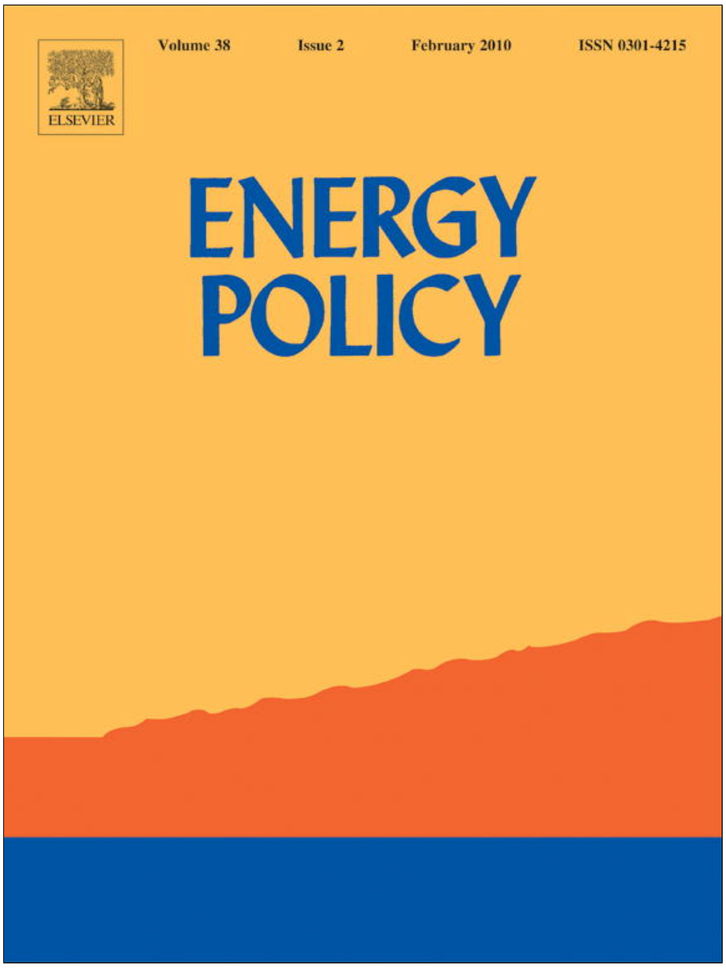
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Renewable energy costs, potentials, barriers: Conceptual issues

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A B S T R A C T

Renewable energy can become the major energy supply option in low-carbon energy economies. Disruptive transformations in all energy systems are necessary for tapping widely available renewable energy resources. Organizing the energy transition from non-sustainable to renewable energy is often described as the major challenge of the first half of the 21st century. Technological innovation, the economy (costs and prices) and policies have to be aligned to achieve full renewable energy potentials, and barriers impeding that growth need to be removed. These issues are also covered by IPCC's special report on renewable energy and climate change to be completed in 2010. This article focuses on the interrelations among the drivers. It clarifies definitions of costs and prices, and of barriers. After reviewing how the third and fourth assessment reports of IPCC cover mitigation potentials and commenting on definitions of renewable energy potentials in the literature, we propose a consistent set of potentials of renewable energy supplies.

0. Introduction

Since the start of the IPCC process in 1988, interest grew for improved assessments of greenhouse gas emissions *mitigation* "potentials" and "costs" related to achieving those potentials. The Third Assessment Report, Working Group III devoted chapters to "Barriers, Opportunities, and Market Potential of Technologies and Practices" (Sathaye et al., 2001), and "Technological and Economic Potential for Emissions Reductions" (Moomaw et al., 2001). Long discussions in cross-sectional meetings, with participation of lead authors from all Working Group III chapters, were spent on more precise definitions of what the various levels of potentials mean. The discussions were structured around, while adapting and improving, Fig. 5.1 in Sathaye et al. (2001, p. 348), further shown as Fig. 4 in this publication. Because "potential" inherently refers to something that may happen but which is not necessarily achieved, every level of potential depends on the assumed conditions and actions that affect its realization in the future. The difficulties in defining precisely mitigation potentials were multiplied by the rather vague definition of the term mitigation used as the relevant adverb before potential. Confusion further grew by the adoption of different definitions for market and economic mitigation potentials adopted during the process of IPCC's fourth assessment report (IPCC-WGIII, 2007, p. 819 (Glossary)).

In 2008/2009, IPCC launched the SRREN: Special Report on Renewable Energy (Hohmeyer and Trittin, 2008). A significant part of the SRREN is assigned to the assessment of the potentials of renewable energy (RE) supplies by various sources and technologies for delivering energy, or more precisely, energy services as an important component of the climate change mitigation effort. Some RE literature introduced RE potential concepts, quite differently from the IPCC definitions, without agreement on a consistent set of concepts in a coherent framework. The use of different concepts, often with underlying assumptions and restrictions that are not transparent, frequently adds confusion to debates on the potential for RE. This article

Abbreviations: AR4, Fourth Assessment Report by the IPCC (2007); IPCC, Intergovernmental Panel on Climate Change; EE, energy efficiency; RE, renewable energy; SRREN, Special Report Renewable Energy Sources (2009–2010); TAR, Third Assessment Report by the IPCC (2001); WGIII, Working Group III of the IPCC

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addresses the present confusion and argues in favor of a common conceptual framework and definitions of costs, potentials and barriers.

This is important since perceptions of potentials matter for how policies are formulated and thus for how energy systems are shaped. Until recently, it was a widely held belief, or conventional wisdom, that RE can make only a marginal contribution to future energy supplies. This belief was plainly uniformed or based on implicit or undefined sets of barriers. A static mindset concerning technologies, costs, possibilities for siting, limits to the penetration of variable power sources, etc., has contributed to such beliefs. But technologies develop, costs are reduced, and siting and integration possibilities expand over time. Wind power, now moving off-shore or even into forests using high towers, is a case in point. In addition, control technologies and grid operation strategies facilitate higher penetration levels. Thus, similar to the estimates of fossil fuel reserves, the RE "reserves" are indeed dynamic, but with a vastly greater resource base.

There are seven sections. Section 1 highlights the relationships between the major factors that affect RE supplies and potential supplies. Section 2 argues why clear definitions and metrics of RE supplies are helpful in quantifying potentials. Section 3 deals with costs and prices and how the former can be transformed into the latter; also the addition of rents is mentioned. In Section 4, IPCC (TAR and AR4) definitions of mitigation potentials are examined. Section 5 reviews a few references that present renewable energy potentials. Section 6 offers definitions for potential levels that may be useful for policy formulation. In Section 7 a short introduction to the complexity of barriers is based on the energy efficiency barriers literature.

1. Connectivity of driving factors

Mitigation of climate change is a multi-faceted effort (IPCC-WGIII, 2007). Substituting renewable energy supplies for non-sustainable energy sources is considered to be one of the major mitigation options. For climate policy planning, the "potentials" of renewable energy supplies therefore need to be assessed as accurately as possible. IPCC's SRREN initiative has been set up as a project to improve IPCC-AR4's estimation of the economic potential for renewable energy, with more and better information about all important aspects related to an accelerated deployment such as: co-benefits; the technology and market status and future developments; integration into energy supply systems and markets; economic and environmental costs, benefits, risks and impacts; capacity building, technology transfer and financing in different regions; policy options, outcomes and conditions for effectiveness (Hohmeyer and Trittin, 2008, pp. xi–xiv).

Estimating RE potentials is a difficult task, demanding a better understanding of several aspects of natural resources by region, technology, economics, politics, human behavior, etc., requiring the contribution of tens of experts. Estimating any energy application requires an analysis of the desired energy service and the amount of energy required to meet that demand, which can vary by an order of magnitude (Laitner, 2009). For some RE potentials for distributed use and especially in developing countries with less connected markets, demand efficiency may determine the deployment of specific technologies. For organizing the dialogue and co-operation among a large variety of scientists, defining well the basic concepts and clarifying their relationships pays off.

Fig. 1 provides an overview of how costs, barriers, technological innovation and policies may interact and affect RE supplies. RE supplies are the combination of RE resources that are tremendously large (Moomaw, 2008) and of operational energy technologies for harvesting the available resources (Twidell and Weir, 2006). "Supplies" as flows of energy (power; light) or accumulation of stocks (biofuels; reservoirs) emphasizes actual effectiveness in delivering energy or energy services. The purpose of Fig. 1 is to highlight the interactions among the factors. "Technological Innovation" and "Policies" are printed in dashed lines because they are not analyzed in this publication on costs, potentials and barriers.

