC will be more difficult to reach and more fossil fuels will be consumed, leaving less of them available for the transition period.

The challenge for structural change is thus set from a natural resources viewpoint.

Chapter 8 closes this thesis with some reflections on the institutional and socio-psychological aspects of a transition to sustainability. One of the main reasons why the required energy transition cannot be ruled by an unrestricted free market system is the absence of a price ticket on greenhouse gas emissions (the strongest constraint on fossil energy use) and the weak protection of the future in general. Therefore, a goal-oriented policy seems required, which will be demanding on social sciences to guarantee implementation. It is argued that the initiation of an energy transition is the responsibility of the main CO2 emitters of the present; i.e. the First World countries. Some comments in this light are made on the concept of Joint Implementation (J.I.) versus Technology Transfer; it is suggested that J.I. be defined as decreasing the environmental impact of per capita consumption in First World countries as calculated by an LCA approach[7]. Technology Transfer then should relate to decreasing per capita environmental impact in Third World countries based on the same accounting method. Next, the concept of *Environmental Sphere of Influence* is introduced, which shows that by applying various ways of accounting the environmental impact caused by various actors (i.e. natural persons, countries) their influence turns out to be larger than by using one single method (i.e. the 'Environmental impact per unit of GNP' or the LCA method). Finally, a few examples are given which show that even on the short term or on the meso-level environment and economy need not be conflicting issues.

7. LCA = Life Cycle Analysis.