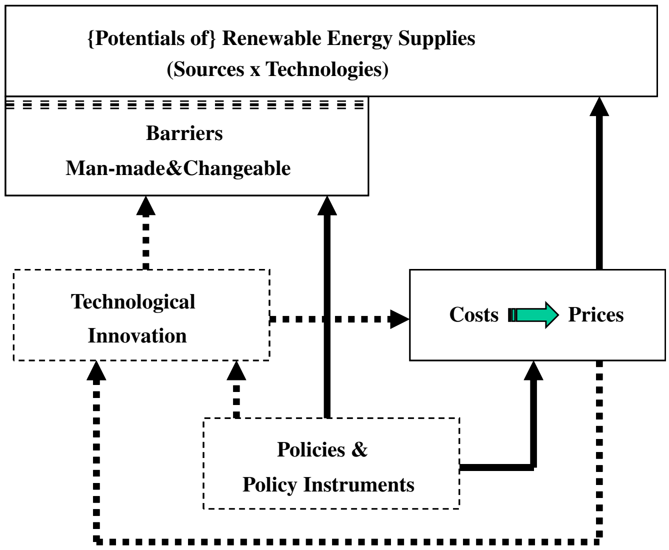

Fig. 1. Interconnection of factors affecting renewable energy supplies.

Prices of goods and services, and in particular of energy goods and services, have a high impact on RE supplies. How prices of energy supplies may be linked to their costs is the subject of Section 3, and significantly affects the deployment of renewable energy. RE supplies may also be hampered by specific natural factors (e.g., topography) and by man-made barriers (e.g., improper orientation of buildings). Technological innovation is an important factor for dissolving barriers and for lowering costs of options. Policies can address barriers directly or via supporting technological innovation (R&D, demonstration, diffusion) and perhaps mainly by controlling the transformation of costs into prices, with resultant feedbacks on technological innovation (Fri, 2003). The relations shown in Fig. 1 are expressed by Jaffe et al. (1999, p. 15) as: "Although continued research is needed to pin down the precise magnitudes, it seems clear that economic motivations—operating directly through higher energy prices and indirectly through falling costs of technological alternatives due to innovation—are effective in promoting the expanded market penetration and use of more energy-efficient, GHG-reducing technologies."

The relationships of Fig. 1 are valid for historical study or static analysis, and for assessing what the future can bring. The future-oriented perspective adds the connotation "potential" to RE supplies. Merriam-Webster's Collegiate Dictionary (tenth edition) describes "**potential**" as "something that can develop or become actual." This implies gaps between the actual (present) state and the potential (future) state. Neglecting the future time perspective rids the concept potential of its development dynamics, degrading it to the equivalent of "lost opportunities".

Gaps may be caused by a wide range of factors related to, for example, nature, climate, physical conditions, development and diffusion of technologies, economics, institutions or other societal conditions. The factors may be described as natural or man-made, with several factors blended: some factor attributes are natural and other attributes are man-made. Man-made factors are changeable by man and change may stimulate the realization of particular potentials, or may hinder it, the latter, for example, in the case of well-intended regulations causing perverse effects.

In a policy context, "**barriers**" (synonyms: obstacles, hindrances, impediments) are man-made factors or attributes of factors that operate in between actual and potential RE development or use. They can be both intentional and unintentional. A barrier prevents or hinders action, impedes progress or achievement in realizing potentials. IPCC-WGIII (2007, p. 810 (Glossary)) defines barrier as "any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy, programme, or measure. Barrier removal includes correcting market failures directly or reducing the transactions costs in the public and private sectors by, for example, improving institutional capacity, reducing risk and uncertainty, facilitating market transactions, and enforcing regulatory policies." Therefore, in Fig. 1, barriers has as specification "Man-made & Changeable".

Depending on the goals pursued, the term "barriers" may refer to facts and conditions that should be maintained or strengthened to avoid the realization of perverse goals: for example, public opposition against nuclear power risks and weapons proliferation is a barrier for the nuclear renaissance (IEA, 2006, p. 134; GIGATON Throwdown, 2009, p. 97).

2. Renewable energy supplies[1] : definitions and metrics

A quite trivial, but often overseen, prerequisite for clearly defining particular potentials is the identification of the object of study itself. For example, climate change "mitigation" is but loosely defined (IPCC-WGIII, 2007, p. 818 (Glossary)), and so are "mitigation potentials". For the assessment of RE supplies and potentials, object identification is more straightforward. There exist some differences in opinions about considering passive solar energy (Arzivu, 2008) as renewable energy supplies or as energy efficiency. Qualifying the various renewable energy supplies for measuring their degree of sustainability is an unsolved issue; for example, see the contribution by the European Parliament (2008) on the qualification of various bioenergy supplies in the debate on the latest EU Directive for the promotion of the use of energy from renewable resources. Qualification is necessary for identifying the right categories of RE supplies (fundamental and distinct classes to which entities belong). Categorizing is a necessary step for avoiding errors caused by the uniform treatment of different cases. The negative effects of missing qualification and categorizing of renewable electricity generation are discussed by Verbruggen and Lauber (2009).

The literature provides several definitions of RE supplies. For example: Twidell and Weir (2006, p. 3) define RE as "energy obtained from the continuing or repetitive currents of energy occurring in the natural environment". The Dictionary of Energy edited by Cleveland and Morris (2006, p. 371) says renewable energy is "any energy source that is naturally regenerated over a short time scale and either derived directly from solar energy (solar thermal, photochemical, and photoelectric), indirectly from the sun (wind, hydropower, and photosynthetic energy stored in biomass), or from other natural energy flows (geothermal, tidal, wave, and current energy)." IPCC-WGIII (2007, p. 814 (Glossary)) combines the above two quotes: "Renewable energy is obtained from the continuing or repetitive currents of energy occurring in the natural environment and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves and geothermal heat, as well as carbon-neutral technologies such as biomass." This definition can be refined, for example, by adding the notion that some renewable sources can be exhausted by overexploitation.

In addition to concise definitions, it is necessary to detail the various types of RE supplies. The literature provides various examples of more detailed specifications. For example: "By IEA definition, RE sources include combustible renewables and waste (solid biomass, charcoal, renewable municipal waste, gas from biomass and liquid biomass), hydro, solar, wind and tide energy" (RETD, 2006, p. 16). Hoogwijk and Graus (2008, p. 6) provide an overview in a table. Contributors to the SRREN scoping meeting (Hohmeyer and Trittin, 2008) categorized RE into six main groups: bioenergy, direct solar, geothermal, hydropower, ocean, and wind energy, with each defined in greater detail. For example, ocean energy represents four classes based on conversion principles: wave energy, hydrokinetic energy, ocean thermal energy, osmotic energy (Soerensen and Weinstein, 2008, p. 94). Most extended will be the taxonomy of bioenergy; for example Moreira (2008, p. 15) provides "an overview of selected biomass commodities", already consisting of three classes and 17 elements. It is expected that the final SRREN report will deliver a comprehensive and authoritative nomenclature and classification of RE supplies.

Metrics for measuring the quantity of RE vary; some studies use energy units (Joules or Wh), others provide results in capacity (J/s or Watt). For energy units to be unequivocally comparable, one should specify whether it is net delivered energy, gross delivered energy or primary energy (Hummel, 2007). For example, output from solar photovoltaic panels is mostly measured as net delivered energy to the end-user or to the grid. Bioenergy is measured mostly as primary flows or stocks that need further conversion and transfer to become useful energy. When energy quantities are labeled properly, no confusion arises. One compares apples and oranges if one neglects proper conversion to compatible units.

Metrics related to defining capacity are not always clear either. Solar PV capacity is generally clear by its established standard of 'peak-capacity', being the output of a panel under standardized laboratory illumination. Given the geographical location of the PV panel, its particular installation (fixed orientation and inclination, or sunbeam tracking) and average meteorological conditions at the site, the yearly energy delivery of a rated peak kW is assessed within narrow ranges. For other RE sources and technologies, there may be no such clear standards on rating the capacity, giving rise to confusion about what energy the given capacities could potentially deliver.

The emphasis on RE supplies and clear metrics does not imply that quantities of RE generated linearly measure the success of particular RE technologies or of RE in general. Successful RE deployment often displays particular characteristics: it occurs near to where energy services are demanded; capacity loads are managed; it goes hand in hand with high energy efficiency of end uses; there is a good paring of various RE options to provide the requested service. This will often result in lower quantities of supplied RE for meeting energy services demanded by end-users. Overall, quantities of energy traded may significantly shrink during the transition to a RE economy. Measuring transition progress requires other indicators than simple quantities of supplied energy or installed capacities but, for assessing RE potentials, clear metrics help in comparing results of studies.

3. Costs and prices

"Costs" rank among the most-used words on earth. In daily practice, people understand quite well what is covered by the

[1] Renewable energy supplies are the result of a combination of RE sources with operational RE technologies. For power (mostly electricity) supplies technological apparatus is always necessary; for some heat supplies (e.g., solar drying), natural ventilation, daylight, less or no apparatus is needed.

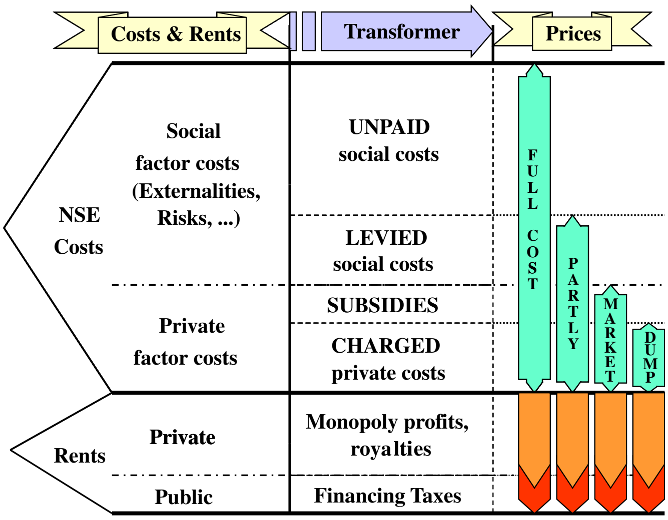

Fig. 2. Non-sustainable energy (NSE) supply costs transformed into energy prices.

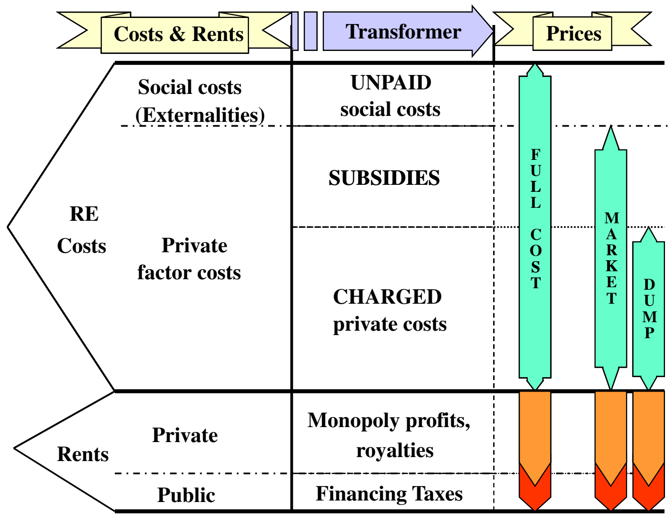

Fig. 3. . Renewable energy (RE) supply costs transformed into energy prices.

term. In science, the term "costs" gives rise to misunderstandings and confusion (e.g., Jaccard et al., 2003; Jaccard, 2004; Kümmel et al., 2008). The cost vocabulary of economic theory (micro and public economics) is almost unknown outside the economics profession and inside use is often ambiguous. In the economics profession, costs refer to the use and consumption of real resources or production factors (land, materials, labor time, buildings, utensils, etc.); all costs boil down to "opportunity" costs, i.e., the results foregone by assigning the real resources and factors to project A making them unavailable for the next-best project B. Costs as such are measured independently of who pays them and what prices the various production factors and outputs obtain in the actual functioning of a society. "Goods of different specification can only be compared in terms of initial resource content or final utility value. Since there are many individuals with varied preferences, a single utility measure is out of the question, and thus resource input measures must be used." (Lancaster, 1979, p. 33).

Between costs and prices one finds working transformers that may cause large deviations between both realities. This is shown in Fig. 2 for the supply of non-sustainable energy, while Fig. 3 applies the format of Fig. 2 on the supply of renewable energy.[2]

One can classify costs by distinguishing between private and social costs. Private costs are – in principle – those paid by private entities (individuals, households, companies or other limited organizations). Social costs refer to the residual use of real production factors, not falling on private entities. Prime examples are the use of natural and environmental resources, social capital, knowledge freely available in the public domain, etc. But a full inventory of all social costs, a fortiori a comprehensive assessment and quantification of their true extent, are not available and not attainable. Not everything can be monetized, some costs are unknown and there may exist ignorance about important effects and their related costs (Stirling, 1997).

Costs do not steer people's decisions directly, but prices play a crucial role: prices mainly determine demand and how production is organized (Becker, 1971). A transformer links prices to costs (Fig. 2). This transformer is man-made, largely steered by the distribution of influence in society across market parties and across private decision makers and public authorities.[3] Social costs are split in an unpaid and levied part; private costs may be partly subsidized, leaving a smaller part charged to end-users.

Rents are income flows not directly based on real costs but dependent on market structures and on property rights (again man-made constructions). Rents are raised on top of the real costs, and may be cashed as monopoly profits, royalties, etc. by private parties. Fiscal or financing taxes are rents obtained by the treasury (representing the public interest).

Depending on which slices in the costs' transformer column find their outlet in the prices paid by end-users, one obtains different reference prices that further may be enhanced by rent add-ons (Fig. 2). The "best" price is the full-cost price with full payment of all costs: social costs via public levies and without subsidies and rents. The partly levied price comes in as second-best. Market price is third. With subsidized private factor costs one is left with dumping prices. To the above prices may be added rents. Adding monopoly profits to full-levied social costs may significantly overcharge end-users; in practice, because of demand elasticity, they are generally mutually exclusive, or only partly levied social costs may allow addition of monopoly rents. Pure monopolies often find ways to get their activities subsidized, so they can turn a larger share of the charged prices into profits.

Depending on the influence of parties involved, prices can vary significantly. Fig. 2 may help in understanding that the correspondence between costs and prices is not a one-to-one technical relationship but is tricky, multi-faceted and policy influenced. For example, a high price for non-sustainable energy may be due to good public governance applying full levies on social costs, or to high monopoly profits as a result of weak governance. The same price tag covers two opposite realities with quite diverging impact on the development of renewable energy.

Fig. 3 applies the structure of Fig. 2 to the case of renewable energy with the ratio social costs to private costs reversed (partly levied social costs is omitted as a case). Comparing Figs. 2 and 3 shows that charging market prices penalizes renewable energy compared to non-sustainable energy, as has been documented by many (Scheer 2001). It is important to assess the (likely, approximate) height of the social costs of the various – mainly non-sustainable – energy supplies, such as damage to nature and environment, long-term risks, unequal

[2] The figures in this publication have no cardinal scaling. For example the real ordinate of Fig. 2 may be a multiple of the ordinate of Fig. 3; the same comment is valid for Figs. 4 and 5.

[3] We do not assume perfect markets for granted but consider the reality of politics, networks, monopolistic power, lobbyism, etc.

distribution of benefits, etc. Even more important is the design and operation of a good transformer between costs and prices, in particular for including levies on non-sustainable energy and for excluding monopoly profits (which provide financial power to incumbents that base their production on non-sustainable options).

The vocabulary terms "benefits" and "costs" refer to concepts that cover the joint public and private domain (with welfare measured as the difference between benefits and costs). The term "economic" then includes all costs. For private entities (households, companies) one uses the words "revenues" and "expenditures" (quantities of goods and services times the prices paid by the private entities) with the differences called profits or losses. This corresponds with what are called "market" conditions. For example, financing taxes added to a commodity do not reflect direct[4] economic costs (economists call it "transfers") but they are expenses for the purchasing private entity (who will see these as "costs"!). In practice, it may be wishful thinking to expect an interdisciplinary scientific community to understand the term "economic" as economics prescribed in general equilibrium analysis.

4. IPCC (TAR and AR4) on mitigation potentials

Cross-cutting meetings of WGIII TAR and AR4 discussed concepts for understanding mitigation potentials, barriers, and actions for addressing barriers to realize potentials. TAR devoted Chapter 5 on "Barriers, Opportunities, and Market Potential of Technologies and Practices" (Sathaye et al., 2001). Fig. 5.1 of this Chapter 5 (retrieved as Fig. TS.7 in the Technical Summary of the TAR, and here as Fig. 4) provides a visual framework of potentials, barriers and actions.

The figure itself and its many callouts were the outcome of merging quite different visions of the lead authors. First, the TAR figure introduced the future time perspective to the study of potentials, extending the more static character of the "efficiency gap" discussions (e.g., Jaffe and Stavins, 1994). Secondly, the interdependencies among potentials, barriers and actions were clarified and illustrated. Thirdly, the potentials were analyzed bottom-up, starting from coverage presently achieved and expanding the occupied area upwards over market and economic potentials towards technological and physical potentials. As baseline evolution or expected future in a business-as-usual scenario, the TAR figure used the term "market potential", defined as the "actual use of environmentally sound technologies and practices", or more fully as "the amount of GHG mitigation that might be achieved under forecast market conditions, with no changes in policy or implementation of measures whose primary purpose is the mitigation of GHGs" (Sathaye et al., 2001, p. 347). Because the baseline evolution was called market potential, two types of economic potentials were added: economic (something like improved market) and socioeconomic. The economic potential was defined in the TAR figure as "approached by creation of markets, reduction of market failures, increased financial and technology transfers", or more fully as "the level of GHG mitigation that could be achieved if all technologies that are cost-effective from consumers' point of view were implemented. Because economic potential is evaluated from the consumer's point of view, cost-effectiveness would be evaluated using market prices and the private rate of time discounting, and also take into account consumers' preferences regarding the acceptability of the technologies' performance characteristics" (Sathaye et al., 2001, p. 352).

During the writing process of the Fourth Assessment Report (2003–2006), the definitions of potentials were partly reset to the terminology where the discussions in the third assessment process started. The TAR figure was shelved, yet it had gained some popularity. The definitions of "potential" by the AR4 (IPCC-WGIII, 2007, p. 819 (Glossary)) are:

Potential: In the context of climate change, potential is the amount of mitigation or adaptation that could be but is not yet realized over time. Potential levels are identified as: market, economic, technical and physical.

- *Market potential* indicates the amount of GHG mitigation that might be expected to occur under forecast market conditions including policies and measures in place at the time. It is based on private unit costs and discount[5] rates as they appear in the base year and as they are expected to change in the absence of any additional policies and measures.
- *Economic potential* is used in most studies as the amount of GHG mitigation that is cost-effective for a given carbon price, based on social cost pricing and discount rates, including energy savings but without most externalities. Theoretically, it is defined as the potential for cost-effective GHG mitigation when non-market social costs and benefits are included with market costs and benefits in assessing the options for particular levels of carbon prices (as affected by mitigation policies) and when using social discount rates instead of private ones. This includes externalities, i.e., non-market costs and benefits such as environmental co-benefits.
- *Technical potential* is the amount by which it is possible to reduce GHG emissions or improve energy efficiency by implementing a technology or practice that has already been demonstrated. No explicit reference to costs is made but adopting 'practical constraints' may take into account implicit economic considerations.
- *Physical potential* is the theoretical (thermodynamic) and sometimes, in practice, rather uncertain upper limit to mitigation.

The new definitions do not solve the confusion between baseline scenarios and expected achievements as "market potential" because the phrase "with policies and measures in place at the time" may allude to business-as-usual or to enhanced policies. In general, markets cannot be considered as perfect and their working can be improved by policies that untie barred potentials. The TAR socioeconomic potential is renamed by AR4 as economic potential, in line with the formally correct economics vocabulary. The definitions of technical and physical potential were not changed over the two IPPC assessment periods. IPCC TAR and AR4 devote little attention to the technical and physical potentials because they are out of range of realization and actual policy making during the coming decades.

Renewable energy development and deployment is but one option within the wider range of greenhouse gas emissions

[4] Financing taxes create indirect costs when distorting first-best economic equilibrium. Applying levies charging for social costs and substituting for taxes then generates a "double dividend".

[5] IPCC-WGIII (2007, p. 813 (Glossary)) defines discounting and discount rates as follows: **Discounting:** A mathematical operation making monetary (or other) amounts received or expended at different points in time (years) comparable across time. The operator uses a fixed or possibly time-varying discount rate (>0) from year to year that makes future value worth less today. In a descriptive discounting approach one accepts the discount rates people (savers and investors) actually apply in their day-to-day decisions (private discount rate). In a prescriptive (ethical or normative) discounting approach the discount rate is fixed from a social perspective, e.g., based on an ethical judgement about the interests of future generations (social discount rate).

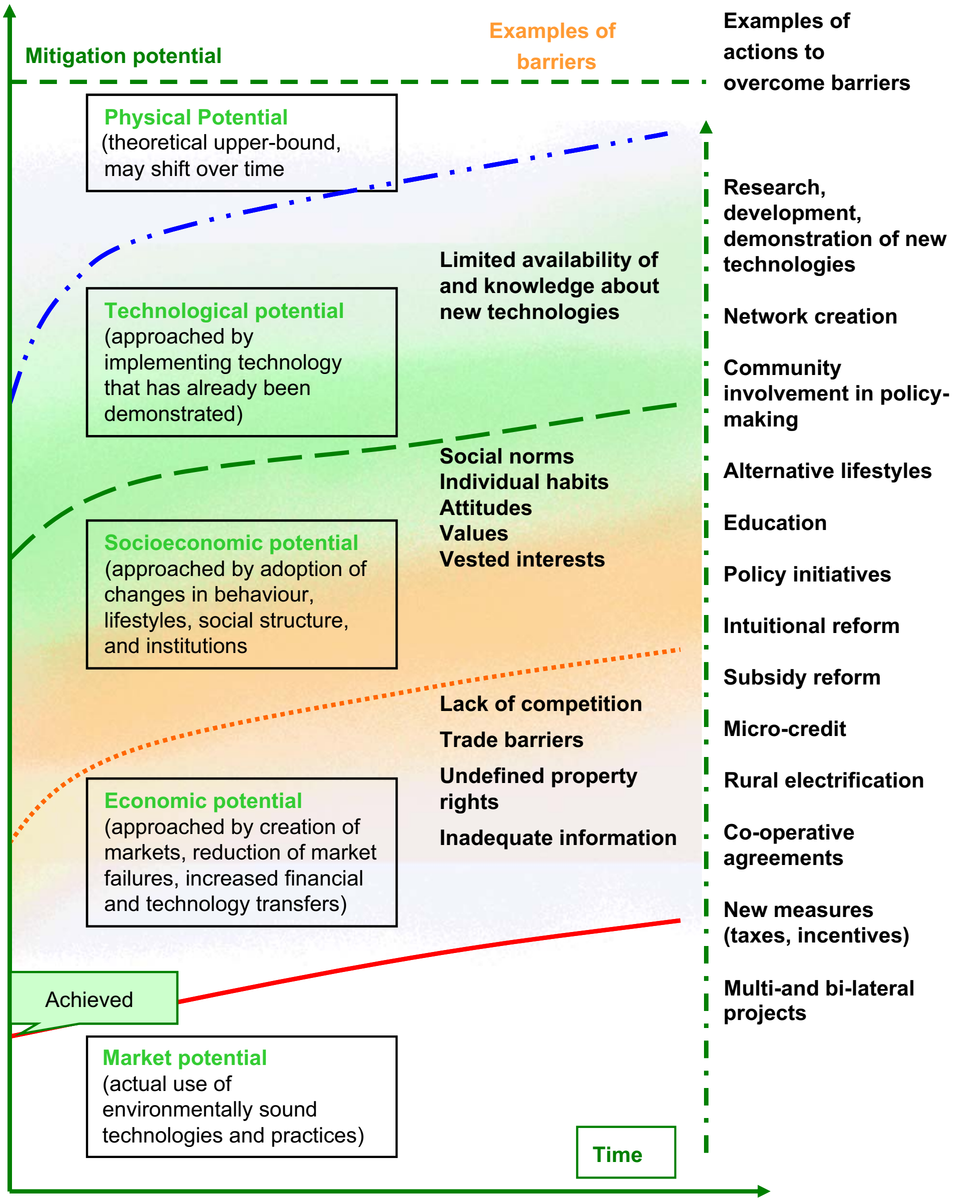

Fig. 4. . IPCC mitigation potentials [*Source*: IPCC-WGIII (2001, Chapter 5)].

mitigations. This greater specificity of the SRREN reduces complexity and allows more accurate definitions and implementation of the concepts. This helps in integrating the TAR and AR4 debate results in a new framework while applying it on the development and deployment of renewable energy sources and technologies (see Section 6).

5. RE potential definitions from the literature

The renewable energy literature provides several definitions of RE potentials, not tuned to one another and open to criticism. Here are discussed five references, in sequence of their publication date. They were selected and included here from a wide range of studies to show the variety in approaches and definitions.

5.1. RETD (2006)

This report focuses mainly on barriers, opportunities to resolve the barriers and involved stakeholders. Eight main barriers are identified without classification (see Table 3 in RETD, 2006, p. 10). Their interconnections are not analyzed and they are not related to the realization of particular potentials. Related to RE potentials, the report mentions three levels: current use, technical potential, and theoretical potential in Table 7 (RETD, 2006, p. 30), referring to Johansson et al. (2004). Except for the exploration of the eight main barriers, the report does not add to the conceptual understanding of potentials in relation to barriers.

5.2. Stangeland (2007)

This author presents a few potential definitions based on work of other authors:

"*Theoretical potential*: The total physical amount of energy for a given source.
Technical potential: The amount of energy that can be utilized with today's technologies.
Realistic potential: The amount of energy that can realistically be utilized after marked barriers and barriers such as; social

acceptance; environmental factors; and area conflicts are considered.
Realizable potential: The energy which can be realized within a given timeframe. This energy potential depends on economic conditions as well as global market production capacity.''

The definitions look simple but contain several puzzles. For example: what is the physical amount of energy for a given source? The technical potential is defined in a static way (''today's technologies''), which is a step back compared to most potential concepts nowadays. The barriers that uphold the realistic potential are quite general. The same can be said of the ''realizable potential''. Moreover, this is a strange term because a potential is by definition something that can be realized (see Webster's definition in Section 1).

5.3. Hoogwijk and Graus (2008)

Hoogwijk and Graus (2008, pp. 6–7) mention following RE potentials:

- ''*Theoretical potential*: The highest level of potential is the theoretical potential. This potential only takes into account restrictions with respect to natural and climatic parameters.
- *Geographical potential*: Most renewable energy sources have geographical restrictions, e.g., land use land cover that reduce the theoretical potential. The geographical potential is the theoretical potential limited by the resources at geographical locations that are suitable.
- *Technical potential*: The geographical potential is further reduced due to technical limitations such as conversion efficiencies, resulting in the technical potential.
- *Economic potential*: The economic potential is the technical potential at cost levels considered competitive.
- *Market potential*: The market potential is the total amount of renewable energy that can be implementation in the market taking into account the demand for energy, the competing technologies, the costs and subsidies of renewable energy sources, and the barriers. As also opportunities are included, the market potential may in theory be larger than the economic potential, but usually the market potential is lower because of all kind of barriers.''

They focus on only the technical potential that they define as ''the total amount of energy (final or primary) that can be produced taking into account the primary resources, the socio-geographical constraints and the technical losses in the conversion process.'' (p. 7).

Some comments on their nomenclature:

Theoretical potential seems equal to the physical renewable energy resources available on earth. As such it is not a potential of RE supplies, because no technologies for harvesting the resources are considered. Geographical potential appears to include only ''physical'' aspects in its first definition, but then includes land-use as well as ''socio-geographical constraints'', i.e., the full range of socio-economic, political and institutional (e.g., property rights) factors enter the definition.

Technical potentials are the multiplication of the geo-graphically reduced resource base with conversion efficiencies of RE technologies. As shown in Fig. 1, technologies and their development are affected by policies and prices. The physical to technical potentials are very large. On the one hand, this top-down vision may help in overcoming disbelief that RE can meet the energy needs of the world. On the other hand, bottom-up analysis is needed for practical insight in how policies must be re-invented and re-designed to set prices right, overcome barriers, and stimulate technological innovation (Fig. 1).

Economic potential as ''technical potential at cost levels considered competitive'' is short but unspecified. As discussed in Section 3, costs cover private and social parts, and do not relate to competitiveness in a linear way. This fact is at the heart of the potentials-barriers debate and requires clarification.

The definition of market potential is also problematic. First it takes ''into account the demand for energy''. How much energy is required to supply a given energy service depends specifically on the process used to provide that service and its inherent energy efficiency. Given the large range of energy required to deliver the same energy service in different ways raises the question of how is the demand side of the energy market introduced into the assessment of potentials for RE to supply a specific portion of the required energy? Potentials of RE supplies (energy, capacities) that can be delivered under particular conditions and in given circumstances, are a supply side concept. In principle, market equilibriums are found at the crossing of demand curves with supply curves, and one needs ''independent'' assessment of the respective curves to get informed about the likely equilibriums. Also practically speaking, it is already difficult to come up with good estimates of supply curves, so why should one (at least) double complexity by adding assessment of the demand side to the task?

In addition, ''competing technologies'' for RE are not of direct relevance for estimating RE potentials and can better be left out. ''Costs and subsidies'' of RE are a decisive factor (Fig. 1 in Section 1) and merit full attention and specification (Figs. 2 and 3 in Section 3). Further is stated that ''also opportunities are included'', again widening their definition of market potentials. Indeed one can observe an ''increased level of complexity'' as the arrow in their Fig. 1 mentions. But because the authors ''focus on the technical potential'', they think they are not hindered by the complexity and confusion created by their definitions of economic and market potentials. However, as stated above, land-use is an extremely socio-political dimension and no technologies are free of socio-political influences.

5.4. Krewitt et al. (2008).

Krewitt et al. (2008) assess RE deployment potentials in large economies, and start with definitions based on Hoogwijk and Graus, but changing the contents:

- ''*Theoretical potential*: The theoretical potential is derived from natural and climatic parameters (e.g., total solar irradiation on a continent's surface). The theoretical potential can be quantified with a reasonable accuracy, but the information is of little relevance.The theoretical potential of renewable energy sources is huge compared to global energy demand, and there are various constraints in exploiting the theoretical potential.
- *Technical potential*: The technical potential takes into account geographical restrictions (e.g., land use cover that reduces the theoretical potential) as well as technical and structural constraints. Due to technical progress of energy conversion technologies, the technical potential may change over time.
- *Economic potential*: The economic potential is the technical potential that can be exploited at competitive costs. As the break even between renewable energy technologies and conventional technologies change over time (rise in fossil fuel prices, reduction in renewable energy generation costs), the economic potential is highly dependent on framing conditions.
- *Deployment potential*: The deployment potential characterises the potential market uptake of renewable energy technologies

under pre-defined framing conditions. It depends on e.g., the structure of the existing supply system, the development of energy demand, and on energy policy targets and instruments in place.

- *Demand potential*: With increasing competitiveness of renewable energies, in the future the economic potential may exceed the energy demand. In such a case the deployment potential of renewable resources is of course limited by the energy demand."

Overall the changes have improved the Hoogwijk–Graus definitions:

Theoretical potential: one may doubt that they "can be quantified with a reasonable accuracy". But as Krewitt et al. (2008) state: "the information is of little relevance" and therefore few are really concerned about the accuracy of the estimates.

Technical potential here integrates the geographical and technical levels of Hoogwijk–Graus, but adds "structural constraints" and a notion of time dynamics.

Economic potential is based solely on "competitive costs" (where it is uncertain whether the authors mean costs or rather prices; Figs. 2 and 3 above), "highly dependent on framing conditions" (without specifying what is understood by this general term). Contrary to IPCC work on economic potentials, issues of private versus social costs and discount rates are not mentioned here. Therefore one is uncertain whether the authors converge to the IPCC AR4 definition of "economic" or at the TAR definition, where "market economic" is meant (Section 4 above).

Deployment potential is also not defined unequivocally: is it a baseline (business-as-usual) potential or a market potential (after removal of some market barriers)? The term "pre-defined framing conditions" is not specified, but the last part of their definition points more to baseline developments.

Demand potential remains unclear until the essential components of demand for energy are clarified, for example: the balance (stalemate) between RE and non-sustainable supplies; the future role of energy efficiency[6] as factor in lowering energy intensities including lifestyles and GDP restructuring; the extent of markets[7]; ability to pay (mainly in developing nations revealed demand as "willingness to pay" is much lower than latent demand); technological innovation in storage, transport, regulation, affecting aggregation of demand and load management. In principle, demand side considerations are covered in the assessment of potentials, most obviously in "market potentials" but also very influential on "sustainable development potentials" (Section 6)—however, without engaging in the full study of the demand for energy services and derived from this the demand for energy supplies (from renewable and from non-sustainable sources). Integrated assessment models address the interactions of demand and supply (Edenhofer et al., 2006; Pizer et al., 2006).

The potentials definitions of Krewitt et al. (2008) again are quite distant from the ones introduced by IPCC TAR and AR4 and, in particular, what market and economic potentials cover.

5.5. *Resch et al. (2008)*

In an article where the "core objective [was] to present an overview on the RE potentials and prospects globally", Resch et al. (2008, p. 4049)) introduce their terminology as follows:

> "*Theoretical potential*: For deriving the theoretical potential general physical parameters have to be taken into account (e.g., based on the determination of the energy flow resulting from a certain energy resource within the investigated region). It represents the upper limit of what can be produced from a certain energy resource from a theoretical point-of-view—of course, based on current scientific knowledge.
> *Technical potential*: If technical boundary conditions (i.e., efficiencies of conversion technologies, overall technical limitations as, e.g., the available land area to install wind turbines) are considered the technical potential can be derived. For most resources, the technical potential must be seen in a dynamic context—e.g., with increased R&D conversion technologies might be improved and, hence, the technical potential would increase.
> *Realisable potential*: The realisable potential represents the maximal achievable potential assuming that all existing barriers can be overcome and all driving forces are active. Thus, general parameters, such as market growth rates and planning constraints, are taken into account. It is important to mention that this potential term must be seen in a dynamic context—i.e., the realisable potential has to refer to a certain year.
> *Mid-term potential*: The mid-term potential is equal to the realisable potential for the year 2020."

Their definitions of theoretical and technical potentials are practically identical to the Krewitt et al. (2008) definitions (see comments above). Their "realizable potential"[8] definition (the 2020 mid-term potential is just a point on the curve) is fully dependent on how they would define "all existing barriers" and "all driving forces". But apart from the following sentence "Thus, general parameters as, for example, market growth rates, planning constraints are taken into account" the article provides no clarity on the implied barriers and driving forces.

5.6. *Findings*

The brief overview of five literature sources shows that the notion of RE potentials is an unsettled concept. Most authors come up with their own definitions that are mostly not well explained, sometimes seemingly simple but difficult to understand and to generalize. Although some figures drawn by the authors (Krewitt et al., 2008; Resch et al., 2008) seem inspired by the IPCC-TAR figure (Fig. 4), there is no explicit link made to the IPCC definitions of mitigation potentials and barriers.

The differences between these and IPCC definitions are significant. Contrary to the upward IPCC approach of mitigation potentials (from achieved to market and to economic), the authors mentioned above all take a downward approach starting from the "theoretical potential", i.e., the physical resource base of renewable energy. The reviewed publications prefer theoretical, geographical, technical potentials and their assessment of policy relevant potentials is reductive (downwards). The reviewed publications offer no clear definitions of market and economic potentials of RE supplies. One has to consider specific factors in order to move up from present low levels to higher market shares of RE supplies.

[6] The amount of energy required for a specific energy service depends upon the efficiency characteristics of the end use conversion device (Laitner 2009).

[7] For example, Norwa demand for energy may be a few times lower than its RE potential; when considering Norway isolated, the estimates will limit the RE potential to the demand by Norway; when, however, Norway is seen as part of an European/world market demand is not a constraint.

[8] Realizable potential is also a strange term.

Rather than dissecting more published RE potentials terminology, we develop in Section 6 a proposal that we consider workable for the IPCC SRREN work.

6. Potentials of renewable energy supplies

Because of the many terms and definitions associated with "potentials", we propose a unified taxonomy with an emphasis on policy-driven aspects. This new set of definitions may be clearer and more useful to analysts and policy makers than the earlier versions discussed in Sections 4 and 5. It may be adopted in the SRREN and in subsequent IPCC documents and provide a useful benchmark in other studies.

Renewable energy sources and technologies are diverse and their future depends on a variety of circumstances. This diversity requires a clear nomenclature of types of supplies (sources and technologies) considered for given areas and periods. Once this specificity is provided, RE supply potentials can be better defined than the wider issue of greenhouse gas emissions mitigated. This is thanks to the numerical clarity in RE supply metrics (Section 2) and the ease of classification as electricity production, heat supply, or bio-fuel (SRREN). Applying metrics that provide transparent outcomes offers solid ground for clarity in reported results.

To be useful in a policy context, potentials are best estimated from the bottom-up,[9] starting at achieved RE supplies in a given reference year and documenting how the supplies can be increased from that level onwards, what barriers should be removed and what policies are available to do so [IPCC does not "prescribe" policies]. Providing a value for achievable RE supplies in 2010 delivers a solid fixed point for potential estimates. Setting out baseline points for future years (2020 and 2030 in Fig. 5) may be considered too. Baseline estimates are the amounts of RE output expected to be achieved in the future, given a *business-as-usual* evolution of technological development and diffusion, circumstances and *current* policies. For "current", one must adopt a given time period; for the SRREN, the year 2005, or the period 2005–2010. When business-as-usual is irrelevant for the future, baseline estimates can be skipped (presumably the most efficient choice when studying the development of RE). In another interpretation, the baseline is what happens when circumstances and policies are *frozen*. In this interpretation, the uncertainty about future scenarios is lower but so is the practical relevance of a frozen world. Again one may question the added value of all the efforts investing in assessing baseline potentials. In the modelling approach of potentials assessment, a baseline scenario is created for benchmarking the other scenarios.

Several potential levels for assessing possible future RE supplies could be retained (Fig. 5). The picture shows that potential estimates cover broad bands because clear-cut boundaries on potentials are impossible to define. Yet qualitative different levels help in structuring the potentials graduating from lower to higher supplies.

A description of the levels is as follows:

- *Market potential*: the amount of RE output expected to occur under forecast market conditions that are shaped by private economic agents and are regulated by public authorities. Private economic agents realize private objectives within given, perceived and expected conditions. Market potentials are based on expected private revenues and expenditures, calculated at private prices (incorporating subsidies, levies, and rents) and with private discount rates. in reality, the private context is partly shaped by public authority policies.
  Public regulations change over time (Fig. 1): man-made barriers can be addressed directly by dedicated policies; prices experienced by market parties can be shifted by changing subsidies, levies and taxes; technological innovation may lower costs of RE options and help in abolishing man-made barriers. In realizing the market potential, lifting such barriers happens within the perspectives and boundaries of established socio-economic contexts and without disruptive changes. Because contexts and policies differ by region or country, market potentials also are different by region or country. Since it is not possible to forecast the exact response to a certain policy instrument, as well as future costs, prices and consumer preferences, there is by default a level of uncertainty concerning the size of the market potential.
- *Economic potential*: the amount of RE output projected when all – social and private – costs and benefits related to that output are included. in realizing the economic potential, negative externalities and co-benefits of all energy uses and of other economic activities are priced, while social discount rates are used to balance the interests of consecutive human generations.
  The definition reveals that economic potential is a theoretical ideal. Steps in its direction are made by increasing internalization of externalities in the prices end-users face and by more focus on long-term interests. By construction, economic optima do not take into account the distribution of wealth between or within countries, or stated in economists' language: every distribution (however, much skewed) will exhibit its own Pareto optimum. In comparison to the market potential, the size of the economic potential is adding another layer of uncertainty, mainly due to limits in our knowledge of the extent of the external costs or how we should value identified externalities. Furthermore, there is uncertainty in the forecasting of various costs and prices. Economic potentials are ostensibly rational and value neutral but in reality hide important assumptions with ethical ramifications. Case in point is the present values of (loss of) life of persons in poor versus rich countries when calculated from the unequal income levels. Discounting over long periods (50–100 years and more) reduce future values to insignificant amounts, even when discount rates are fairly low.

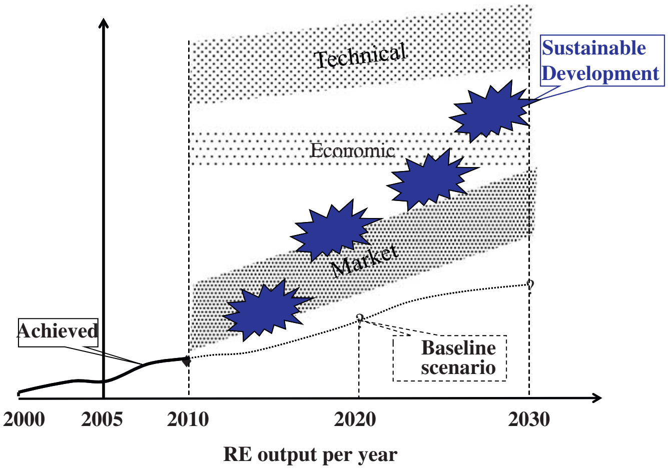

Fig. 5. RE supplies potentials by RE-type and by region or country.

[9] This does not diminish the importance of understanding the theoretical potential of RE supplies, which supersedes human consumption by thousands of times, i.e., renewable energy is not constrained by the resource but by technical, economic and political factors.

- *Sustainable development potential*: the amount of RE output that would be obtained when all four sustainability dimensions of WCED[10] are taken into account in an integrated holistic manner. This contrasts with the market and economic potentials, which take only partial account of social and environmental issues in working towards sustainable development, issues of governance need to be addressed explicitly (Sathaye et al., 2007).
  At present, the environmental dimension is imposed in such a way that it may curb the implementation of market potentials, for example, by opposing investments in biomass, hydro, and wind projects at particular sites (This is why in Fig. 5 the near-term sustainable development potential is lower than the market potential). When public governance is more directed to developing RE, the environmental, economic and social interests can be better balanced and integrated. For example, in the economic sphere one can envision a more complete internalization of social costs of non-sustainable options in market prices (Figs. 1 and 2), the application of low social discount rates instead of private ones for adhering more weight to the future, a shift in public investments from expanding infrastructures in industrialised nations to basic infrastructures in developing nations, the development and transfer of climate and environmentally benign technologies—in particular in energy supplies, the redirecting of almost all R&D resources to energy efficiency and renewable energy options away from non-sustainable energy options and more. In the socio-political sphere: adaptations and, eventually, fundamental changes in institutions, habits and lifestyles, vested interests (e.g., reducing the impact of large corporations on the public agenda setting), social structures, income and wealth distribution. A significant redistribution from the affluent part of the globe to the developing part may boost RE applications globally by turning latent demand into revealed demand.
  Social innovation, being crucial for a full deployment of sustainable development potentials, induces changes in existing institutions by social networks, notably through collective actions (Van de Kerkhof et al., 2009). The innovating role of civil society for the implementation of wind power was recently illustrated in several European countries, showing how social networks can contribute in the emergence of wind power projects (Agterbosch et al., 2009; Nadaï and Labussière, 2009).
  The sustainable development potential may be seen as adding further uncertainty compared to market and economic potentials through the stronger focus on equity and governance. But for that reason ignoring the widely embraced paradigm of sustainable development in the assessment of potentials is not acceptable.
- *Technical potential*: the amount of RE output obtainable by full implementation of demonstrated and likely to develop technologies or practices. No explicit reference to costs, barriers or policies is made but when adopting *practical constraints* analysts implicitly take into account economic and socio-political considerations.

Technologists often prefer to converge on technical potentials because they seem easy to derive from estimates of physical RE sources. From the perspective of building the path from where we are today to a high future penetration of RE supplies in the real energy economies of the nations, technical potentials provide less support to the policy process than market, economic and sustainable development potentials do.

Fig. 1 shows that potentials are affected by many factors with barriers hindering their smooth deployment.

7. Barriers

Like potentials, barriers are contextual and dynamically evolving over time, difficult to identify accurately. In the 1980–1990s an active debate took place on the significance of barriers for the level of energy efficiency (e.g., Jochem and Gruber, 1990; Reddy, 1991; Joskow and Marron, 1992; Koomey and Sanstad, 1994; Jaffe and Stavins, 1994; Porter and Van der Linde, 1995; Sutherland, 1996; DeCanio, 1998; Jaffe et al., 1999). This debate was also lively during the IPCC TAR process (Sathaye et al., 2001). The opposite views are summarized by Jaffe et al. (1999, p. 3) as: "At the risk of excessive simplification, we can characterize "technologists" as believing that there are plentiful opportunities for low-cost, or even "negative-cost" improvements in energy efficiency and that realizing these opportunities will require active intervention in markets for energy-using equipment to help overcome barriers to the use of more efficient technologies. These interventions would guide choices that purchasers would presumably welcome after the fact, although they have difficulty identifying these choices on their own. This view implies that with the appropriate technology and market creation policies, significant GHG reduction can be achieved at very low cost.

Most economists, on the other hand, acknowledge that there are "market barriers" to the penetration of various technologies that enhance energy efficiency but that only some of these barriers represent real "market failures" that reduce economic efficiency. This view emphasizes that there are tradeoffs between economic efficiency and energy efficiency—it is possible to get more of the latter, but typically only at the cost of less of the former. The economic perspective suggests that GHG reduction is more costly than the technologists argue and it puts relatively more emphasis on market-based GHG control policies like carbon taxes or tradable carbon permit systems to encourage the least costly means of *carbon efficiency* (not necessarily *energy efficiency*) enhancement available to individual energy users".

The distinction between market "barriers" and "failures" is precarious: for example, Brown (2001) calls "insufficient information" a market failure, while Sutherland (1996) unveils the public and private good character of information, the latter acquired by consumers along their willingness-to-pay for it. The debate was fierce in the USA, where electric utilities organized Demand Side Management (DSM) programs for their customers (or subgroups) recovering the expenditures in the rates of all electricity users. In the 1990s, electricity intensity in the USA was above 400 Wh/$ GDP, with countries like Germany and Japan at less than half that value (IEA, OECD statistics). Electricity prices in Europe and Japan were double (or more) the prices in the USA, explaining most of

[10] "In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" (WCED 1987, p. 46). IPCC-WGIII (2007, p. 821 (Glossary)) further added: "Sustainable Development integrates the political, social, economic and environmental dimensions."By influential publications (Munasinghe, 1992; Munasinghe and Swart, 2005) attention was almost exclusively focused on the economic, social and environmental dimensions, further reduced by the 3P speak (Profit, People, Planet). "The pillar-focused approaches have gained great popularity, particularly in business circles, but they have often suffered from insufficient attention to overlaps and interdependencies and a tendency to facilitate continued separation of societal, economic, and ecological analyses (Kemp et al., 2005). Alternative depictions stressing interconnection and consideration of institutional aspects – as in the PRISM model of Spangenberg et al. (2002), Farell et al. (2005) and the SCEN model of Grosskurth and Rotmans (2005) – offer useful ways forward." (Kemp and Martens, 2007, p. 2).

the differences in intensity (largely due to differences in efficiency; Geller and Attali, 2005). Sutherland (1996) argued that prices [should] direct user choices and that DSM was a waste of resources. Koomey and Sanstad (1994) as many other "technologists" present large free and low-cost potentials (see Enkvist et al., 2007 for a recent version). Porter and Van der Linde (1995), DeCanio (1998) among others illustrate that in real life significant opportunities for higher efficiencies at negative or zero cost remain unused, i.e., there are barriers at work.

Fig. 1 shows the truth is on both sides and that policies may walk three main avenues, two indirect ones via the detour of prices and technological innovation (R&D) and one direct by targeting particular barriers via dedicated initiatives.

SRREN plans to identify all major barriers for a disruptive deployment of RE sources and technologies. A specific literature on RE barriers is developing (Beck and Martinot, 2004; Margolis and Zuboy, 2006). IPCC will assess the available knowledge and may provide taxonomies and lists of barriers for better understanding how RE supply potentials can be unleashed by improved policies.

8. Wrapping up

This article proposes more extended, and hopefully also clearer, definitions of some major factors and relationships that affect the development and deployment of RE supplies in given energy economies (Fig. 1). Because of limits on time and space, the focus is on costs and prices, RE supplies potentials, with little attention paid to barriers and even less to technological innovation and policies. The presented concepts are open for discussion and improvement within a community of scholars of various disciplines some of whom will edit the SRREN by end 2010. Of significance for designing policies, market, economic and sustainable development potentials are maintained below a ceiling technical potential (Fig. 5). The assessment of baselines is considered of little added value to understand future developments because "business-as-usual" and "frozen" worlds regarding RE development are unrealistic. Sustainable development potential opens new perspectives: the potentials graduate from short-run fencing in some RE investments to long-run full RE substitution for non-sustainable energy supplies. The latter requires action on all four dimensions of sustainable development: better governance, improved economics with full-cost pricing attaining spatial and temporal efficiency, less intensive resource use, more equity.

No extensive taxonomies or lists of barriers are provided here. It may be expected that SRREN will deliver authoritative results regarding barriers as well regarding a nomenclature of RE sources and technologies annex a better qualification of RE supplies.

References

Agterbosch, S., Meertens, R.M., Vermeulen, W.J.V., 2009. The relative importance of social and institutional conditions in the planning of wind power projects. Renewable and Sustainable Energy Reviews 13, 393–405.

Arzivu, D.E., 2008. Potential role and contribution of direct solar energy to the mitigation of climate change. In: Hohmeyer and Trittin, 2008, o.c., pp. 33–58.

Beck, F., Martinot, E., 2004. In: Renewable Energy Policies and Barriers. Encyclopedia of Energy. Academic Press/Elsevier Science 22pp.

Becker, G., 1971. In: Economic Theory. Alfred A.Knopf, New York 222pp.

Brown, M.A., 2001. Market failures and barriers as a basis for clean energy policies. Energy Policy 29, 1197–1207.

Cleveland, C.J., Morris, C. (Eds.), 2006. Dictionary of Energy. Elsevier 502pp.

DeCanio, S., 1998. The efficiency paradox: bureaucratic and organizational barriers to profitable energy-saving investments. Energy Policy 26, 441–454.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., Köhler, J., 2006. Induced technological change: exploring its implications for the economics of atmospheric stabilization: synthesis report from the innovation modeling comparison project. The Energy Journal (Special Issue), 57–107.

Enkvist, P-A., Nauclér, T., Rosander, J., 2007. A cost curve for greenhouse gas reduction. The McKinsey Quarterly 1, 36–45.

European Parliament, 2008. Promotion of the use of energy from renewable sources. European Parliament legislative resolution of 17 December 2008. Adopted by the Justice and Home Affairs Council on 6 April 2009 as 8037/09 ADD 1, Inter-institutional file no. 2008/0016 (COD).

Farell, K., Kemp, R., Hinterberger, F., Rammel, C., Ziegler, R., 2005. From "for" to governance for sustainable development in Europe: what is at stake for further research. International Journal of Sustainable Development 8 (1–2), 127–150.

Fri, R.W., 2003. The role of knowledge: technological innovation in the energy system. The Energy Journal 24 (4), 51–74.

Geller, H., Attali, A., 2005. The experience with energy efficiency policies and programmes in IEA countries: learning from the critics. IEA Information Paper, 43pp.

GIGATON Throwdown 2009. Redefining What's Possible for Clean Energy by 2020. The Gigaton Throwdown Initiative, San Francisco, 141pp. 〈http://www.gigatonthrowdown.com〉.

Grosskurth, J., Rotmans, J., 2005. The scene model: getting a gripon sustainable development in policy making. Environment, Development, and Sustainability 7 (1), 135–151.

Hohmeyer, O., Trittin, T., 2008. IPCC Scoping meeting on renewable energy sources. In: Proceedings of Lübeck Meeting, 20–25 January 2008, 174pp.

Hoogwijk, M., Graus, W., 2008. Global potential of renewable energy sources: a literature assessment. Ecofys by order of: REN21–Renewable Energy Policy Network for the 21st Century, 45pp.

Hummel, H., 2007. Interpreting energy technology & policy implications of climate stabilization scenarios. International Energy Workshop, Precourt Institute on Energy Efficiency, Stanford University, 26 June 2007.

IEA, 2006. In: Energy Technology Perspectives. International Energy Agency, Paris 479pp.

IPCC-WGIII, 2001. In: Climate Change 2001. Mitigation. Cambridge University Press 752pp.

IPCC-WGIII, 2007. In: Climate Change 2007. Mitigation of Climate Change. Cambridge University Press 851pp.

Jaccard, M., 2004. Greenhouse gas abatement: controversies in cost assessment. Encyclopedia of Energy 3, 57–65.

Jaccard, M., Nyboer, J., Bataille, C., Sadownik, B., 2003. Modeling the cost of climate policy: distinguishing between alternative cost definitions and long-run cost dynamics. The Energy Journal 24, 49–73.

Jaffe, A., Stavins, R., 1994. The energy efficiency gap: what does it mean?. Energy Policy 22, 804–811.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 1999. Energy-efficient technologies and climate change policies: issues and evidence. resources for the future. Climate Issue Brief no.19, 19pp.

Jochem, E., Gruber, E., 1990. Obstacles to rational electricity use and measures to alleviate them. Energy Policy 18, 340–350.

Johansson, T.B., McCormick, K., Neij, L., Turkenburg, W., 2004. The potentials of renewable energy. Thematic background paper for Renewables 2004.

Joskow, P., Marron, D.B., 1992. What does a negawatt really cost? Evidence from utility conservation programmes. The Energy Journal 13 (4), 41–74.

Kemp, R., Parto, S., Gibson, R., 2005. Governance for sustainable development: moving from theory to practice. International Journal of Sustainable Development 8 (1–2), 13–30.

Kemp, R., Martens, P., 2007. Sustainable development: how to manage something that is subjective and never can be achieved?. Sustainability: Science: Practice & Policy 3 (2), 1–10.

Koomey, J., Sanstad, A., 1994. Technical evidence for assessing the performance of markets affecting energy efficiency. Energy Policy 22, 826–832.

Krewitt, W., Simon, S., Pregger, T., 2008. Renewable energy deployment potentials in large economies. DLR (German Aerospace Center), 37pp.

Kümmel, R., Schmid J., Lindenberger, D., 2008. Why production theory and the Second Law of Thermodynamics support high energy taxes. IAEE Conference, Perth, 14pp.

Lancaster, K., 1979. In: Variety, Equity, and Efficiency. Columbia University Press, New York 373pp.

Margolis, R., Zuboy, J., 2006. Nontechnical barriers to solar energy use: review of recent literature. National Renewable Energy Laboratory. Technical Report NREL/TP-520–40116, 26pp.

Munasinghe, M., 1992. Environmental economics and sustainable development. Environment Paper, United Nations Earth Summit Rio de Janeiro. World Bank.

Munasinghe, M., Swart, R., 2005. In: Primer on Climate Change and Sustainable Development. Cambridge University Press 445p.

Laitner, Skip, 2009. In: The Positive Economics of Climate Change Policies: What the Historical Evidence Can Tell Us. ACEEE, Washington, DC.

Moomaw, W., 2008. Renewable energy and climate change: an overview. In: Hohmeyer and Trittin, 2008, o.c., pp. 3–11.

Moomaw, W., Moreira, J., et al., 2001. IPCC AR4, Chapter 3, Technological and Economic Barriers to Reducing Emissions. Cambridge University Press, Cambridge, UK.

Moreira, J.R., 2008. Biomass for energy: uses, present market, potential and costs. In: Hohmeyer and Trittin, 2008, o.c., pp. 13–31.

Nadaï, A., Labussière, O., 2009. Wind power planning in France (Aveyron): from state regulation to local experimentation. Land Use Policy 26, 744–754.

Pizer, W.A., Burtraw, D., Harrington, W., Newell, R., Sanchirico, J., 2006. Modeling economy-wide versus sectoral climate policies using combined aggregate-sectoral models. The Energy Journal 27 (3), 135–168.
Porter, M., Van der Linde, C., 1995. Green and competitive: ending the stalemate. Harvard Business Review, 120–134.
Reddy, A.K.N., 1991. Barriers to improvements in energy efficiency. Energy Policy 19, 953–961.
Resch, G., Held, A., Faber, T., Panzer, C., Toro, F., Haas, R., 2008. Potentials and prospects for renewable energies at global scale. Energy Policy 36, 4048–4056.
RETD, 2006. Barriers, Challenges and Opportunities. Renewable Energy Technology Deployment (International Energy Agency), 105pp.
Sathaye, J., Bouille, D., et al., 2001. Barriers, opportunities, and market potential of technologies and practices. IPCC Third Assessment Report, Working Group III, Chapter 5, Cambridge University Press, pp. 345–398.
Sathaye, J., Najam, A., et al., 2007. Sustainable development and mitigation. IPCC Fourth Assessment Report, Working Group III, Chapter 12, Cambridge University Press, pp. 691–743.
Scheer, H., 2001. In: A Solar Manifesto. James & James Ltd., London 258pp.
Soerensen, H.C, Weinstein, A., 2008. Ocean energy: position paper for IPCC. In: Hohmeyer and Trittin, 2008, o.c., pp. 93–102.
Spangenberg, J., Pfahl, S., Deller, K., 2002. Towards indicators for institutional sustainability: lessons from an analysis of Agenda 21. Ecological Indicators 21 (1–2), 61–77.
Stangeland, A., 2007. In: The Potential and Barriers for Renewable Energy. The Bellona Foundation, Oslo 12pp.
Stirling, A., 1997. Limits to the value of external costs. Energy Policy 25, 517–540.
Sutherland, R.J., 1996. The economics of energy conservation policy. Energy Policy 24, 361–370.
Twidell, J., Weir, T., 2006. In: Renewable Energy Resources. Taylor & Francis 601pp.
Van de Kerkhof, M., Cuppen, E., Hisschemöller, M., 2009. The repertory grid to unfold conflicting positions: The case of a stakeholder dialogue on prospects for hydrogen. Technological Forecasting and Social Change 76, 422–432.
Verbruggen, A, Lauber, V., 2009. Basic concepts for designing renewable electricity support aiming at a full-scale transition by 2050. Energy Policy, 37, doi:10.1016/j.enpol.2009.08.044.
WCED, 1987. In: Our Common Future. World Commission on Environment and Development. Oxford University Press 383pp.